The Libyan Journal of Science
University of Tripoli Vol. 27, No. 03
https://uot.ed.ly/journals/index.php/ljs

Modeling of groundwater dynamics and the impact of development scenarios at Sarir wellfield

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ARTICLE INFO

Article history:

Received 17/02/2023

Received in revised form 04/09/2024

Accepted 22/10/2024

ABSTRACT

The study area (Sarir field) is part of the man-made river project (MMRP) in Libya. The wellfield includes 126 production wells aligned on three parallel east-west lines, 1.3 km between the wells on each line, 10km between the three lines and includes over 24 exploratory and piezometric wells. The wellfield has two relatively separated aquifer systems: a shallow unconfined aquifer of Post Middle Miocene age and a deep semi-confined aquifer of the Middle Miocene age; both are composed of multi-layered sand, silt, shale, siltstone, and clay. The study aims to construct a Three-dimensional numerical model using finite difference method to simulate deferent development scenarios of the wellfield. Processing Modflow for Windows (PMWIN) had been used to construct, calibrate, optimize production, calculate budget and predict the drawdown of various development scenarios. At present, the Sarir well field produces approximately 600,000 m3/day and is planned to produce 1,000,000 m^3/day in the future. The subsea depth to the top of the main aquifer is around 220 m, and the main aquifer thickness is around 250 m. A very good record of groundwater levels and water production data since it started on 1/1/1999 and up to 30/8/2005 is available for transient calibration. 140 boreholes have been used in the model and checked as active to benefit from most of the available data. A steady-state calibration has been performed against very well defined drilling information. A very good match between the simulated and the initially specified heads has been achieved. The transient simulated time is 2400 days, including 40 stress periods, during which the wellfield produced 714910755 m^3, where a reasonable match between the measured and calculated water heads has been attained in the majority of the piezometer's hydrographs. Three operation scenarios with differing locations of the planned new wells have been made; the best was the second one, in which the new wells are along the three well field lines since it has the lowest maximum drawdown recorded (25 m) and the least reduction in storage (128000 m^3). For the sake of additional assessment, additional model calibration is needed, to benefit from a large number of piezometers and exploratory wells available; this can only be attained if the water levels and production rates in the wellfield are recorded in smaller and more regular time intervals.

Keywords: Three Dimensional Numerical Model, Finite Difference Method, Groundwater Flow Dynamics, Model Calibration, Pumping Optimization, Drawdown Prediction, Wellfield Extension Scenarios, Water Budget, Optimization.

1. Introduction

One of Libya's phase 1 well fields for the Man-Made River Project is the study area (Sarir well field). Figure 1 depicts its location as being in the Sarir Basin in eastern Libya.

The Sarir basin contains high-quality groundwater deposit from which groundwater is drawn. Another two notable water wellfields in the Basin are the South Sarir Agricultural Project (NSAP) and the North Sarir Agricultural Project (SSAP). Around 560 kilometres are needed to reach Sarir Well Field from the shore.

The Sarir well field now produces around 600,000 m^3/day, and its future production is expected to be 1,000,000 m^3/day.

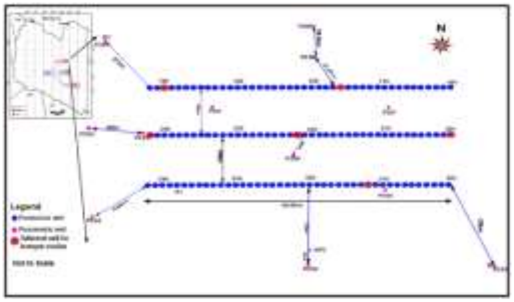

Fig .1. Location and outline of the study area

The producing horizons of the wellfield are not suffering at the present from high drawdown or land subsidence due to the limited flow rate (max: 600,000 m^3/day). MMRA planned to drill additional 45 wells adjacent to the existing Sarir Field wells, aiming to replace the water shortage of the Tazerbo wellfield south of the Sarir field [4].

The Tazerbo field currently suffers from the cone effect of drawdown in its centre and the subsidence of the ground due to a limited flow (max: 500000 m^3/day). This study aims to use available construction and operational data to develop a modular, three-dimensional, finite difference numerical model for groundwater. The Processing Modflow for Windows (PMWIN) used to run simulations [1]. The model aims to predict the impact of various planned new well locations and operating scenarios, calculate budgets for each scenario, and analyse the results. This study contains both steady and transient calibrations. Exploitation scenarios are used to forecast the long-term effects of pumping. Long-term predictions are to estimate the sustainability of water resources in the Sarir field area.

