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Mine water supply assessment and evaluation of the system response to the designed demand in a desert region, central Saudi Arabia

Yohannes Yihdego · Len Drury

Abstract The efficient use of water resources in arid region has become highly relevant in the evaluation and mining planning, since the exploration phase to closure. The objective of the numerical groundwater model was to assess the potential for groundwater extraction to meet mine water demand from one of the driest area in the world. Numerical groundwater models were used to assess groundwater resource. Modelling was undertaken using MODFLOW-SURFACT code, an advanced MODFLOW based code, within the framework of Visual MODFLOW version 4.6. A steady state model was developed to assess the regional groundwater flow pattern and to calibrate the recharge and hydraulic conductivity parameters in the model. The model was calibrated with a correlation of coefficient of 0.997, and root-mean-squared error is 0.3 m. A transient simulation model was used to predict the impact of 1.5 million cubic metre/year extraction for 10 years on the main aquifer hydrogeological regime, including after cession of pumping. Modelling simulated four hydrogeological scenarios. Model results for the 'worst case' scenario suggested that the Saq Sandstone aquifer should be capable of supplying the mine water demand (1.5 million cubic metre (MCM)/year) for 10 years. However, the long-term water-level drawdown shows a continuous decrease without achieving steady state conditions; thus, the majority of water is being taken from aquifer storage, and in the long term, there will be a mutual interference from a borefield located to the north of the model area. In this area, the hydraulic gradient is relatively steep and over-pumped for more than 28 years. Other scenario shows that there will be a recovery of around 8 m out of the 11.6-m drawdown, after 18 years of cession of pumping, implying that the aquifer will be stressed and a large percentage of water taken from aquifer storage. To minimise hydrogeological impacts, it is recommended to laterally spread out production bores, bores should be located where the Saq Sandstone is deepest, and operate the bores at low extraction rates. Overall, this study presents a useful numerical model output for mine water supply assessment and will contribute towards improving water resources management under different conditions in one of the world driest area.

Keywords Numerical modelling · Mine water use · Water resources management · Impact prediction · Middle East · Mining & Mineral processing

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Introduction

Water is the key component in the development of the mining industry, from potable water for human use to industrial water for mineral recovery. A need exists for a more comprehensive, physically based approach that

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utilises site-specific data. In recent years, hydrological models, with various degrees of sophistication, have been used in various settings to evaluate water budgets under various climate or land use scenarios (e.g. Turner et al. 2015; Whittier et al. 2010; Yihdego et al. 2015). In general, a water-budget model is used in estimating recharge, which is used as input to groundwater models. Sustainability indicators such as acceptable head or water-quality levels are examined based on climate and management decisions affecting water extraction and land use. Due to limitations in models and data availability for model calibration, field monitoring of sustainability indicators should be an important part of any sustainability planning effort. A resource evaluation procedure using numerical flow modelling illustrates the importance of incorporating the structural complexity of the aquifer (e.g. Mair et al. 2013; Yihdego and Webb 2015; Yihdego and Becht 2013) and in assessing groundwater yield, an approach not available with conventional projection using analytical methods (Gingerich 2008; Sophocleous 2000). Difficulties arise in applying analytical solutions where the simplifying assumptions are not supported by field data. Numerical modelling is used in assessing the groundwater potential. In this context, the use of numerical models as a tool for diagnosis, management and prediction of water behaviour in the ground, has been gaining considerable importance in the recent years.

On the study area, central Saudi Arabia, as is the case for many semi-arids, detail assessment of groundwater resources is especially important given the increasing water demands from urban and agricultural development and the mine projects lack of reliable surface-water resources (Al-Salamah et al. 2010; Hagedorn et al. 2011; Won et al. 2005).

In arid zone, like the study area, the rational and efficient use of water resources has become more relevant in the evaluation and mining planning, since the exploration phase to closure. This study presents a methodological approach for setting numerical model for mine water supply in one of the world driest areas. The objective of the numerical hydrogeological model was to assess the potential for groundwater extraction from the transboundary regional Saq Sandstone ('*target aquifer*'), near Khnaiguiyah, central Saudi Arabia. To assess the viability to supply the mine water demand of 1.5 million cubic metre/year (MCM/year) over 10 years from the Saq Sandstone, a regional three-dimensional numerical groundwater model was developed. This work included the preparation of a conceptual hydrogeological model and calibration and

computer running of a numerical groundwater model. The data presented in this paper and interpretations have been sourced from SMEC (2012) consultant's report.

