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Groundwater Modeling & Risk Management
Impact of Groundwater Extraction on land Subsidance in Sarir Area East Central Libya

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ABSTRACT

This research was conducted to study the impact of exploiting groundwater on ground subsidence in Sarir water well fields, East central Libya. There are three major water well fields in this area. Known as North and South Sarir agriculture projects, they are operating since 1975, each has 239 drilled water wells at depths of 300 meters , used for irrigating of 100 hectares. the third well field belongs to the Man-made River Project, where 126 production wells(1MM^3/day) drilled at depths 450m, they were operating since 1992. A comprehensive amount of data were collected on groundwater abstraction and water levers monitoring program Data such as well discharge and the drawdowns were made available for 63 observation wells covering the area of the well fields. There are two main aquifers in the area, the upper (shallow) aquifer with thickness about 150 meters and the deep aquifer is about 800 meters. These two aquifers are frequently separated with about 50m lentecular layers of clay and silt.

All possible collected hydrogeological data were prepared in order to be used and build a conceptual and numerical groundwater model. This process should lead to understand the hydraulic behavior of the groundwater system in the whole area of study. The model was used to correlate the calculated hydraulic parametrs with the observed for calibration and verification. The model was also used to predict the future drawdown and land surface subsidence exerted, due to stresses forced by the long period groundwater abstractions from the three well fields.

The total extracted water is 6.872 bm^{3}since the start of the welfields to the end of 2012. The results obtained from matching the observed drawdowns with the model predictions are as follows: Specific yield and Storage Coefficient obtained from this model ranges from 0.003 to 0.12 and from $4x10^{-7}$ to $4x10^{-3}$respectively, elastic skeletal specific storage from $4x10^{-7}$ to $5x10^{-2}$, and inelastic skeletal specific storage for thin interbeds is in the range from $4x10^{-5}$ to $5x10^{-1}$. The model then used to predict the drawdown and landsubsidence after 50 years of existing and planned exploitation. The maximum drawdown is predicted to be 55meters with land surface subsidence of 2.8 meters.

Keywords: Sarir area, Modflow, aquifers, Hydraulic Parameter, Drawdown, land surface subsidence.

1. Introduction

The study area is located within the southern Sirte basin east central Libya.(Figure 1) There are three large groundwater extraction wellfields in the area. These are the Sarir North Agricultural Project (SNAP) of 175 production wells started since 1975, Sarir South Agricultural Project (SSAP) of 81 production wells started since 1980 and the Sarir Wellfield of the Man Made River Project (MMRP) Phase I of 126 production wells started since 1993. The average depth of the two agriculture well fields is 300 m, each well equipped with self-propelled sprinkler system to irrigate 80 hectares, and the depth of the MMRP wells is (450-470)m [1]. All these wells are tapping the lower aquifer of groundwater system in the area.

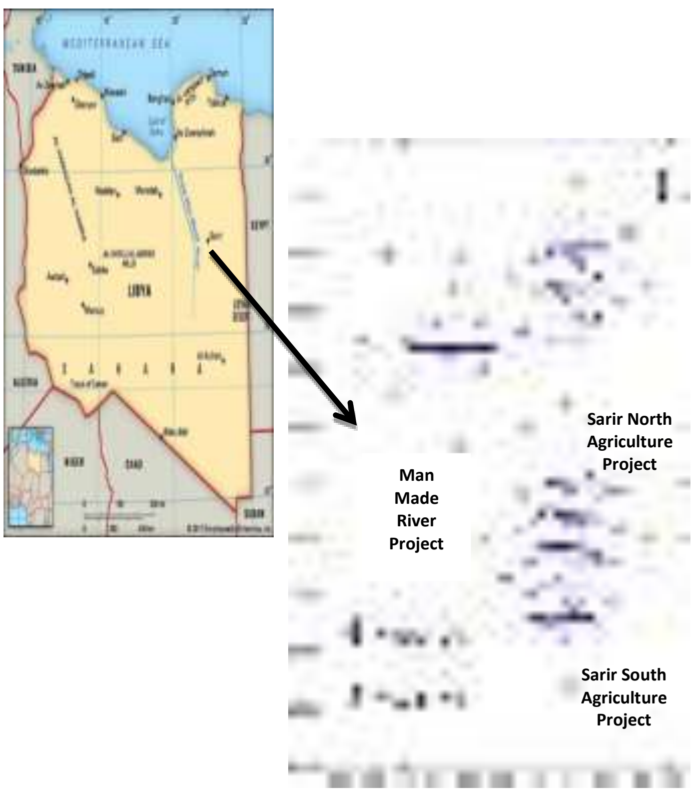


Fig.1. Location map of the study area

Drawdown data are regularly recorded form a network of 63 deep & shallow piezometers covering a large area in and around the wellfields. In summer 1982, earth fissures were observed in South Sarir Field. On the periphery of the agricultural circles The ground subsidence appeared as narrow and shallow cracks (i.e. shallow holes or sink-like of width in the range of 10 cm to depths over 5 meters at that time, and extends to more than 1 km long.), figure (2). The fissures progression increased the possibility of massive land subsidence in the area due to groundwater extraction[2]. Which may cause drastic destruction effecting the infrastructure on the project area. This study is aimed to understand this phenomena with regards to groundwater abstraction and drawdown and implement groundwater model to predict the drawdown and landsubsidence in the future to the helping managing authorities to protect and reduce the effects of this phenomena on the infrastructure in the future [3].