1.1. Hydrogeology

Libya considered a dry land and only 5% of Libya's total area receives a rainfall more than 100 mm per year. Evaporation rates are also high, ranging from 1,700 mm in the north to 6,000 mm in the south [3]. Although the country has very few sources of recharge, groundwater is available in six major underground basins located in different parts of the country. Shallow aquifers are mainly found in the Northern underground basins such as Jiffarah Plain system, Al Jabal Al Akhdar system, and Al Hamada basin, while the deep aquifers (fossil water) are found in most of the Southern part of Libya such as Murzuq basin, Kufra basin, and Sarir basin [1].

The Sarir wellfield is part of the Nubian Sandstone Aquifer System "NSAS", the world's largest aquifer covering approximately 2 million km² in Libya, Chad, Sudan and Egypt.

Sarir wellfield has two aquifer systems: an unconfined shallow aquifer of the Middle Miocene age and a confined semi-artesian deep aquifer of the Middle Miocene age, both are consisting of sand, alluvium, shale, and multi-layered siltstone [5].

Groundwater in the Sarir well aquifer system is naturally flows from south to north. Figures.2 and .3 are East-west & North-South sections illustrating the geometrical levels and flow directions in the Sarir aquifer.

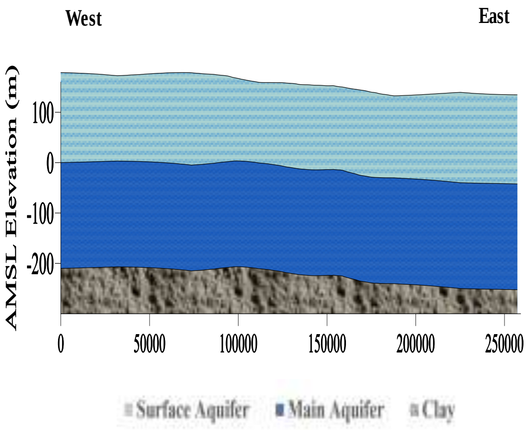

Fig. 2. West to East Cross-Section, Sarir Well Field (the northern portion).

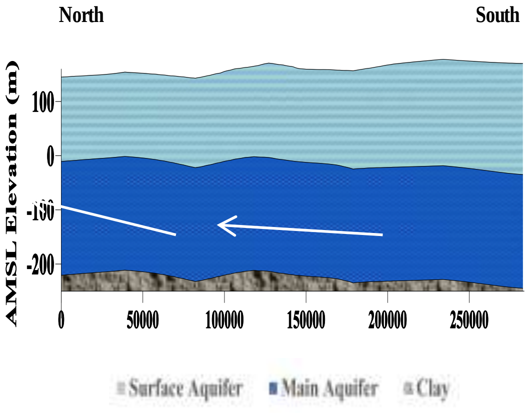

Fig.3. North to South Cross-Section, Sarir Well Field (the middle portion).

The main aquifer is around 220 meters deep, and its thickness is 250 meters due to predominantly continental deposits. The established depths of the wells were 450 meters. Transmissivity, which ranges from.0046 to 0.069 m2/s, and storativity, which ranges from.00021 to 0.0003, were calculated based on the most recent long-term pumping study.

1.2. Water Quality

Sirt Basin in which the Sarir wellfield is situated is of good quality water, with TDS between 587 and 980 mg/l. Good quality water is limited to shallow aquifers and generally degrades with depth, northward displacement, and near borders.

Marine deposition, where marine face striations are frequently observed, is primarily responsible for the variation in water quality in the Sirt Basin. The relatively fresh water of the younger formations of the Sirt basin deteriorates as we go further north and deeper. The inferior quality in the Sirt basin at the northern approach is due to the Cambrian until the Devonian series of marine incursions and regressions towards the south [7].

2. Modelling Conceptualization

This work used PMWIN version 5.3, a graphical user interface for the 3D finite difference modular groundwater model MODFLOW developed by the U.S. Geological Survey [6]. The PMWIN simulation system can use all available memory. It can process models with up to 1000 stress periods, 80 layers, and 250,000 cell per layer [2].