Regional setting

The study area is located in the Province of Ar-Riyadh, in central Saudi Arabia, approximately 170 km from the capital Riyadh. The mine study area site is located within the Governate of Al-Quwayiyah. The outside borefield area and water delivery pipeline footprint extend into the neighbouring Ad-Duwadimi Governate.

The topography is hilly with elevations varying from 800 m above sea level downstream of the lease area to 900 m at the top of the catchment. Vegetation coverage is minimal. Most of Saudi Arabia is typically an arid region with annual average rainfall varying between 50 and 100 mm. Higher rainfall occurs along the Red Sea escarpment and to the north of Riyadh, where annual average rainfall reaches 600 and 200 mm, respectively. Evaporation measured at Riyadh shows an annual average of 2900 mm with daily peak values that may exceed of 18.5 mm/day during summer. Abunayyan and BRGM (2008) estimated evapotranspiration using the Penman equation from five regional meteorological stations. The average annual evapotranspiration is calculated at 2376 mm/year. There is thus a substantial difference in annual rainfall and evapotranspiration of around 90.3:2376 mm, a ratio of 1:26.3.

Hydrogeology

Saudi Arabia is tectonically located on the Arabian Plate. Regionally, this plate can be subdivided into two geological regimes, the Arabian Shield and Arabian Platform (Fig. 1). It consists of Late Precambrian metamorphosed volcanic and volcano-sedimentary rocks intruded by volcanics. The tilting of the Arabian Shield basement has resulted in an eastward dip of these sediments towards the Arabian Gulf. Major commercial gas and oil fields occur between Riyadh and the Arabian Gulf in this sedimentary sequence. The Saq Sandstone is a regionally extensive geological unit which crops out through the central to northern half of Saudi Arabia, Jordan to Syria, over a distance of 1200 km with surface exposure of some 65,000 km^2. The Saq Sandstone is separated by an unconformity from the overlying Khuff Formation of Permian age. The closest major

sedimentary aquifer system to the Khnaiguiyah Project is the regionally extensive Saq Sandstone. Being a regionally extensive aquifer, it stores a significant amount of groundwater (about 280 billion cubic metres). Its southernmost extent is some 10 km north of Khnaiguiyah, where it pinches out against a palaeo-basement high. The Khuff Formation is a lesser important discontinuous aquifer system. It extends closer to the mine study area.

The highest water-level decline in the Saq Sandstone concentrated in the Qassim and Tabuk regions, with declines of 140, 170 and 210 m in the Tabuk, Buraydah and Ad Dawadimi areas, respectively. Water-level draw-down stretched parallel to the impermeable basement outcrop. Due to the withdrawal and groundwater reduction, the piezometric surface is slowly regionally recovering (Fig. 1). Baseline literature reports a transmissivity range of 200 to 7000 m²/day, permeability of 6 to 70 m/day and porosity of 20 to 25 %. The aquifer is unconfined

to the west and confined to the east under the Ash Shiqqah Aquitard of the Khuff Formation. Individual groundwater yields are usually around 50 to 100 L/s. Natural groundwater flow direction is towards the north-east except where a reversal of groundwater hydraulic gradient has resulted from major water-level declines.