Fig. 2. Earth Fissures in Sarir Area, after (Abdussalam S. T., (2004)).

2. Geology of the Study Area

The sedimentary successions of the Sirt basin were deposited on the sinking foreland between the ancient African Craton and the mobile Tethys belt, [1]. The lower Tertiary formations (Paleocene and Eocene) included thick extensive carbonates and shales. At this age a major marine transgression extended southwards from the main basin into a deep embayment reaching the Tibesti region and possibly beyond. The Post Eocene Sequence is divided lithostratigraphically into four rock units.

2.1 Post Middle Miocene (PMM) Unit

This unit is represented in the eastern part of the study area where it reaches a maximum thickness of 180m. The PMM consists mainly of unconsolidated fine to coarse sands that locally include thin limestone beds. However, such lithologic sequence of the PMM is rather homogenous over a large part of the eastern side of the basin, whereas intercalation of thin clay layer is more developed westwords. In the northeast, the clastics of the PMM overlay the clay carbonates alternations of the Lower Middle Miocene (LMM). However, the boundary between both rocks can be easily determined from geophysical logs.

2.2. Lower Middle Miocene (LMM) Unit

The total thickness of this unit varies from east to west, with an average of about 300m. The LMM consists of an alternations of limestone, dolomite and clay, with subordinated sandstone. Some unconsolidated sand horizons occur as well. Clay layer abouth 30m thick is developed locally. The occurrence of anhydrite, gypsum as well as glouconite has been observed in some oil wells. Towards the west and south, the upper lithological sequence changes into sand and clay with the clay being subordinate. The sand particles are medium to coarse grained, but intercalation of lime sands occur also.

2.3. Oligocene Rock Unit

The thickness of this unit ranges between 260m in the west and 400m in the eastern part of the study area. Sand, clayey sands and sandstone compose the main part of this unit. In the northeast the sand horizons are subordinate to the sandstone and frequent intercalations of sandy limestone, limestone or dolomites occur, whereas clay layers are scarce. Towards the west and south the sands predominate mainly in the upper part of the formation. In the lower part, intercalations of sandstone and sandy limestone are locally well developed, as well as clay layers. The sands in general are medium to coarse grained, but also fine sands may occur in the lower parts of the formation.

3. Hydrogeology of the Study Area

The overall hydrogeologic status at Sarir is best understood by envisioning north-south regional hydrogeologic cross section extending from the southern boundary of Sirt basin (close to Al Kufrah) and passing though the two wellfields towards Jalu area, figure (3). This cross-section is clearly illustrates the difference between hydrogeologic conditions at SNAP were the shallow aquifer is clearly separated from the deep aquifer by a thick clay/shale sequence, and that of the SSAP [4]. It also illustrates regional patterns of groundwater movement. The hydraulic gradient is an indication of a slow groundwater recharge of the aquifers in the area and discharge through evaporation from Sabkhas in the northern part of the basin. [5].

In the Sarir wellfields, groundwater is withdrawn from two main aquifers that are hydraulically separated over a considerable part of the study area. The shallow aquifer consists of unconsolidated sediments of Post-Middle Miocene age. It is under water table conditions (unconfined) with depth to water table ranges from about 70m at the south of the study area to about 45m in northern areas. The deep multi-layered leaky aquifer is interbedded sequences of unconsolidated and semi-consolidated sands, silts, shale, clays and siltstones.

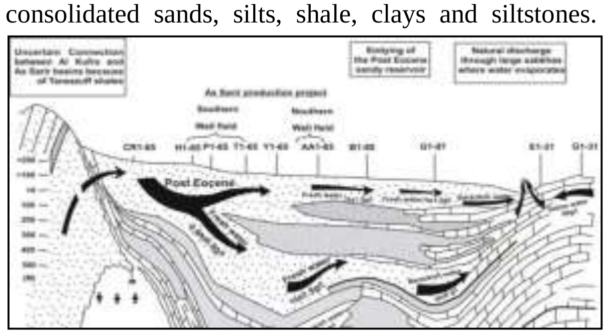


Fig.3. Hydrogeological cross section of the Sirte basin across the Sarir Agricultural Projects area (Modified after Pallas, 1980)

Figure (4) exhibits a hydrogeologic cross-section running across the area of study. Relatively thick and continuous sand sequences are identifiable on logs representing the lithology in the Sarir North area. They clearly point to the presence of the deep aquifer which extends roughly from150 to 700m. In general, the tapped thickness penetrated by the production wells is ranging from 140m to 450m. The sediments separating the shallow and the deep aquifers are only clearly defined on well logs of the SNAP area, where the piezometric potential in piezometers that penetrate the deep aquifer averages 3m higher than the upper aquifer. Nevertheless in the SSAP, differences in water level between the two aquifers are far less pronounced, where the static head in the shallow aquifer is few centimeters higher than the observed piezometric surface in the deep aquifer.