The integrated scanner and field interpolator allow the model grid to be adjusted, rotated, refined, and model data to be defined as regions or even automatically interpolated for each finite-difference cell. It can import matrix graphics (bitmap), vector graphics (DXF or Line Map) as background sitemaps, and any type of existing standard MODFLOW templates and SURFER grid files. It can automatically transfer the results of the regional model as the boundary condition for the local-scaled sub-model and check models for potential problems before running the simulation.

This modelling study was conceptualized utilizing geometrical raw data that was taken from multiple drilling site final reports, sorted, and classed before being loaded into PMWIN via the field interpolator (Figures 4 and 5). This geometry was then used to draw several cross sections and stored again as the real geometry of the aquifer. The N-S and W- E cross sections, which represent the geometrical levels of the model layers and have been slightly modified to include the majority of the model geological and hydrogeological features of the study area's aquifer system, serve as the conceptual model for this modelling study.

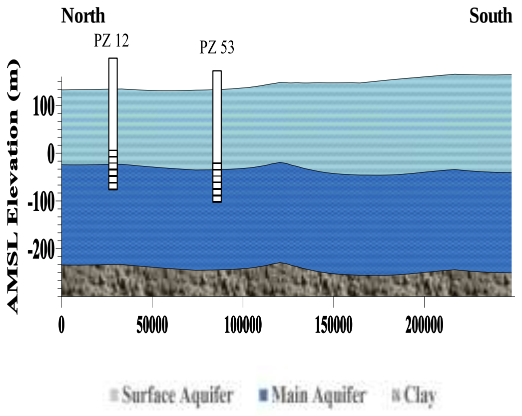

Fig. 4. Sarir Well Field's North to South Cross-Section (the eastern portion)

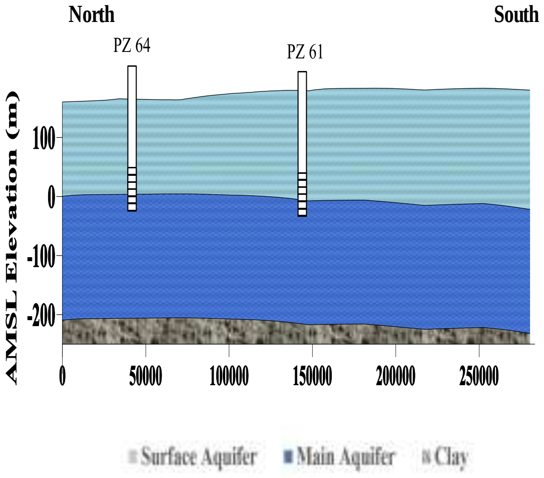

Fig. 5. Sarir Well Field's North to South Cross-Section (the western portion)

3. Model Design

The block-cantered grid of the 335,606 km^2 model is designed with 78 columns and 65 rows according to the properties of the aquifer, field data availability, boundary conditions, and well locations (figure 6). Additionally, Layer 1 was selected as strictly unconfined, and Layer two as convertible between confined and unconfined.

PMWIN calculates transmissivity. Hydraulic heads in all of the model boundaries were defined using the General-Head Boundary Package. Transmissivity has been selected to be computed for each model layer using the given horizontal conductivity and layer thicknesses.

Raw data from the final drilling report, presented as excel xyz.dat files before being interpolated using the PMDIS field interpolator. Figures 7 and 8, the producing layer top and bottom contour maps were created using stored (XYZ.dat) model data.