Historical Data

The assumed mine water demand is 1.5 MCM/year for 10 years. Such a water supply is not currently available from wastewater treatment facilities, surface water or storage dams. A long-term groundwater supply may be available from several production bores in the Saq Sandstone. Historically, large groundwater extraction has taken place from the Saq Sandstone for agricultural and town water supply purposes, including the Al-Quwayiyah and Labhka Borefields. Transmissivity of the confined Saq Sandstone aquifer is between 100 to
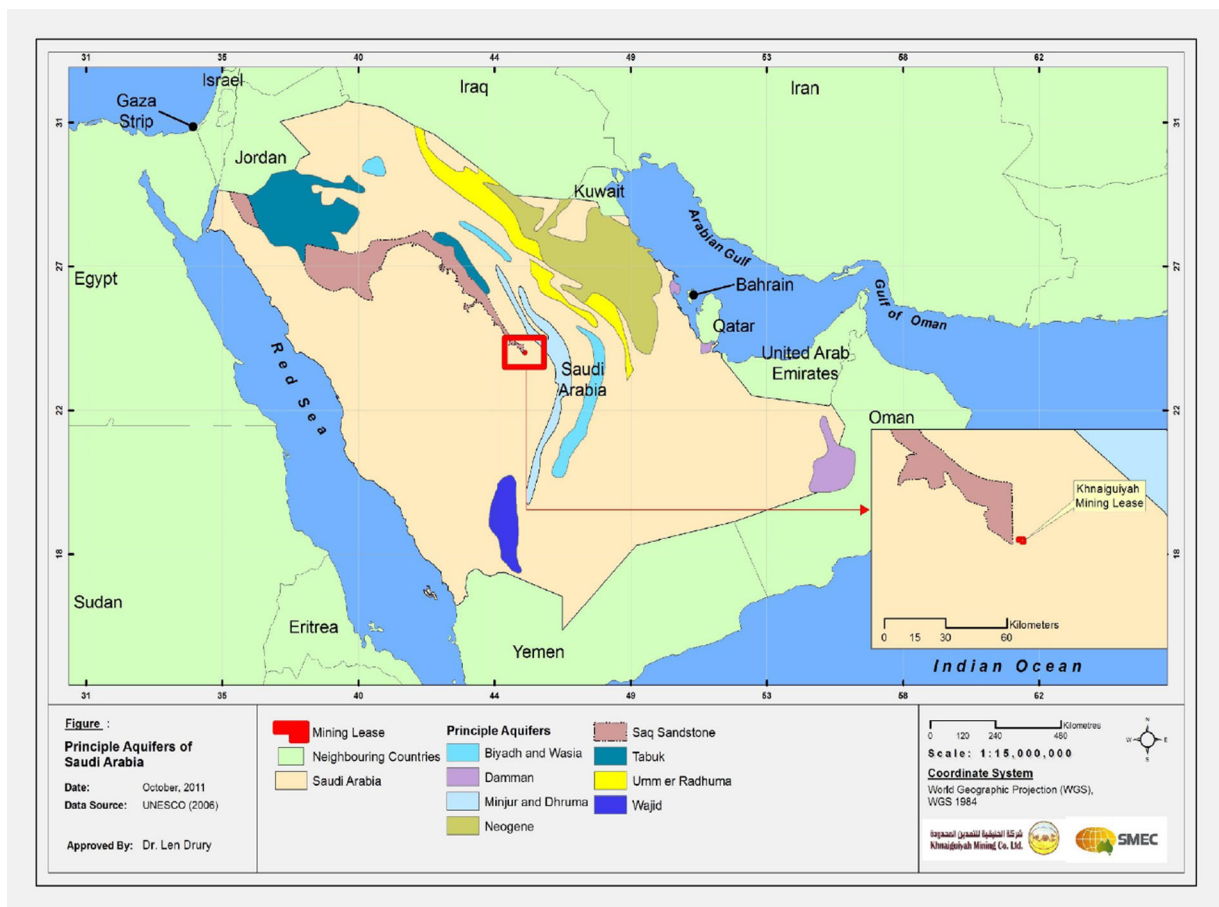