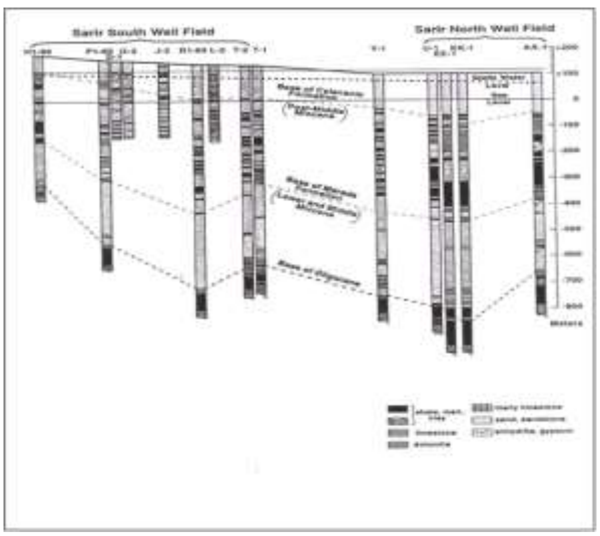


Fig.4. Hydrogeologic cross- section in Sarir Wellfields (Modified from Pallas, 1980)

4. History of Pumping Operations

The average designed rate of discharge per well is about 76 litter per second to meet the required water demand to irrigate an area of 80 hectares per well. The wells commenced operation since 1975 at the SSAP field, in 1980 for the SNAP field. However, in 1993, the MMRP had started the partial operation, where, the actual operational pumping rates from these wellfield were , reduced when repaired by installing 8" prepacked-Fiberglass inside the 10,3/4." stainless steel screens. accordingly resulted a low productivity of some of the wells . Figure (5) summarizes the actual total,yearly extracted, volumes of water from all wellfields in Sarir area since 1975 up to the end of 2012[6]. The total volume of extracted groundwater is more than 6.87 BM^3. Figure (5), table (1) and figure (6) show the accumulative extracted water from each wellfield [7] [8].

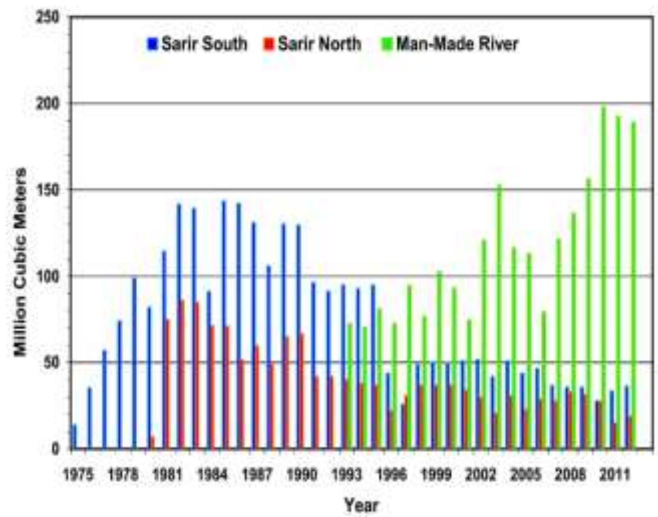


Fig.5. The annual extraction from the wellfields after (Rashrash, S. and Twibi, Nabila (2015))

Table .1. The cumulative pumping rate of the well fields in Mm^3

	1980	1990	2000	2012
Sarir South	362,100,000	1,632,600,000	2,278,008,800	3,132,036,080
Sarir North	7,060,000	689,120,000	1,052,990,880	1,394,832,480
Man Made river wells	----	-----	605,881,944	2,345,894,302
Total	369,160,000	2,321,720,000	3,936,881,624	6,872,762,863

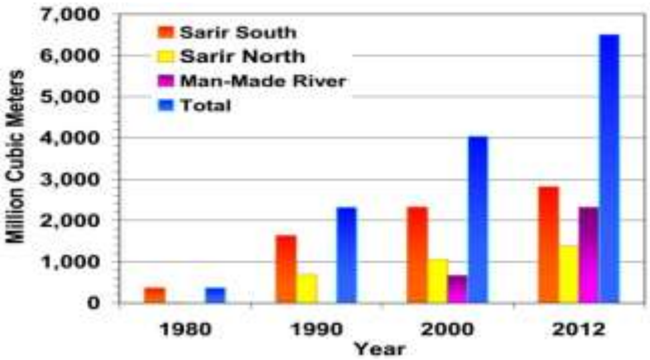


Fig.6. Total cumulative volume of extracted water from the three wellfields, after (Rashrash, S. and Twibi, Nabila (2015))

5. Groundwater Decline

A large number of observation wells were drilled in the study area have provided an excellent coverage for accurate monitoring of groundwater level. The distribution of observation wells (completed as dual shallow and deep piezometers) is illustrated in figure (1). Water level data from 63 piezometers represent the Sarir North. South and Man Made River Project respectively were examined in the course format and used for groundwater numerical model. The processed data cover a period from 1980 till 2013.Sample of the hydrograph records are shown in figure (7) for three dual piezometers (one in each wellfield) [6].