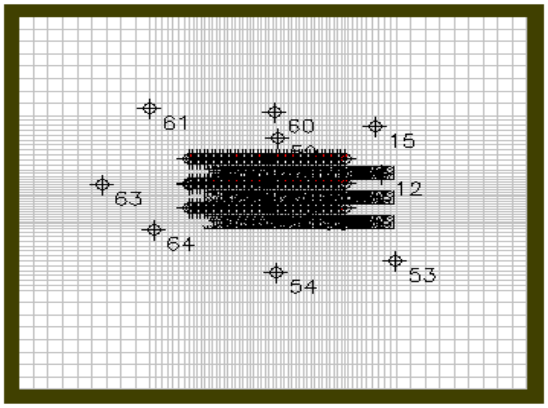

Fig. 6. Model grid design

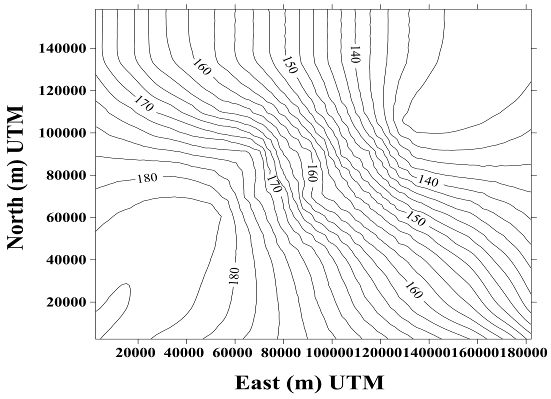

Fig. 7. Top of 2nd (producing model layers) (mamsl)

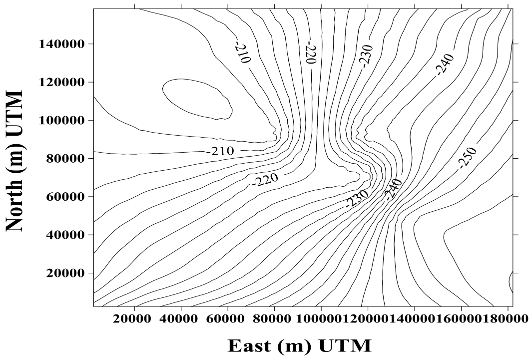

Fig. 8. Bottom of 2nd producing) model layer (mamsl)

MODFLOW computes the initial time step DELT (1) and the further time steps DELT (2, 3, 4…) using the following equations (6 and 7).

$$\mathrm{DELT}(1) = \frac{PERLEN\,(1-TSMULT)}{1-TSMULT^{NSTP}} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\mathrm{DELT}(A+1) = \mathrm{TSMULT} \times \mathrm{DELT}\,(A) \ldots\ldots\ldots\ldots\ldots(2)$$

Where **PERLEN** is the length of a stress period, **TSMULT** is the time step multiplier, **NSTP** is the number of time steps and **DELT (A)** is the length of time step A in a stress period.

The Sarir wellfield has been in operation since January 1, 1992, with periodic replacement of the active wells. For transient calibration, a very accurate record of actual water production from January 1, 1999, through August 30, 2005, is available as shown in Table.1.

Table .1. Stress Period Design of Transient Simulation

No of wells	Period No	From	To	Production (m^3)	Period length (days)
42	1	1/01/ 1999	30/02/ 1999	13860120	60
Periods from 2 to 39					
62	40	1/07/ 2005	30/08/ 2005	23197227	60

For every model cell in this study, the actual values for the initial heads of both of the model layers were provided. For the General-Head Boundary Package (GHB1), those initial heads have been utilized as hydraulic heads at the boundaries. The main challenge to obtaining the true head of the aquifer system is always a lack of data. Figures 9 and 10 successively show the initial water levels of the two model layers (as it is on 1/1/1999).

140 boreholes were employed in this study and verified as active in order to show boreholes in the data editor and interpolate the simulation findings to them. The available observed head data are measured at the beginning of the model simulation and have been defined against each borehole in ascending order.

All of the model layers have had their horizontal hydraulic conductivity defined and calibrated; PMWIN uses this information along with layer thickness to determine transmissivity, and the corresponding transmissivity flag is calculated for each model layer in the Layer Options dialog box. Only for transient flow simulations, MODFLOW requires the dimensionless storage terms. Storage coefficient (for confined aquifers), which equals specific storage [1/L] × layer thickness [L] is required by layers of type 0, 2, and 3, while in unconfined aquifers, the storage term is given by specific yield (drainable porosity) and required for layers of type 1, 2 and 3. The specific yield has been specified to be calculated by PMWIN for the first and second aquifers. Storage coefficient is also specified to be calculated by PMWIN for second aquifers.

The General-Head Boundary package were to simulate head-dependent flow boundaries, where all the boundary cells have been defined by the values of the GHB hydraulic conductance C_b [L^2/T] and Hydraulic head h_b [L]. The Flow through the general-head boundary Q_B [L^3/T] is calculated by MODFLOW using the following equation:

$$Q_b = C_b \cdot (h_b - h) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where h is the hydraulic head in the aquifer**.**

In this study, initial water levels have been used in all simulation periods as Hydraulic heads at the boundary and the GHB hydraulic conductance taken 600 m^2/day has been used in all of the aquifer boundaries. The head at the boundary was kept constant through all of the simulation periods because no real drawdown has been noticed at the modelled boundaries and there is no expectation of a high drawdown at the boundaries shortly. PMWIN defines an injection well by a positive cell value of the recharge rate (Q) [L^3/T] and a pumping well by a negative cell value.