Fig. 1 Location map of the study area and principal aquifers of Saudi Arabia (UNESCO 2006)
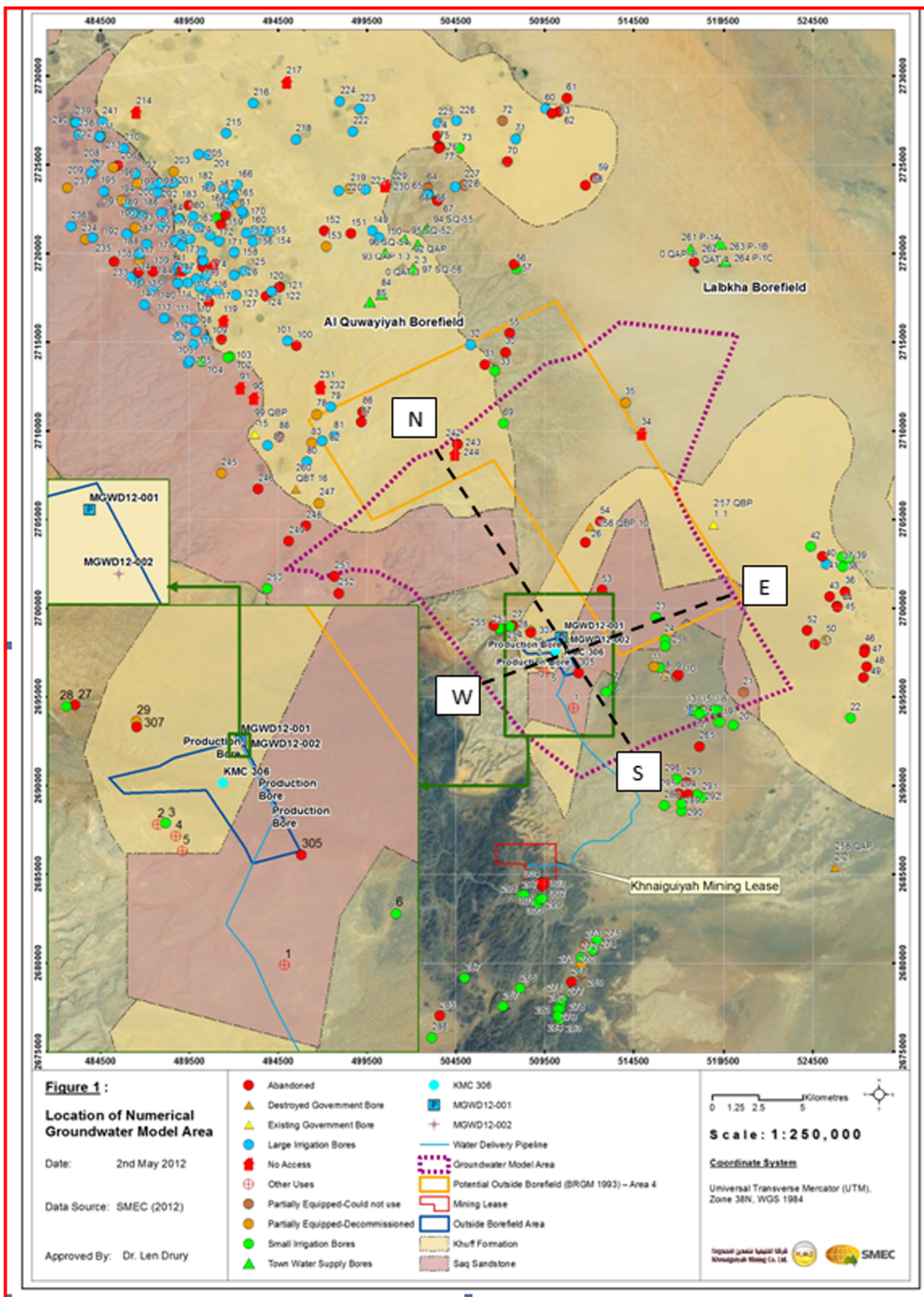
Fig. 2 Location of the study area

200 m²/day (1.2 to 2.3 × 10⁻³ m²/s), permeability of 1 to 3 m/day and storage coefficient of 10⁻⁴ to 10⁻⁵. The

assessed aquifer permeability is on the lower limit of that reported elsewhere. Exploitable yield from

Table 1 Calibrated aquifer parameters

Layer	Horizontal conductivity (m/day)	Vertical conductivity (m/day)	Specific storage (1/m)	Specific yield
Khuff Formation	4.2	0.42	1×10^{-5}	0.15
Saq Sandstone	6	0.6	1×10^{-6}	0.28
Basement	0.0001	0.00001	1×10^{-8}	0.001

individual production bores ranges between 20 and 50 L/s. Water salinity ranges from 1360 to 17,000 mg/L, the latter assumed to be vertical leakage from the overlying Khuff Formation and shallow alluvium draining the Arabian Shield's eastern periphery (Al-Salamah et al. 2010; Abunayyan and BRGM 2008).

