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SIMULATION OF DIFFERENT PUMPING SCENARIOS ON THE GROUNDWATER - SEA WATER INTRUSION INTO THE TRIPOLI AQUIFER, LIBYA

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Abstract

In arid and semi-arid regions; increasing groundwater salinity is one of the significant signs of groundwater quality degradation. This is a particularly serious environmental problem in coastal cities where the groundwater resources are being contaminated by sea water intrusion in coastal aquifers. In the coastal aquifer of the Tripoli region, the sea water intrusion continues to expand and the salinity of many wells has increased drastically in the last decades. The volume of groundwater being abstracted from this aquifer has exceeded the safe yield of the aquifer, causing a very significant drop in the water table, thus drying some of the wells. This issue of increased salinity in many parts of the aquifer has become a major cause of the deterioration of the aquifer structure. To address this issue, numerical modelling has been used to effectively manage groundwater resources to predict future responses, particularly in complex aquifer systems and heterogeneous formations. The ModelMuse model has been used as an indicator tool of this serious problem in the Tripoli aquifer. In this paper, three suggested pumping scenarios with varying abstraction rates for the next 80 years (from 2020 to 2100) were suggested. The impact of each scenario on groundwater level were investigated by using MODFLOW 2005 under ModelMuse software. The pumping scenarios; include: firstly, maintaining the fixed pumping rate of 70×10^6 m^3/yr for the study period, then increasing pumping rates due to population growth and in the third scenario, maintaining the pumping rate by using the sustainable abstraction of 19×10^6 m^3/yr for the period from 2020 to 2100. Results indicate that the first and second scenarios have a negative effect on the groundwater level, where these scenarios will lead to a significant decrease in the groundwater level. It is predicted that most of the wells will be dry by the year 2100 and sea water intrusion will extend to the boundary of the Tripoli aquifer in the South. However, when a sustainable quantity will be pumped from the aquifer (third scenario), a clear recovery of the aquifer will occur (increase in groundwater levels with reverse movement of the sea water from the aquifer towards the sea).

Keywords: Groundwater level, Pumping scenarios, Sea water intrusion, Sustainable abstraction, Tripoli aquifer.

1. Introduction

In Libya, the majority of the population can be found in the Mediterranean coastal zone, with most people concentrated in the main city of Tripoli located in the Jifara plain in the Northwest of Libya. Groundwater is the major source of fresh water in the Tripoli region for households, industries and for irrigation in Libya due to its semi-desert climate for this district of Libya. Population concentration in this region results in a high demand for water even as increasing demand for groundwater has already been over-pumped for the last few decades since the early 1960s. Increased use of the shallow aquifer below the Jifara plain for both municipal and agricultural purposes with minimal surface water recharge in this region has led to severe depletion of the aquifer, subsequently resulting in the substantial sea water encroachment into the coastal ground aquifer system [1]. The sensitive abstraction of a coastal aquifer typically causes issues of quantity and quality [2]. Salinization is a very common type of groundwater contamination, in aquifers along the coast, and is indicated by the increased presence of Total Dissolved Solids (TDS) and certain chemical elements [3-5]. In numerous instances, the pumping rates exceed their natural water transmission capacity and this causes a drawning of sea water into the system and disrupting the regional groundwater balance.

The sea water intrusion issue can also take place due to over-pumping at individual wells, thus lowering the potentiometric surface locally and causing the balance of the natural interface between freshwater and saline water. In the assessment of the impact of sea water on an aquifer along the coast, it is necessary to explain where the salinity comes from and be knowledgeable about the hydraulic and hydrogeochemical dynamics [6]. Cedestrom and Bastai Ola [7], have well researched the problem as evidenced by the number of papers published in which, they investigated water resources in the Tripoli area and found sea water intrusion impacts on the groundwater resources in the vicinity of Salt Canal and they indicated sea water intrusion in a few places in the coastal aquifer, especially in North Sug Al Juma, which is located in Tripoli area where the salt canal was built during the Italian occupation of Libya. The raising of sea water level in the salt flats caused a reverse flow of salt brines landward, and increased the salinity nearby wells. The authors concluded that the lowering of the water level was a little near the coast in the northern part, however, attained 13 meters in the vicinity of Qasr Ben Ghashir.