The same flow rates (6800m^3/day) of all wells have been used in the model although in the fact they are slightly different, where minor errors have been accepted. PMWIN supports four packages (solvers) for solving systems of simultaneous linear equations: The Preconditioned Conjugate-Gradient 2 (PCG2) package has been used throughout the modelling process. The Output Control Package is used to control the model result output saving frequency, which later can be extracted, presented, saved, or printed. The output terms are: Hydraulic Head in each finite-difference cell are saved in the unformatted (binary) file HEADS.DAT.

Drawdown are the differences between the initial hydraulic heads and the calculated hydraulic heads. Drawdowns in each cell are saved in the unformatted (binary) file DDOWN.DAT and the Cell-by-cell Flow Terms**:** these are flow terms for individual cells, including four types: 1- cell-by-cell stress flows, which are the flows into or from an individual cell due to one of the external stresses, 2- cell-by-cell storage terms, which give the rate of accumulation or depletion of storage in an individual cell; 3- cell-by-cell constant-head flow terms, which give the net flow to or from individual constant-head cells and 4- internal cell-by-cell flows, which are the flows between adjacent model cells. The four flow terms are used for calculating water budgets. The water budget indicates the overall acceptability of the model.

4. Modelling Calibration

Horizontal hydraulic conductivity and boundaries conditions have been adjusted until a good match between the simulated and the initially specified heads has been achieved. Finally, simulated heads of the two layers of the aquifer systems as shown in Figures 9 and 10 have been saved to be used as the initial head for transient simulation.

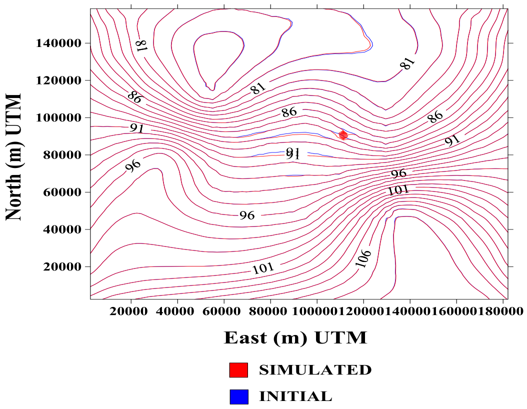

Fig .9. Steady Simulated Head (m.a.m.s.l) of the Surface (Shallow) Aquifer (1st)

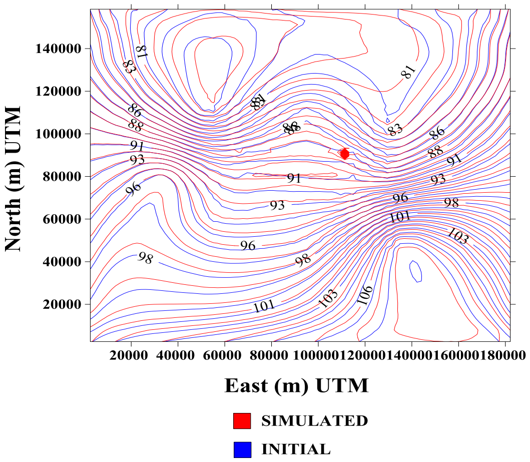

Fig. 10. Steady Simulated Head (m.a.m.s.l) of the main Aquifer (2nd)

The transient simulated time is 2400 days, including 40 stress periods, during which the wellfield produced (714910755) m^3, as shown in table 1.The calibration was performed against the available water head data that was measured manually at the same time intervals.

Hydraulic parameters have been specified and adjusted by trial–and–error as shown in Figures 11 to 12 until a reasonable match between the measured and calculated water heads has been attained.