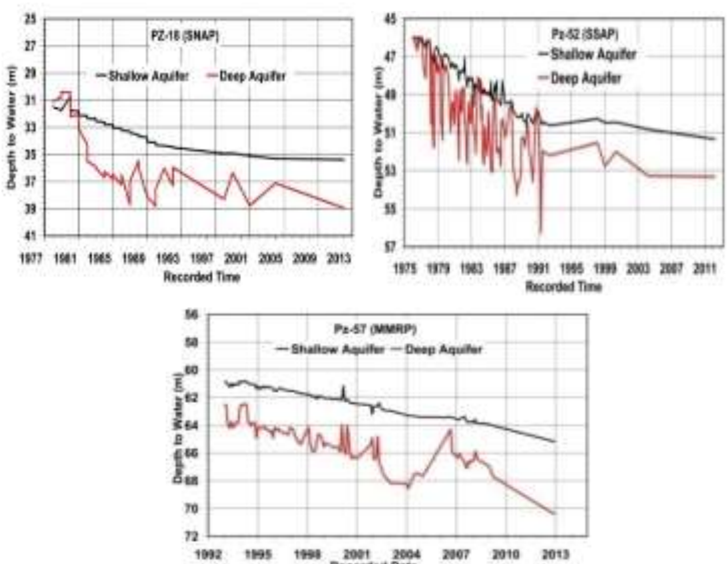
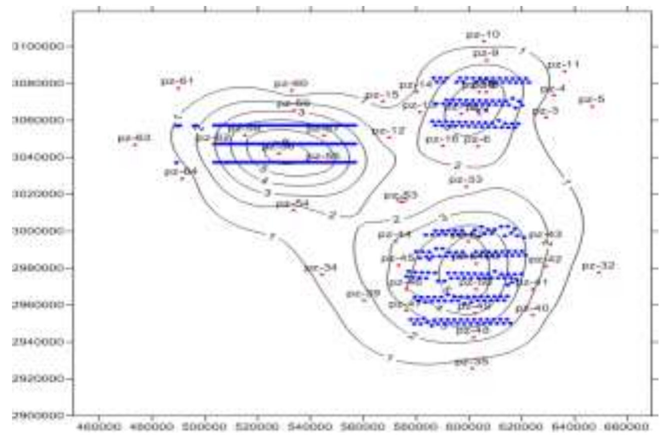
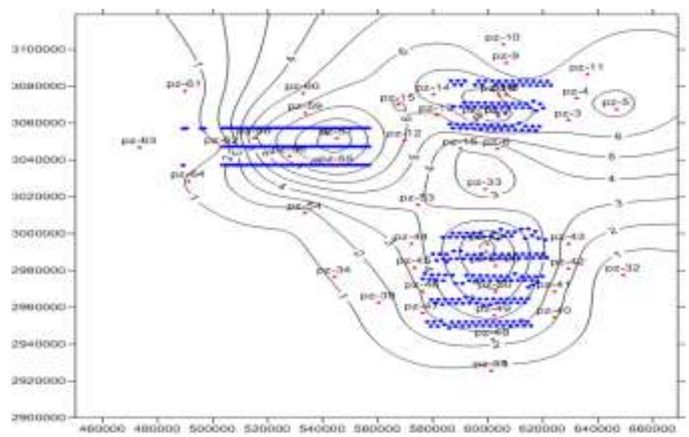


Fig.7. Sample of piezometer hydrographs (SNAP, SSAP and MMRP wellfields)

Figure (8) shows the drawdown maps for shallow and deep aquifers during this period. The maximum drawdown is 10 m observed in the deep aquifer in the MMRP area [6].



A



B

Fig .8. Drawdown maps of the shallow (A) and deep (B)

6. Groundwater Flow Model

6.1 Conceptual Model

The intent of implementing groundwater flow model in the area of study is to represent the actual hydrogeological status numerically (digitally) and then use this model to predict the future behavior of the aquifer system in future, to assist managing the existing water resources. This activity starts with building the conceptual hydrogeological model to represent the groundwater flow system conditions using all geological and hydrogeological available data. All geological and hydrogeological data are smoothed and put together to build the groundwater flow conceptual model. Figure (9) shows the simplified groundwater flow conceptual model of the area.