Several studies indicated that the increase in water consumption has resulted in drastic declines in water levels, which could impact the direction of water flow, (i.e., it would flow from North to South). Kruseman and Floegel [8] indicated that in the first few kilometres along the coast in the Tripoli region, the extracted groundwater from the Quaternary aquifer was partially replaced by the sea water intrusion. Floegel [9] noted that the rise in the rate of water consumption led to very significant lowering of water levels, which could impact the direction of water flow (i.e., it would flow from north to south) and the region stretching along the shoreline from Az Zawiah to Tajura to a depth of 2 km was subjected to sea water intrusion. The decline in water level will reduce the quality and increase invasion of sea water along the coastal regions. Meludi and Werynski [10], investigated the sea water intrusion issue in Gargaresh area at Swani Well Field, and concluded that extent of water intrusion into the area was becoming greater and that it was compounded by the pumping of groundwater, particularly at the well field, because these wells had been supplying water o the Tripoli area since 1976. Shawi and Philbert [11] used chemical analysis of 123 water samples in the upper aquifer in Tajura area located 10 km east of the main Tripoli city. Their findings revealed that the increase in water requirements due to domestic, agricultural and industrial development was responsible for the sea water intrusion going further inland in the 1990's compared to the 1980's. The decline in water level reduced the quality and increased invasion of sea water along the coastal regions. The sea water intrusion in the coastal area dramatically and seriously covers a vast area. In the year 1995, the sea water intrusion had already invaded 10 km inland and covered an area of 250 km^2 in the Tripoli region [12]. The problem of sea water intrusion in Tripoli aquier is become more serious in the last decade [13].

The objectives of this paper are to evaluate the long-term pumping effect on sea water intrusion and groundwater level from Tripoli aquifer, assess the performance of groundwater simulation model using MODFLOW 2005 under ModelMuse software, and show the suitability of the model for managing withdrawal and controlling sea water intrusion. However, it could focus on the establishing a projection of the future fresh groundwater situation under different scenarios, including fixed pumping rate, increasing pumping rate due to population growth, and sustainable abstraction.

2. Description of the Study Area

Libya is the southern Mediterranean and North African country lying between latitudes 33°10' N and 18°45' N and longitude 9° 58' E and 25° E. The Libyan climate varies between the Mediterranean Coast and the Sahara Desert [14]. It shares borders with Egypt to the east, Algeria to the west, Tunisia to the northwest, Chad, and Niger to the south, and Sudan to the southeast [15]. Libya’s total area is 1,752,000 km^2, with a 1900 km shoreline.

The area of this study covers the center of the Jifara Plain’s coastal area in NW Libya known as the Tripoli aquifer, which comprises a nearly rectangular area approximately 763 km^2 from the Mediterranean Sea in the north of Sawni city and Bin Gashir city is located in the southern part (Fig. 1). Most of the water needs for domestic, irrigation and industrial purposes are sourced from an unconfined upper aquifer. The region’s climate is semi-arid, Mediterranean, with average yearly rainfall of about 250 mm, in the study area, where the summer is hot, dry and the winter is moderately warm with rains between November and April [16]. There is high precipitation in the coastal region in comparison with the elevated southern region. The recharge rates are distributed over a range of 7-16 mm/yr corresponding to rainfall. The total abstraction amount from this aquifer well was 70 M m^3/yr [17]. An examination of lithological logs reveals that the aquifer is from the quaternary period and is typified by alternating sand layers, sandstone, gravel and limestone [9]. The water level depths of the unconfined upper aquifer range from 10 to 160 m underground, with saturated thickness varying from about 10 m to 90 m. The study by Floegel [9] of sea water intrusion in the Tripoli region is extended from Al Maya in the West to Tajura in the East. The Tripoli aquifer includes five profiles, namely, Al Mayah, Janzur, Gergaresh, Eyn Zarah and Tajura profile. The names of the profiles were given based on the area of their locations. About 65 wells were used in this study by Kruseman and Floegel [8] and their depths range between 14 m and 120 m and all these wells were producing from the first aquifer or the shallow aquifer.