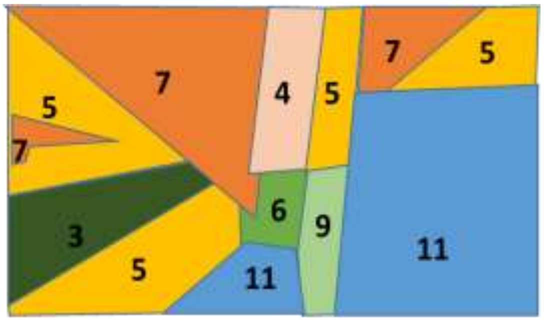

Fig. 11. Calibrated Conductivity (m/day) of Main Aquifer (2nd)

Fig. 12. Calibrated Specific Yield of 1st Aquifer

Fig. 13. Calibrated Specific Yield of Main Aquifer (2nd)

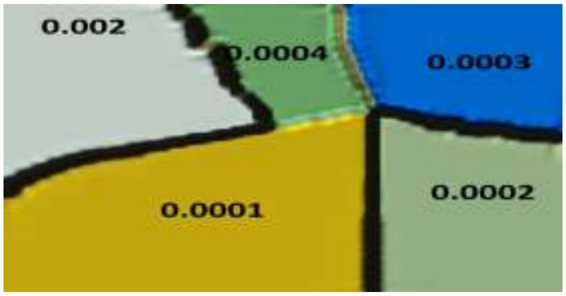

Fig. 14. Calibrated Storage Coefficient of Main Aquifer (2nd)

Generally, fair to very good matches between the computed and observed hydrographs (Time in days versus head in meters) have been attained as shown in Figures 15 to 19. However, some errors can be accepted.

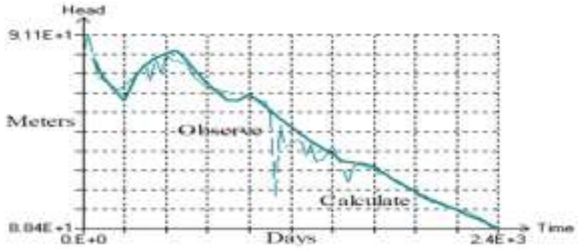

Fig. 15. Hydrograph Response of PZ55

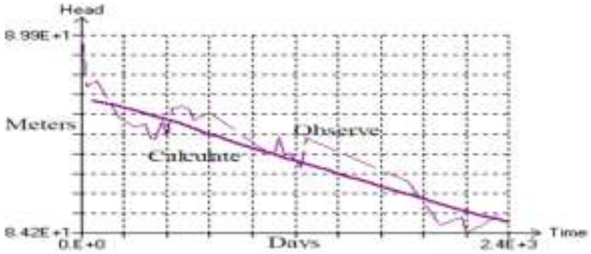

Fig. 16. Hydrograph Response of PZ57

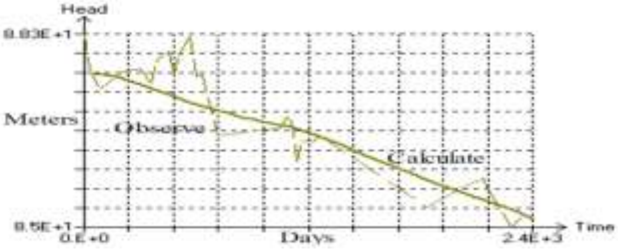

Fig. 17. Hydrograph Response of PZ58

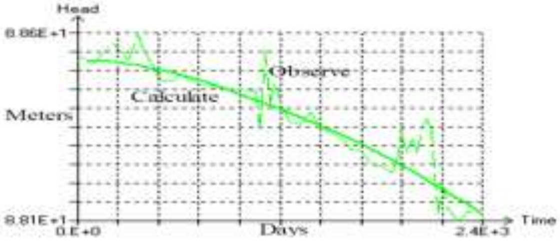

Fig.18. Hydrograph Response of PZ62

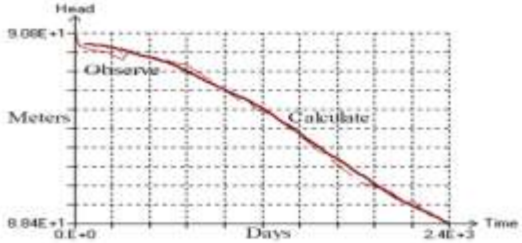

Fig. 19. Hydrograph Response of PZ56

5. Operation Scenarios

Three operation scenarios have been used in this modelling study to determine the likely future drawdown in the Sarir area. The main characteristics and the results of the operation scenarios are summarized in Table 2.