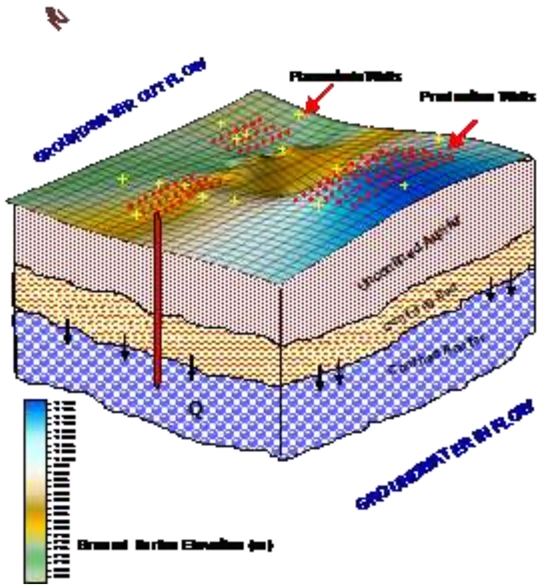
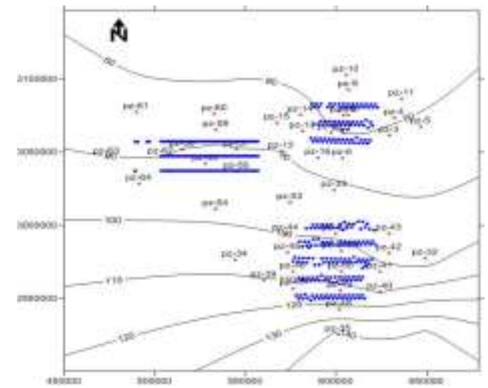
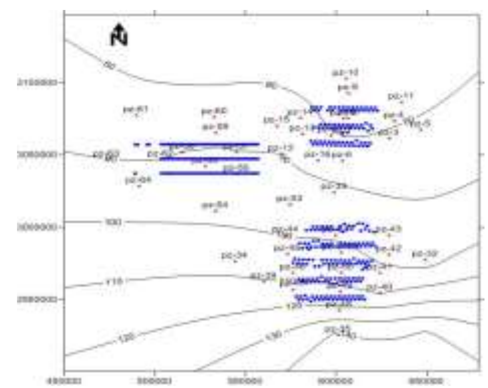


Fig.9. Schematic conceptual groundwater flow model of the study area

The groundwater flow system in the area is composed of two aquifers. The shallow unconfined aquifer is mostly consists of unconsolidated sandstone with an average thickness of 150m. The deep confined aquifer consists of sandstone (consolidated to semiconsolidated) with thickness reaches more than 800 m. All production wells taping this aquifer are partially penetrating this aquifer with depths not more than 450m. These two aquifers are separated by confining layer aquitard consists of clay and silt with average thickness of 50 m. The groundwater level is gradually slopping from south to north indicating that the general groundwater flow is from the south to the north. Figure (10) shows the water level maps of the shallow and deep aquifers before any development in the area.



(A)



(B)

Fig.10. Predevelopment Water Level Maps (A) Shallow Aquifer, (B) Deep Aquifer

6.2. Numerical Modeling

The groundwater flow system was modeled using the will known groundwater flow program MODFLOW, developed by the USGS. This package can handle three dimensional groundwater flow system with multi-aquifers and aquitards in steady and transient states .However, handling the ground surface subsidence due the effect of drawdown exerted by continuous pumping stresses. For the modeling purpose the area is divided into 80 rows by 120 columns covering a surface area of more than 56000 km^2. The width of the rows and columns are variable ranging from 1300 m in the area of the well fields to 5000 m at the model borders area. Then the system was subjected to steady state groundwater simulation and unsteady state (transient) simulation.

6.2.1 Steady State Numerical Simulation

The steady state simulation was constructed to represent the predevelopment groundwater flow conditions by matching the observed water levels to the model calculated in trial and error procedure. The model was calibrated using the hydraulic conductivities of the aquifers (shallow and deep) and vertical hydraulic conductivities of the aquitard. These parameters were varied within reasonable range at each trial, until the match between the observed and the model calculated water level were obtained. Figure (11) shows the match between the observed and the calculated water level.

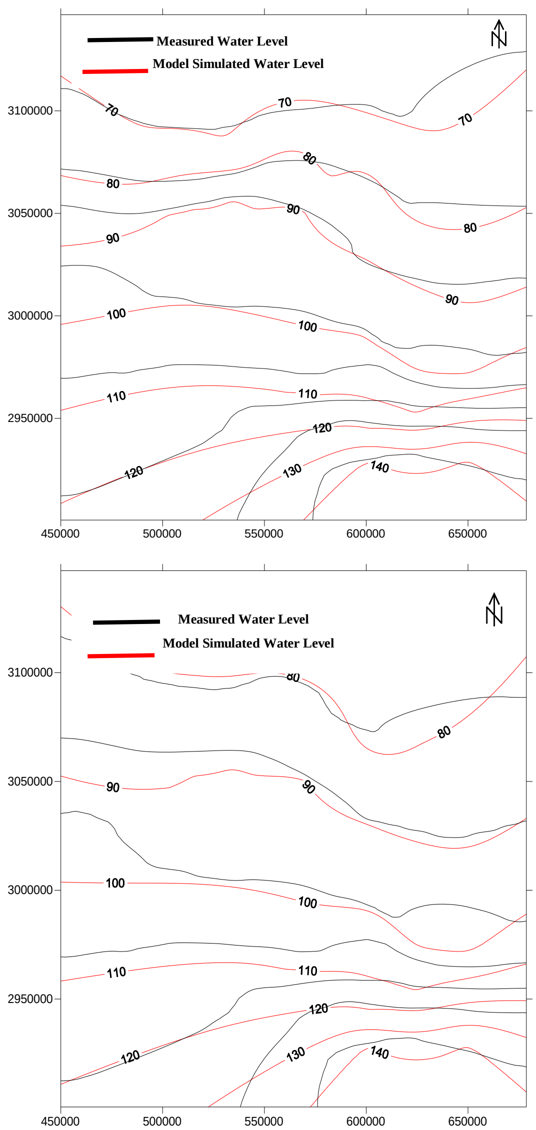


Fig.11. Measured and Model-Simulated Water Level Maps for (a) Shallow Aquifer and (b) Deep Aquifer (m)