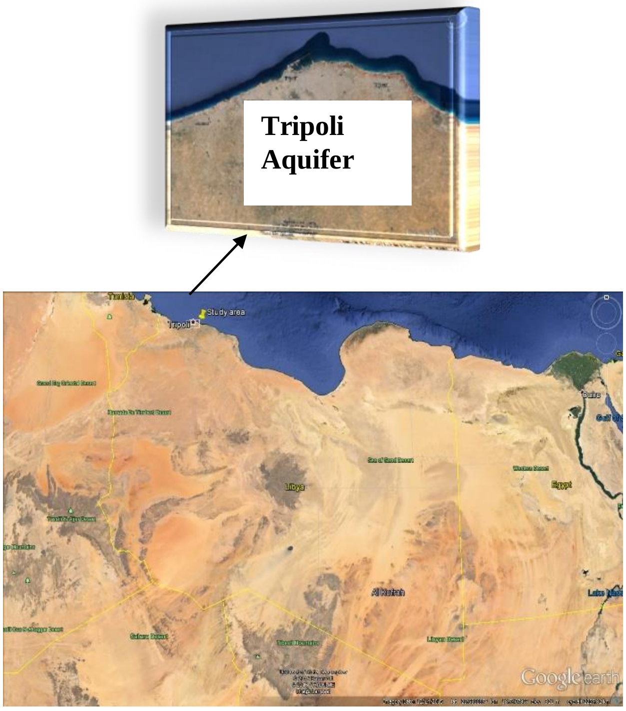

Fig. 1. Study area.

3. Geology and Hydrogeology of the Study Area

The geology and hydrogeology for northern Libya are complex. The Jifara plain, which comprises the study area, has attracted the attention of several geological investigations [18-20]. They provide the most detailed accounts of the aquifer systems in the region. The Jifara plain is located between the Mediterranean Coast in the north and the Nafusa mountains in the South and it is characterized by a flat topography. The topographic elevation shows a gradual incline toward the south and reaches 200 m above mean sea level at the southern end of the plain.

The Jifara plain has a number of aquifers with significant amounts of water [18]. In the north, impermeable clay lenses separate the aquifers, however, define one sizeable unconfined aquifer in the inland part of the plain. The water quality along the coastal areas has deteriorated as a result of overpumping, which has caused sea water intrusion. In the Jifara plain, the upper aquifer is unconfined is Miocene-Pliocene-Pleistocene and extends throughout the Jifara plain. In the center and East of the plain, there is good quality water of 100-150 m thickness. In the Tripoli region, this aquifer is the major and most significant groundwater source, to meet the demands of domestic users and for agricultural irrigation. The middle Miocene aquifer is found at 70-120 m below the surface and well developed in the west of the Jifara plain. The aquifer thickness ranges between 125 and 200 m [8]. Layers of clay separate the aquifer from the Quaternary and lower Miocene aquifers.

The Miocene-Quaternary unconfined aquifer with its location to the northern part of the Al Aziziyah fault is the major source of groundwater in the Jifara plain for both domestic uses and for irrigation. Miocene aquifer in the northern part of the Al Aziziyah fault is of limestone, sandy limestone, dolomitic limestone and clay while the Lower Miocene aquifer comprises sandy limestone that covers the sandy surface of the upper Abu Shaybah formation. The Abu Shaybah aquifer in the north is located between 300 and 700 m underground and made up of a thick layer ranging from 125 to 450 m of sandstone, with intrusions of clay and shells. The Azizia limestone aquifer is in the northern part of the Al Azizia fault and due to its dip, the aquifer formation is as deep as 900 m in the southeast of Tripoli. Much work has been done to study groundwater situation in the Jifara plain and their results show that groundwater in the North of the Jifara plain is tapped from the Quaternary as well as from the Miocene rocks. Figure 2 presents the hydrogeological section of Tripoli. In this study, simulation is done of the upper aquifer of the Tripoli region, which is located in the center of Jifara plain [8].