Table .2. Summary of operation scenario results

	Steady state	transient	Scenario 1	Scenario 2	Scenario 3
Duration (days)	2400	2400	12775	7300	7300
Duration (years)	6.57	6.57	35	20	20
Wells out (m^3)	0	889970368	9713480700	10904840200	11207644200
Average wells out (m^3/day)	0	469200	856800	1020000	1061480
GHB In (m^3)	14526272	149426064	1092375170	1093398530	1093390720
GHB In (m^3/day)	484209	66182	76070	76211	76209
GHB Out (m^3)	14526272	858335936	2379836160	2379449600	2379314690
GHB Out (m^3 /day)	484209	220865	102513	102460	102441
Operating wells	Non	Actual (62)	All wells (171)	All wells (171)	All wells (171)
Max Drawdown (m)	0	7	23	25	26

5.1. Scenario 1

Fourty stress periods from 1999 to 2005 represent the transient period. In this first scenario, the wellfield will be pumped for an additional 35 years, which were divided into 15 years (5475 days) for the period (41) and 20 years (7300 days) for the period (42).

The present flow rate (600,000 m3/day) and operating well distribution, which were used in the last stress period (40) of transient simulation, will continue the same for the period (41), but in the period (42) the existing operating well distribution in the wellfield will be modified to be regularly distributed. The reason behind this design is to see the likely effect of operating the same number of wells for 35 years on the wellfield drawdown. Figures 20. shows the maximum computed drawdown in the main aquifer at the end of the transient simulation period (40) is 6.5m.

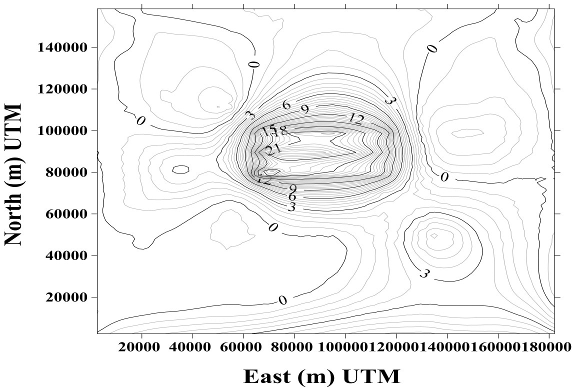

Fig. 20. End of Scenario 1 Simulated Drawdown of the Main Aquifer (2^{nd}), Sarir Area

The drawdown increased up to 12.5m at the end of period (41) and 23.4m at the end of the simulation time of this scenario.

5.3. Scenario 2

In this scenario, 15 wells added to the western side of the wellfield along each of the 3-wellfield lines as shown in figure 21.

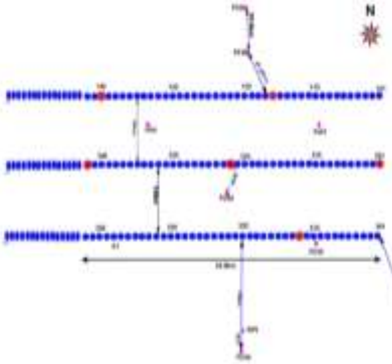

Fig. 21. The layout of western side additional 45 wells along the three lines scenario (2^{nd})

The existing 126 wells and the additional 45 wells have been pumped for 20 years (7300 days). The reason behind this design is to see the likely drawdown in the wellfield if the field pumped to full capacity with 45 additional wells. The maximum computed drawdown in the main aquifer at the end of scenario 2 is 25 m, as shown in Figure 22.

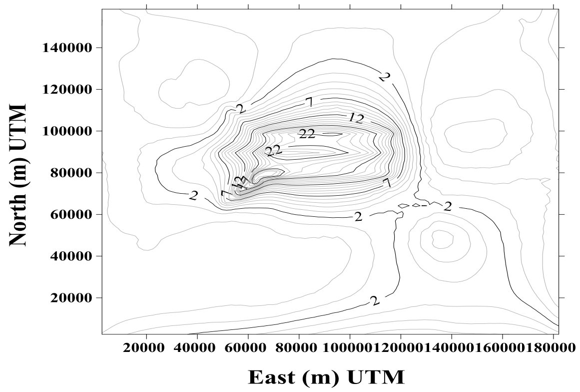

Fig.22. Drawdown due to western side additional 45 wells along the three lines scenario (2nd)

5.4. Scenario 3

In this scenario, 15 wells are added as shown in figure 23 to the western side of the wellfield to each of the 3-wellfield lines, with an angle of 45 degrees to lines 100 and 300 and along the middle line 200.