Conceptual hydrogeological model

The conceptual hydrogeological model (CHM) is the key pre-requisite for describing the hydrogeological conditions of a site in the development of a numerical model. The CHM provides interpreted information on the geology, hydrogeology, occurrence and flow of groundwater, hydrochemistry and current groundwater utilisation. The model covers an area of approximately 357 km^2 ('model area'). The Outside Borefield is located towards the southwest of the modelled area (Fig. 2). The model's western, eastern and southern boundaries have been chosen based on geological features and aquifer extent. The Al Quwayiyah Borefield and the Labkha Borefield are located to the north and northeast of the northern model boundary, respectively.

Geology and aquifers

The geology and hydrogeology of the study area consists of

- Surficial, aeolian, alluvial and colluvium Quaternary sediments overlying;
- Permian Khuff Formation, unconformably overlying;
- Ordovician to Cambrian Saq Sandstone, unconformably overlying; and
- Pre-Cambrian basement Arabian shield complex.

The Saq Sandstone is the primary project target for the mine water supply source. The lower section of the Khuff Formation contains the Ash Shiqqah Unit, consisting of shale and massive conglomerate. The upper section contains fossiliferous marl, dolomite, sandstone and gypsum. The Khuff Formation is a lesser important discontinuous aquifer. Using drill logs, geological/hydrogeological cross sections, published geological maps, geophysical data and geology outcrop maps, a three-dimensional hydrogeological model was prepared using the software package *Hydro GeoBuilder* version 2009. The Saq Sandstone underlying the Outside Borefield is situated over a Pre-Cambrian basement high.

Aquifer hydraulic parameters

The aquifer properties adopted are based on the results of the current hydrogeological investigations and previous studies from the area (Al-Salamah et al. 2010). Where no data is available, literature values (Fetter 2001; Freeze and Cherry 1979) and professional judgement have been adopted. The model was calibrated using the adopted data. The calibrated aquifer parameters are summarised in Table 1.

Groundwater flow systems

Groundwater flow systems occur in all landscapes. Movement occurs through

- Areas of recharge where water can enter the groundwater system;
- Zones of lateral flow which can be very extensive in large basins; and
- Groundwater discharge zones where the groundwater emerges back to the surface, either through natural or artificial pumping systems.

Flow systems can be regional, intermediate or local in scale and are driven to a great degree by the topographic and geologic fabric of the region under consideration. The Saq Sandstone is a regional aquifer system,
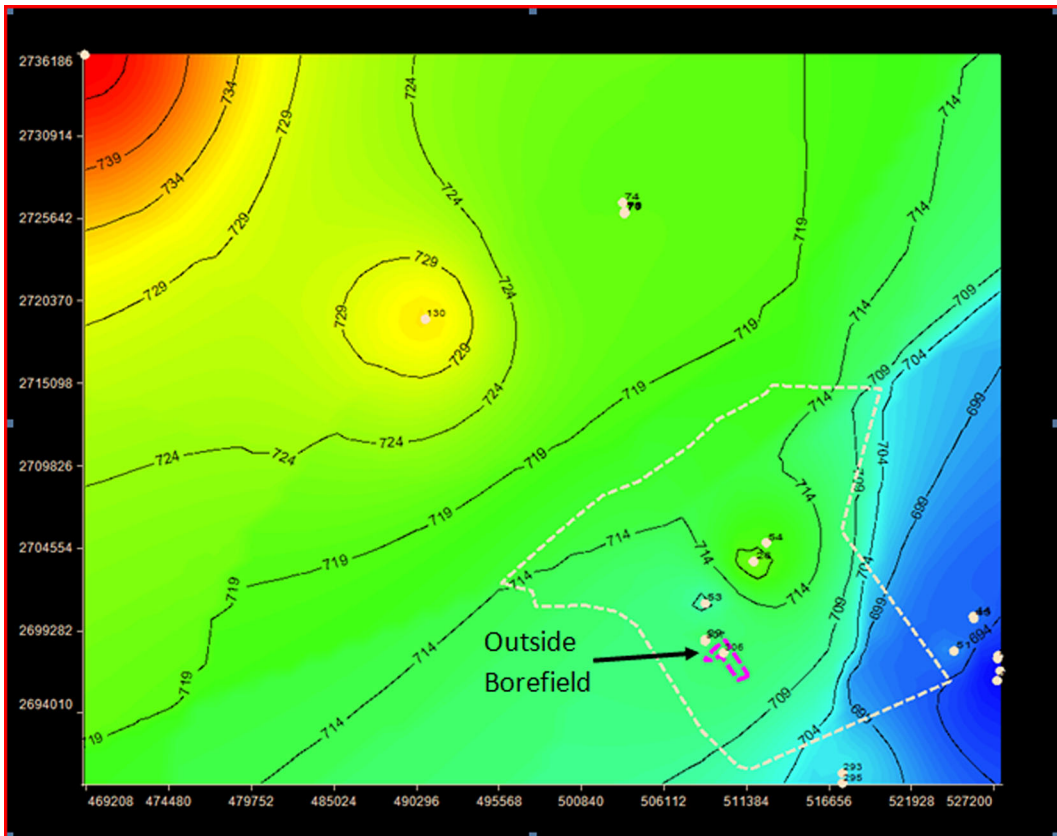
Fig. 3 Groundwater level (pre-development; year 1983). Water-level data points are shown as *grey dots*