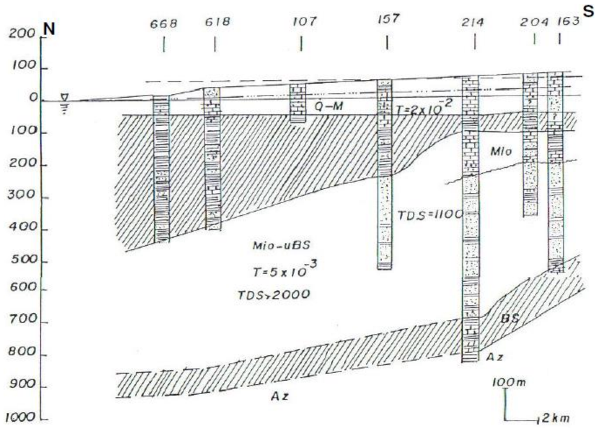

Fig. 2. Hydrogeological section in the study area [8].

4. Description of ModelMuse Model

The MODFLOW-2005 code was employed to simulate groundwater flow using ModelMuse as a Graphical User Interface [21-22]. In the Tripoli aquifer, the model was discretized with a finite-difference grid consisting of 97 rows and 240 columns with uniform cell dimensions of 250 m by 250 m and one layer, because the majority of the pumping wells are extracted from the first layer.

There are 23,280 cells in total and the number of the active cells is 11,227 and an inactive cells number 12,053. The assigned model boundaries are based on the hydrodynamic pattern where the constant head boundary is assigned to the coastline at which, there is a higher precipitation (310 mm/yr) with (head = 0), based on the sea level as a fixed datum. Most of the southern model boundary is with a continuous groundwater flux to the study area and here there is a constant flow of the assigned boundary. The eastern and western boundaries are represented by groundwater flow lines it is assumed as the flow boundary. In the study area, the average annual precipitation is taken to be 250 mm. According to Kruseman and Floegel [8], the average amount of recharge for the Tripoli aquifer is recommended to be 10% from the annual rainfall. The simulation was conducted to study the impact of increasing the pumping on the advancement of sea water intrusion into five zones at the Tripoli aquifer and these zones are Al Mayah, Janzur, Gergaresh, Eyn Zarah and Tajura. The simulation focuses on variations of the groundwater water level in the pumping wells. The simulations include a fixed pumping rate, variable pumping rates and sustainable abstraction rate. The present scenarios are for the purpose of finding appropriate solutions for managing withdrawal and controlling sea water intrusion in the Tripoli aquifer, to evaluate the long-term pumping effect on sea water intrusion. The ModelMuse is used to simulate different scenarios of pumping from the wells for 80 years (2020-2100). In the ModelMuse model, the governing equation generally describes the three-dimensional movements of the groundwater flow of constant density through the porous media, which can be written as follows [23]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\left(\frac{\partial h}{\partial t}\right) \quad (1)$$

where, K_{xx}, K_{yy}, and K_{zz} are the values of hydraulic conductivity along the *x*, *y* and z coordinate axes, which are taken to be parallel to the major axes of the 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 $W<0$ for flow out of the groundwater system and $W>0$ for flow into the system (T^{-1}); S_S is the specific storage of the porous material (L^{-1}); and *t* is time (T). The ModelMuse model is employed for predicting the groundwater level in the Tripoli aquifer, with the time. The statistical tests were used to check the model accuracy by the Mean Error, the Mean Absolute Error and the Root Mean Square Error indices.

5. Data Collection and Analysis

Data on Tripoli aquifer that were used in the present research can be categorized into geological data, hydrogeological data, meteorological data, topographical data, data on population and data on water consumption. Most of the data were collected from the General Water Authority, Tripoli Meteorological Station and Ministry of Planning in Libya. The geological and hydrogeological data include aquifer thickness, hydraulic conductivity and groundwater levels while the topographical data include the locations and elevations of the wells. The meteorological data include data on precipitation and evaporation, which were used to estimate the aquifer recharge. The rainfall and evaporation data in the study area were used in the ModelMuse software to get the rainfall and recharge distribution on the Tripoli aquifer as shown in Figs. 3 and 4. Also, the hydraulic conductivity and groundwater levels were used in model calibration and application. Data on past population growth and present population are used for estimating future water consumption (2020-2100) and pumping rates for scenarios 1 and 2. The pumping rate for scenario 3 was estimated from both rainfall and evaporation data.