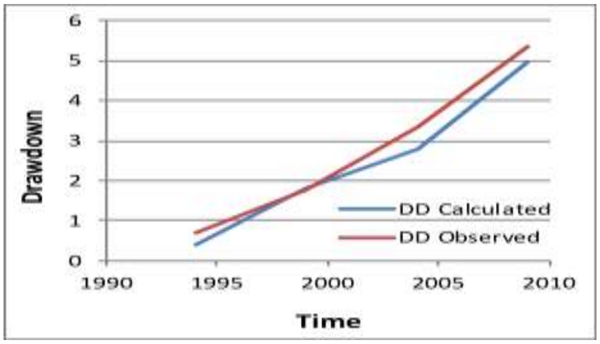
The results obtained from the steady state simulation are:

- The hydraulic conductivity of the shallow aquifer ranges from 0.5 to 20 m/d.
- The hydraulic conductivity of the lower confined aquifer ranges from 0.3 to 13.3m/d.
- The vertical hydraulic conductivity of the confining layer (aquitard) is in the range from $2x10^{-11}$to $2x10^{-2}$ m/d.

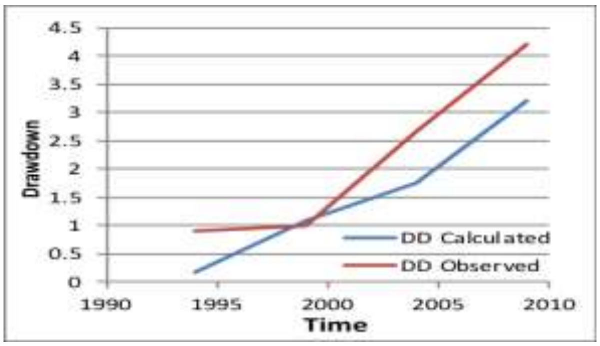
These results are in very well agreement with hydraulic properties obtained from the pumping test field data. The obtained water budget balance is 6.596×10^4 m^3/d.

6.2.2. Transient Simulation Model

The unsteady state (transient) simulation is used to match the historical observed drawdown in the area resulted from the pumping activities in the wellfield since the beginning of groundwater extraction in the area during 1975 to 2009. This time span is divided into 5 years pumping period to enable matching the historical drawdowns observed in the monitoring wells (piezometers) and the model calculated. The transient simulation is built using the hydraulic conductivities of the three layers obtained from the steady state simulation as fixed parameters and the same grid system. The actual extraction rates from each pumping well in the three wellfields are used to match the observed drawdowns. The variables in this simulation are the specific yield of the unconfined aquifer, storage coefficient of the confined aquifer and the compaction parameters of the confining layer (aquitard and interbeds).The model was verified after many scenarios varying these variables, good matches between the observed drawdowns and the model calculated are obtained. Figures (12, 13, and 14) show the matches in a number of monitoring wells representing the area.

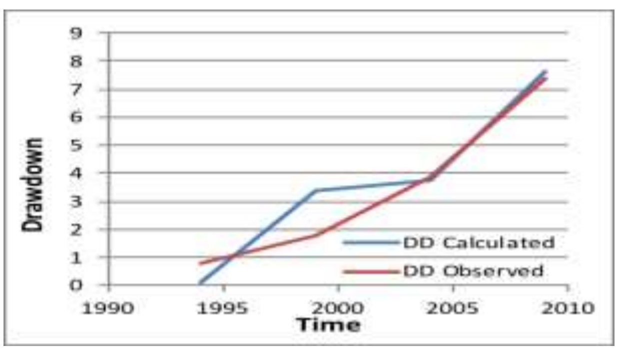


(Deep Aquifer)

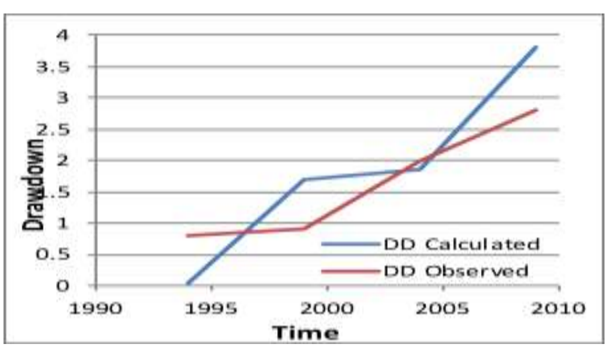


(Shallow Aquifer)

Fig .12. Observed and Calculated Drawdown in Pz56 (Deep Aquifer)

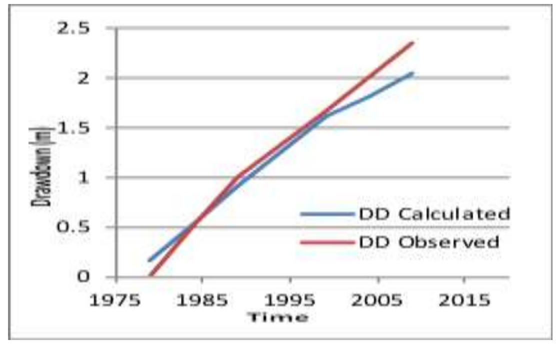


(Deep Aquifer)