outcropping over a 1200 km length. The Outside Borefield is located on the southern termination of this regional aquifer system. The Saq Sandstone generally dips to the east. Aquifer recharge occurs in the area of outcrop. Aquifer discharge is regionally from irrigation and municipal production bores and throughflow. The Khuff Formation is less extensive but occurs throughout the area of the numerical model.

The Saq Sandstone crops out a few kilometres to the west and south of the Outside Borefield (Fig. 2). The potential major influences on groundwater levels and flow patterns within the model area are

- *Groundwater extraction*, from the Saq Sandstone for irrigation and town water supply purposes. For example, the Al Quwayiyah Borefield has been operating since 1984;
- *Topography*, along the outcrop of Saq Sandstone; and
- *Rainfall*, upstream catchments and over outcrop. Recharge to the Saq Sandstone occurs along outcrop by vertical infiltration from ephemeral surface water systems.

On a regional scale, the volume of groundwater withdrawal is not compatible with the amount of aquifer recharge. Thus, the aquifer in many placed is being '*mined*'. Groundwater extraction has induced a steady drop in the regional groundwater level.

Piezometric surface

The initial pre-irrigation head was interpolated from 19 data points, with water levels estimated from the USGS digital elevation model (DEM) (Fig. 3). The impact of groundwater extraction from irrigation and municipal production bores to year 2012 (based on 69 measuring points) is shown in Fig. 4. There has been a significant variation in groundwater flow pattern and hydraulic gradient over the last 28 years. Maximum water-level decline is observed at the Al Quwayiyah Borefield (4.2 m/year). No large-scale groundwater extraction occurs in the Outside Borefield area. There appears to be an artificial groundwater flow divide at RL + 718 m, on which the northern model area has been placed (Fig. 4). Since
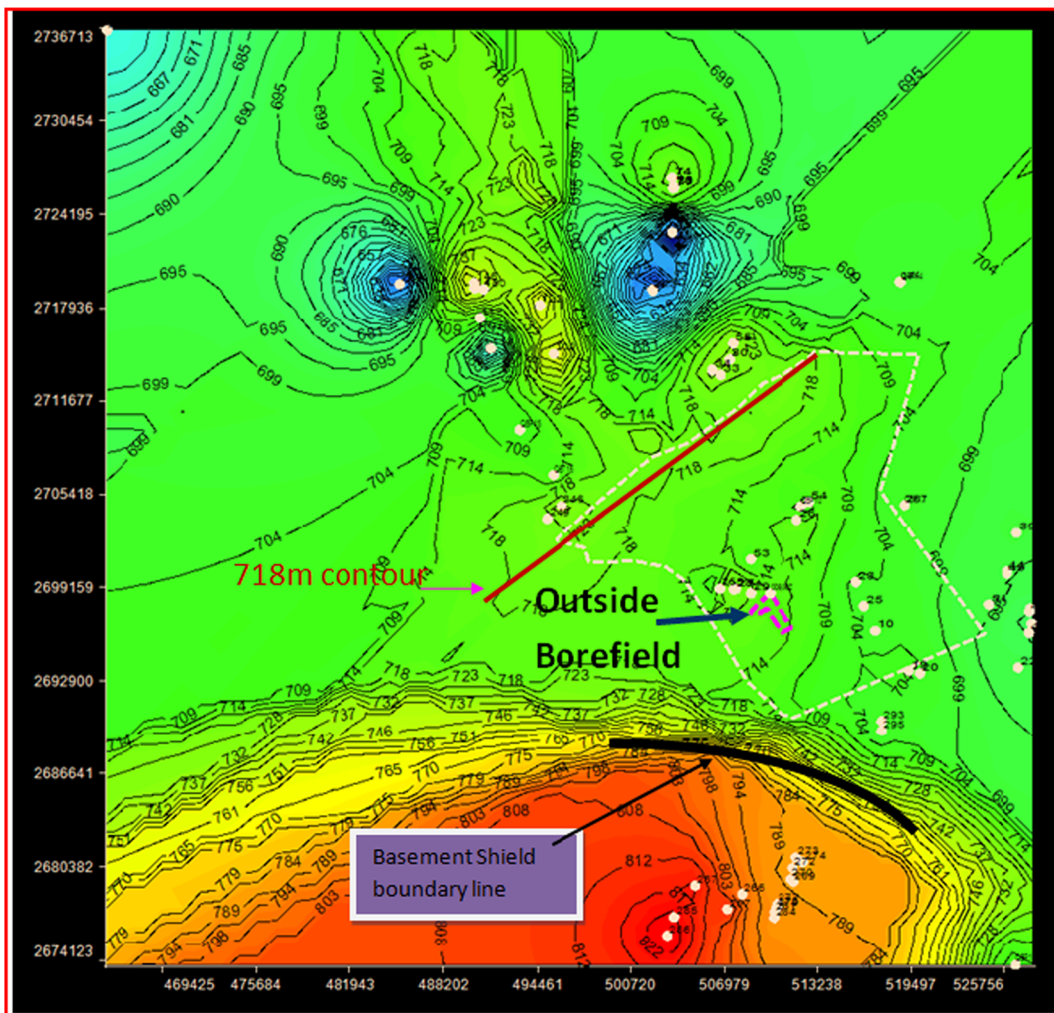
Fig. 4 Groundwater contour (year 2012). Water-level data points are shown as *grey dots* (*circle*)