6. Results and Discussion

Model validation is a crucial stage of the total process, which is focused on assessing the performance of the model in the simulation of groundwater at the chosen site to establish its suitability or unsuitability for use. The General Water Authority [20] firstly employed ModelMuse software on the basis of the historical groundwater data derived for verification of the model. Toward this end, 33 wells were included for the simulation of the groundwater in the area of the study. In this study, the performance of the ModelMuse was statistically evaluated and model accuracy was checked by making a comparison between synthesized data of the groundwater levels in 33 selected wells with simulation levels. The mean error of measured and simulated values, the mean absolute error and root mean square error were found to be 0.31 m, 1.70 m and 2.32 m respectively. In percentage form, the average error in the model prediction was found to be 12% and this shows that the model accuracy is acceptable.

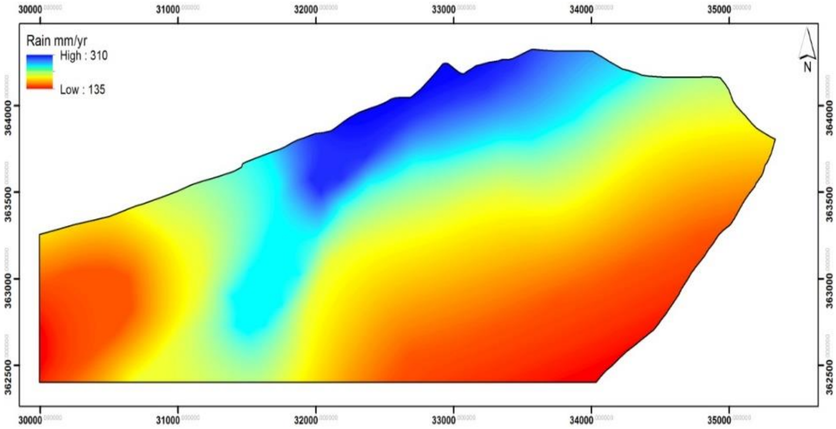

Fig. 3. Distribution of rainfall in the Tripoli aquifer.

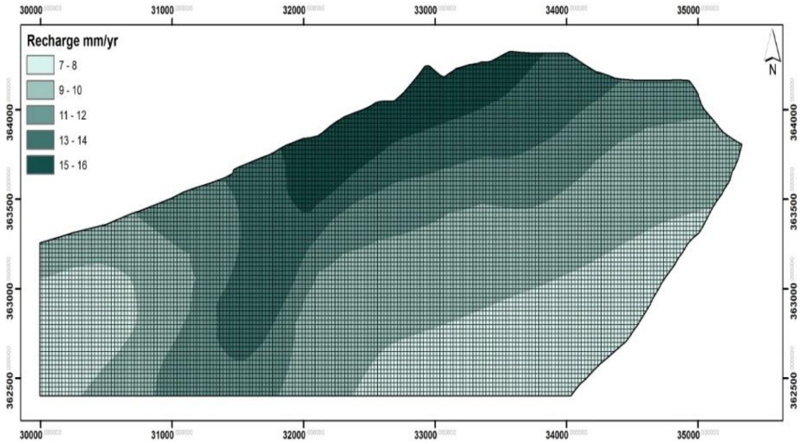

Fig. 4. Distribution of recharge in the Tripoli region.

Pumping rate scenarios

Different scenarios were simulated as highlighted in Table 1. Scenario 1 considers that a fixed pumping rate will remain constant for the next 80 years while scenario 2 considers the response of the aquifer with varying pumping rates. The response of the aquifer to manage the aquifer recharge by sustainable abstraction was considered in scenario 3.

In scenario 1, the simulation results by using ModelMuse indicate that although the pumping rate was fixed at 70×10^6 m^3/yr, it showed an increase in sea water intrusion due to the drop in the groundwater level since the wells of the aquifer are over pumpinged. This increases the affected area by the sea water intrusion and it reflects the aquifer behaviour from 2020-2100. Simulation results also showed that in the year 2100, the maximum drop in the groundwater level will be 13.2 m and it will occur in well number T106 at Al Mayah profile. The maximum rate of decline in the groundwater level will be 14.7 cm/yr and it will occur at Al Mayah profile, while the minimum rate of the groundwater level decreases to 3.0 cm/yr and it will occur at the Janzur profile.