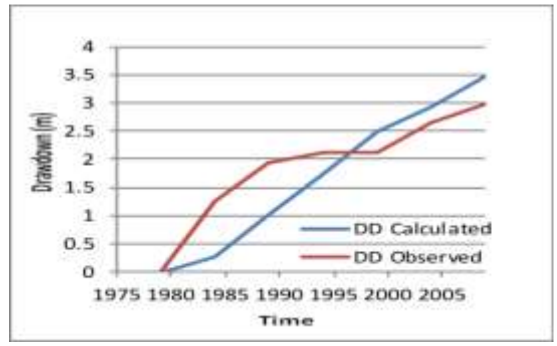


(Shallow Aquifer)

Figure (13) Observed and Calculated Drawdown in Pz62



(Shallow Aquifer)



(Deep Aquifer)

Fig. 14. Observed and Calculated Drawdown in Pz16

The hydraulic properties obtained from this simulation are:

The specific yield of the shallow unconfined aquifer ranges from 0.003 to o.12.

The storage coefficient of the deep confine aquifer ranges from $4x10^{-7}$ to $4x10^{-3}$.

The elastic skeletal inelastic specific storage of confining layer (aqutard and interbeds) range from $4x10^{-7}$ to $5x10^{-2}$ and $4x10^{-5}$ to $5x10^{-1}$respectively.

The ground surface subsidence of 0.85 m is the model calculated to be taken place in the southern boundary of the Sarir South Agriculture Project during the stress period of 1980-1984.

figure (15). This finding match very well with the cracks and fissures observed during this year in the area of study.

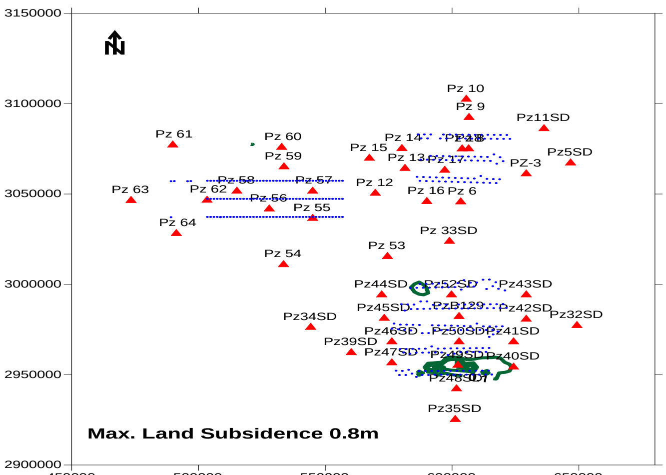


Fig.15. The calculated Land Subsidence in Study Area (1984)

The model simulation using constant withdrawal rates record from 2004-2009 was conducted for the period 2010-2059, i.e. the planned abstraction of the three projects is the same pumping as in 2009. After verifying the model using actual pumping and the observed historical drawdown, the model was assumed to be representative of aquifer systems and the predictive simulation prepared to predict the drawdowns, and the ground surface subsidence, for the future planning of the three wellfields in the study area. The planned abstractions of the three wellfields are kept the same as for the year 2009.The future predictions are presented for twenty five years (2009-2034) and fifty years (2009-2059).

The maximum predicted drawdowns are 14.5m in SNAP, 8.5m in SSAP and 55m in MMRP at the end of the 50 years prediction in the deep aquifer. The predicted drawdowns in some of the piezometers are shown on figures (16) to (18).The maximum model calculated land subsidence is 2.85 m which will effect the SSAP area after 50 years of continuous production (figure (19)).