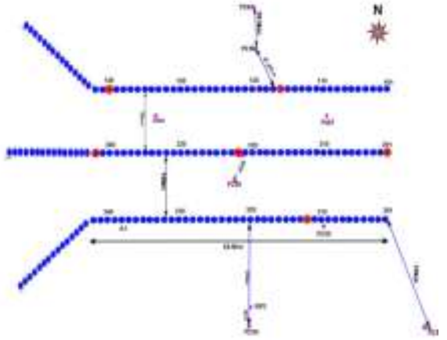

Fig.23. The layout of western side additional 45 wells, 30 of them are diagonal to the well field lines scenario (3rd)

The existing 126 wells and the additional 45 wells have been pumped for 20 years (7300 days).The reason behind this design is to see the likely drawdown in the wellfield if the field is pumped to full capacity with an extension on the western side of the wellfield at an angle of 45 degrees to lines 100 and 300. The maximum computed drawdown in the Main aquifer at the end of Scenario 3 is 25.8m as shown in figure 23.

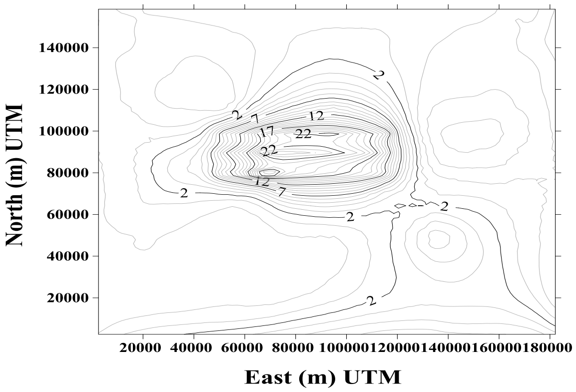

Fig. 23. Drawdown due to western side additional 45 wells, 30 of them are diagonal to the well field lines scenario (3rd)

6. Conclusion

The available pump houses are constructed to accommodate the pumps down to a depth of 216 meters. The estimated maximum drawdown is only about 25.8 meters, so there is no need to be concerned about the estimated drawdown, total pumping lifts over the next 35 years, full field production, or the addition of 45 new wells as an extension of the wellfield. The calibrated hydraulic conductivity for the main aquifer ranges from 1.8 to 16 m/day. The calibrated Specific Yield of the surface aquifers ranged from 0.12 to 0.15. The calibrated storativity for the main aquifer ranged between 0.0002 to 0.003. Drilling information shows that the wellfield consists of two slightly separated, unconfined surface aquifers (approx. 200m thick), and a main aquifer (approx. 250m thick). Despite being performed against a relatively little period of pumping, transient calibration demonstrates very strong history matching; hence, additional future calibration utilizing the freshly emerging data is required. The small head differences between the surface and main aquifer indicate a minor separation between the two aquifers.

The best model scenario is the second one, in which the new wells are along the three well field lines since it has the lowest maximum drawdown recorded (25m), and has the least reduction in storage (-128000 m3/day). The Sarir wellfield must be further assessed in order to benefit from the many piezometers and exploratory wells that are currently available. This can only be done if the water levels in the wellfield are recorded at smaller and more frequent intervals. It is crucial to take into account carrying out a regional modeling analysis, with extra calibration and optimization, using the recently released data and tools, as well as greater resources, for the future evaluation of the Sarir wellfield. Revision of the pump submergence to secure the available pumps from any excessive drawdown and dry run operation. Although this model has a short calibration period, the excellent history matching gives this model a good capability to simulate any field operation or extension scenario. For the sake of additional assessment, future model modification /calibration of Sarir wellfield is very vital and important to benefit from the large number of piezometers and exploratory well available, where this can only be attained if the water levels in the well field recorded in smaller and regular time intervals. For the future assessment of Sarir wellfield, it is important to consider conducting a regional modelling study, with additional calibration and optimization, using the newly emerged data and software has and better recourses. Modelling is the most suffocated method for aquifer management; hence, MMRP authority should invest in reviewing the previously constructed models for further aquifers assessments.

7. References

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