Table 1. Description of simulated scenarios used to study the response of Tripoli aquifer.

Simulated scenario	Description
Scenario 1: Using fixed pumping rate	Simulation includes the impact of fixed pumping rate (70×10^6 m^3/yr) on groundwater level aquifer regardless to climate change, sea level rise and population growth
Scenario 2: Using increasing pumping rates	Simulation includes the impact of future increasing pumping rates due to population growth on groundwater level without considering climate change and sea level rise
Scenario 3: Using sustainable abstraction rate	Simulation includes the impact of sustainable abstraction rate (19×10^6 m^3/yr) on groundwater level without considering climate change, sea level rise and population growth

Scenario 2 focuses on the impact of a future increase in pumping due to the population growth on sea water intrusion by applying ModelMuse. The following factors are taken into consideration: rapid population growth in the Tripoli region and increasing demand for the purpose of covering needs for various sectors such as agriculture, municipalities and industry. All these requirements lead to over-pumping from the Tripoli aquifer, thus, causing a decline in groundwater level and landward migration of the sea water intrusion. Population forecasting is used to estimate the demand of the groundwater. Gupta [24] proposed Eq. (2) to estimate the future increase in the population and the equation while the population census of Tripoli city, taken from the Ministry of Planning [25], which is considered in Eq. (2).

$$p_t = P_o + K_a(t) \tag{2}$$

where P_t is the projected population, P_o is the population in the year 2010, K_a is the uniform growth rate and t is period of projection.

The population forecasting shows that it will increase to about 3 million by 2100, which is showed that the population almost doubled by 2100 compared with the population in 2010. This will be reflected on groundwater pumping from the aquifer. The predictions were done for intervals of 20 years from 2020 - 2100 and selected results are shown in Figs. 5 and 6. However, Fig. 7 shows how the reduced pumping rate in scenario 3 affects sea water intrusion. The prediction indicates that there is a distinct lowering in the groundwater level in some wells in this aquifer. For example, in the year 2100, the maximum drop in the groundwater level will be 15.4 m and it will occur in well number T106 at Al Mayah profile. The maximum rate of decline in the groundwater level will be 17.1 cm/yr and it will occur at the Al Mayah profile, while the minimum rate of decline in the groundwater level will be 4.0 cm/yr and occur at the Gergaresh profile.

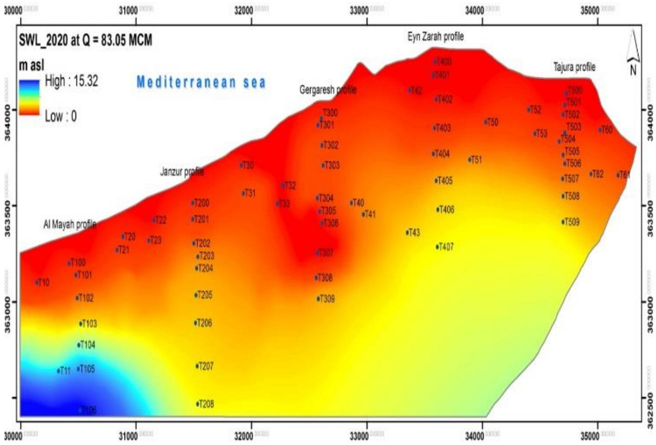

Fig. 5. Predicted groundwater levels using increasing pumping rate for Tripoli aquifer in 2020.