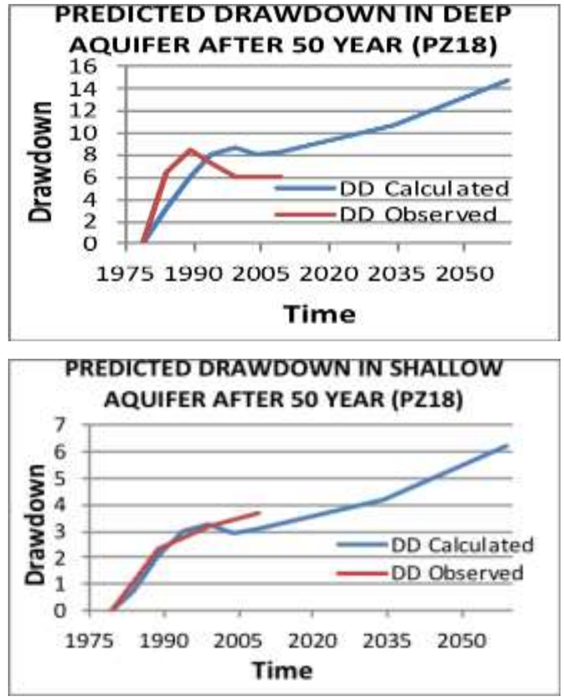


Fig.16. Predicted drawdown in Peizometer no. 18

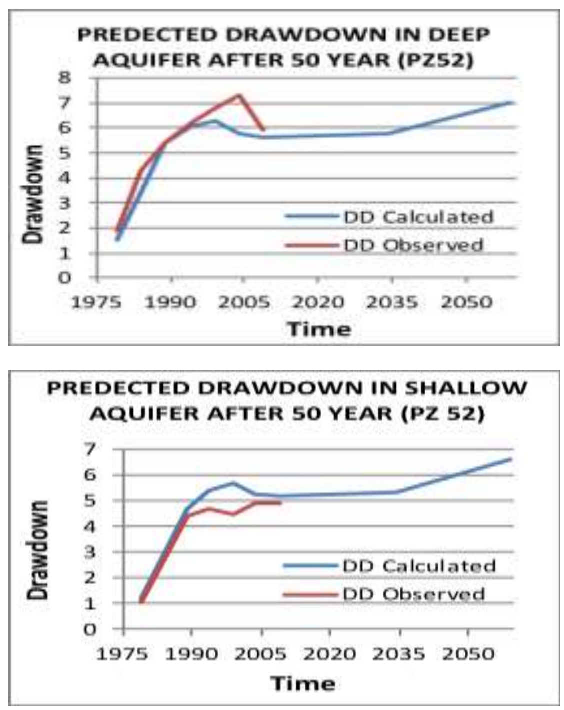


Fig.17.Predicted drawdown in Piezometer no.52)

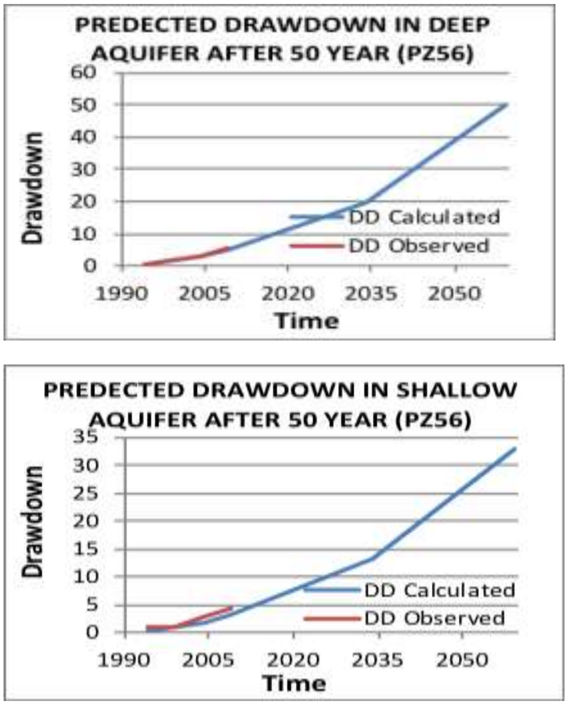


Fig.18. Predicted drawdown in Piezometer no. 56)

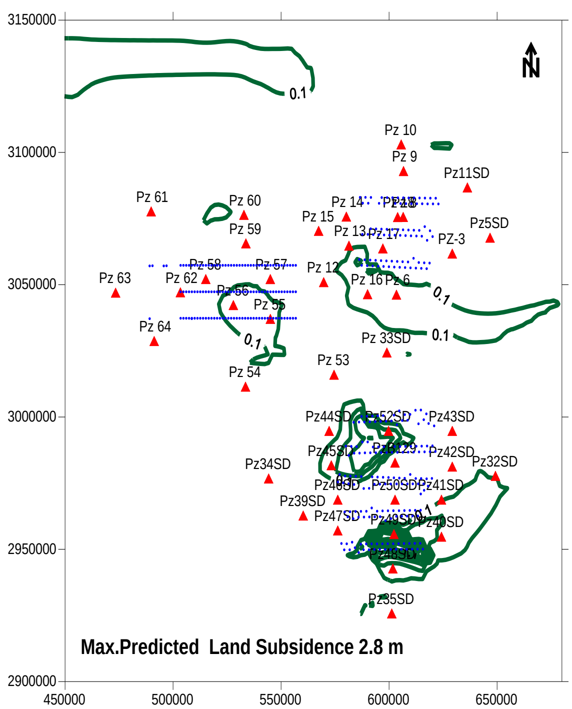


Fig.19. Predicted Land Subsidence in the Study Area (2059)

7. Conclusion

Based on this study, the groundwater flow system in the area is composed of two aquifers, shallow unconfined and deep confined aquifers, separated by semi-confining layer (aquitard and interbeds).

The total extracted water is 6.872 bm^{3}since the start of the welfields to the end of 2012. The results obtained from matching the observed drawdowns with the model predictions are as follows: Specific yield and Storage Coefficient obtained from this model ranges from 0.003 to 0.12 and from 4x10^{-7} to 4x10^{-3}respectively, elastic skeletal specific storage from 4x10^{-7} to 5x10^{-2}, and inelastic skeletal specific storage for thin interbeds is in the range from 4x10^{-5} to 5x10^{-1}. The model then used to predict the drawdown and landsubsidence after 50 years of existing and planned exploitation. The maximum drawdown is predicted to be 55meters with land surface subsidence of 2.8 meters.

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