2008, groundwater level in the Saq Sandstone under the Outside Borefield has remained fairly consistent (depth to water level ~61 m from the surface), indicating that this area is less affected by the large extraction from the borefields located at least 23 km further north.

Groundwater flow directions

Prior to major irrigation and municipal extraction, groundwater movement was in a southeasterly direction, in subdued conformity to the surface topography (Fig. 3). The topographic gradient within the model area is 0.005; the natural groundwater hydraulic gradient was 0.0009 (20-m elevation over a flow path distance of approximately 23 km). The year 2012 groundwater contour map shows significant hydraulic gradient

reversals to the north of the Outside Borefield (Fig. 4). For example, at the Al Quwayiyah Borefield, a steep hydraulic gradient of 0.02 has developed (head lose of ~200 m over a 10-km distance), comparing with the average model area hydraulic gradient of 0.0005 (head lose of 5 m in 10-km distance).
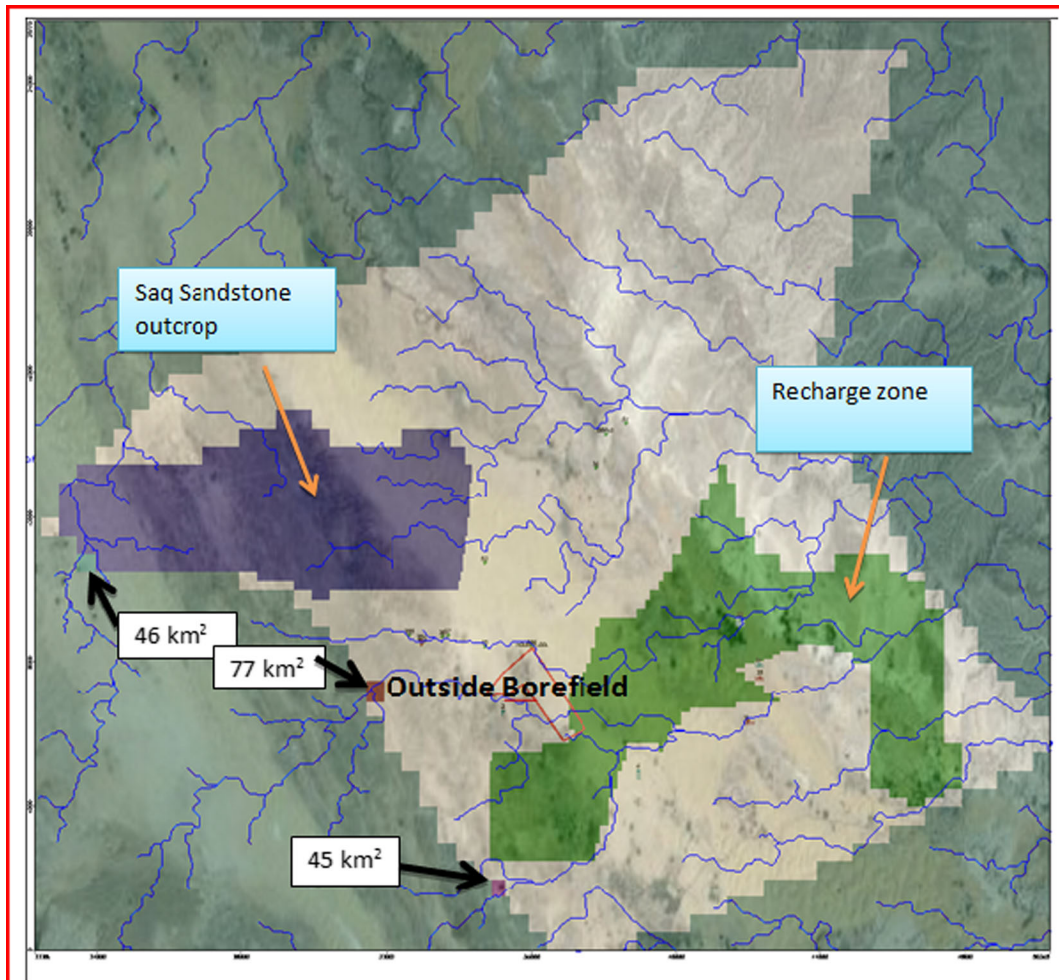
Recharge and discharge

Recharge to the Saq Sandstone groundwater flow system involves rainfall and surface water flow over outcrop. Rainfall infiltration rates in the order of 1 to 5 % have been estimated by Abunayyan and BRGM (2008). Recharge zones were defined. These were based on surface geological units, and natural recharge was estimated as a percentage of precipitation. The Saq

Table 2 Recharge estimates

Rock unit	Average rainfall (mm/year)	Estimated recharge (%)	Area (km^2)	Estimated recharge (m^3/day)
Saq Sandstone	110	5	97	1462
Upland Recharge 1	110	0.1	77	22
Upland Recharge 2	110	0.1	46	13
Upland Recharge 3	110	0.1	45	13