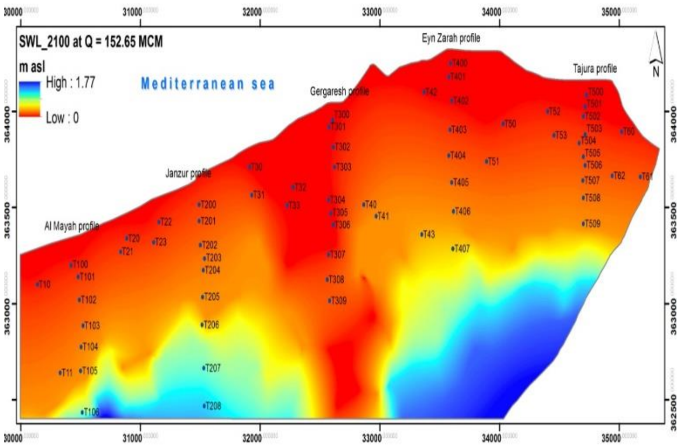

Fig. 6. Predicted groundwater levels using increasing pumping rate for Tripoli aquifer in 2100.

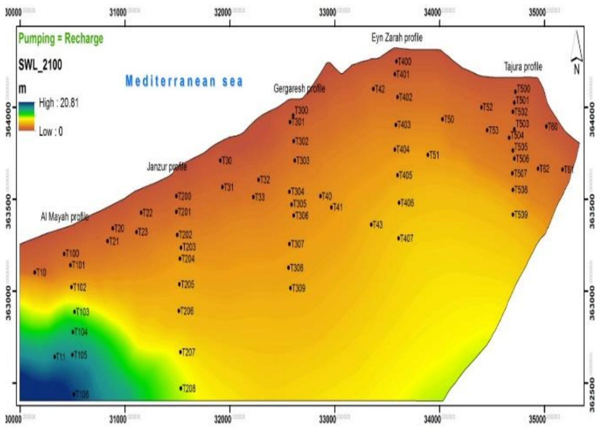

Fig. 7. Predicted groundwater levels using sustainable abstraction for the Tripoli aquifer in 2100.

Scenario 3 is a case study employing modelling techniques for forecasting unconfined aquifer's response to planned abstraction operations and uses the Tripoli aquifer as a case study, where the value of sustainable pumping rate is taken as 19×10^6 m^3/yr and this rate is taken as 10% of the total annual rainfall at the Tripoli aquifer. In the Tripoli region, the main recharge is the infiltration from runoff, this recharge has a high impact on groundwater elevations, therefore, it is crucial to investigate the effect of recharge in any management in order to retain minimum groundwater levels. The maximum annual rainfall was recorded along the developed coastline and found to be 310 mm while the minimum annual rainfall was 135 mm and it is found along the mountainous area [16]. Simulation of the recharge by ModelMuse shows that the maximum recharge ranges from 15-16 mm/yr and it is found in the coastal areas in the northern region of the aquifer while the minimum recharge ranging from 7-8 mm/yr is found in the mountainous region as shown in Figs. 3 and 4. The simulation results of the groundwater levels for 2100 for scenario 3 is presented in the form of GIS maps as shown in Fig. 7. The groundwater levels under the sustainable abstraction will rise from 2020 to 2100.

In the sustainable abstraction (scenario 3), the simulation results show that in the year 2100, the maximum rise in groundwater level will be 3.5 m and it will occur in good number T305 in the Gergaresh profile, while the minimum rise in groundwater level will be 0.2 m and it will occur at well number T202 at Janzur profile and at well number T509 in Tajura profile. The maximum rate of rising in the groundwater level will be 3.9 cm/yr and occur in the Gergaresh profile, while the minimum rate of rising in groundwater level will be 1.4 cm/yr and occur in the Eyn Zarah profile.

In Fig. 8, the impacts of scenarios 1 to 3 on the groundwater levels in selected wells are clearly shown. Since there is a large number of wells in the Tripoli aquifer, the variations in the groundwater levels in selected wells are used in this paper to demonstrate the impact of the above scenarios. The simulation results indicate that scenarios 1 and 2 have a negative effect on the groundwater levels in the wells and this includes a significant decrease in groundwater levels until it became almost equal to the sea water level. However, results showed that scenario 3 has a clear impact on aquifer recovery where the groundwater levels are increased and this helps to control the sea water intrusion. Table 2 summarizes the simulation results. As mentioned before, the wells at Tripoli aquifer are distributed in five profiles and the simulation results for various pumping rates of scenarios 1 to 3 are summarised in Table 2. The results mainly focused on how the groundwater level along these profiles is affected by changing the pumping rates.

The results of scenarios 1 and 2 showed that there is a continuous decline in the groundwater level in these profiles due to fixed and increasing pumping rates. The decline rate in groundwater level ranges between 0.030 to 0.147 m/yr for scenario 1 and between 0.04 to 0.171 m/yr for scenario 2. The results showed that the decline rates in groundwater level are different at different profiles and this is attributed to the fact that the pumping rates from the profiles are different too. The results of scenario 3 showed there is a continuous increase in groundwater level due to a decrease in pumping rate (in this scenario the pumping rate is equivalent to the recharging rate). The increase rate in groundwater level ranges between 0.017 to 0.039 m/yr. The increase in the groundwater level at a different profile is different too and this is attributing to the fact that the pumping rates from the profiles are not the same.

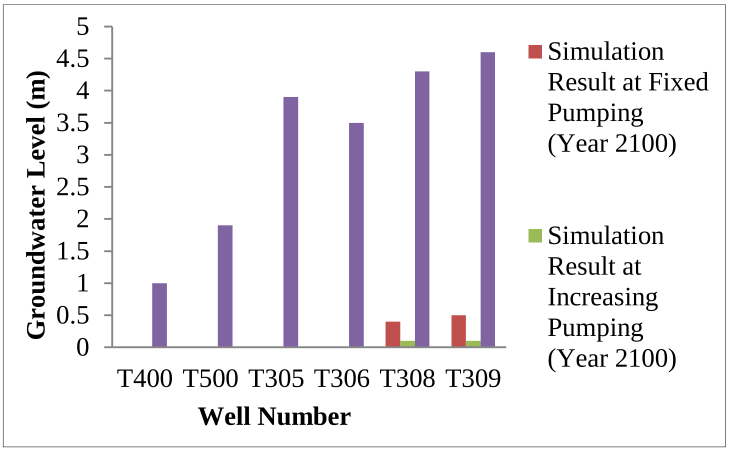

Fig. 8. Comparison between the simulation results and prediction of groundwater levels for fixed pumping, increasing pumping, and sustainable abstraction.

Table 2. Average decline and increase rates in groundwater level under different scenarios.

Profile name	Average decline rate in groundwater along the profile for scenario 1 (m/yr)	Average decline rate in groundwater along the profile for scenario 2 (m/yr)	Average increase rate in groundwater along the profile for cenario 3 (m/yr)
Al Mayah	0.147	0.171	0.020
Janzur	0.030	0.052	0.019
Gergarsh	0.036	0.040	0.039
Eyn Zarah	0.042	0.053	0.014
Tajura	0.046	0.052	0.017

7. Conclusions

In the past years, the large scale of intensive pumping from Tripoli aquifer has resulted in a continuous decline in the groundwater level and salinity rise and these are the main indicators of sea water intrusion problems. Modflow 2005 under ModelMuse software was modified and used to measure the effect of pumping and recharging on the aquifer using three different scenarios. The results showed that the employed model offered an efficient tool to manage the sea water intrusion in Tripoli aquifer. The model is used to predict the response of Tripoli aquifer when various pumping scenarios are considered. Simulation results of scenarios 1 and 2 showed that there is a continuous decline in the groundwater level in the aquifer profiles due to fixed and increasing pumping rates. The decline rate in groundwater level ranges between 0.030 to 0.147 m/yr for scenario 1 and between 0.04 to 0.171 m/yr for scenario 2. Scenario 2 is the worst scenario since more sea water intrudes in the aquifer due to a severe drop in groundwater level. Scenario 3 is the best and recommended scenario since it reduces the impact of sea water due to the continuous increase in groundwater level. The increase rate in groundwater level ranges between 0.017 to 0.039 m/yr.

Nomenclatures

h	Potentiometric head, m
K_a	Uniform growth rate, person/yr
K_{xx}	Hydraulic conductivity along the x-axis, m/day
K_{yy}	Hydraulic conductivity along the y-axis, m/day
K_{zz}	Hydraulic conductivity along the z-axis, m/day
P_o	Present population, person
p_t	Projected population, person
S_s	Specific storage, m^{-1}
t	Time, yr
W	Volumetric flux per unit volume, day^{-1}

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