Sandstone was assigned 5 % of mean annual precipitation. The long-term annual precipitation was assumed to be 110 mm/year. Due to lack of data and to be conservative, no recharge was assigned to the Khuff Formation or the generally dry surficial alluvial sediments. For the transient state model, a time-varying recharge was applied as a percentage (5 %) of average monthly precipitation.

Recharge contribution from upland areas were calculated using monthly rainfall with 0.1 % rainfall recharge. The rainfall recharge applied to the outcropping Saq Sandstone formations is detailed in Table 2. Upland catchment areas have been assessed as 77 km^2 (upland recharge area 1), 46 km^2 (upland recharge area 2) and 45 km^2 (upland recharge area 3). These are shown in Fig. 5, to the west and north

Fig. 5 Recharge zonation, Saq Sandstone

of the model area, and are represented as 0.1 % rainfall recharge, yielding 22, 13 and 13 m^3/day, respectively.

Groundwater yield

Most of the Saq Sandstone aquifer discharge from the model domain occurs as throughflow and from bores (irrigation and municipal extraction purposes). Groundwater extraction is not measured and poorly documented. A groundwater census has been carried out (SMEC 2012). Large volumes of groundwater are extracted some 20 km north of the Outside Borefield (Fig. 2). For example, 8500 and 2000 m^3/day are extracted from the Quwayiyah Borefield and the Labkha Borefield, respectively. Most large irrigation bores continuously yield up to 7000 m^3/day for 5 months per year. There are 109 such irrigation bores north of the model area. Irrigation abstraction from the Saq Sandstone aquifer near the Outside Borefield is relatively small, estimated about 360 m^3/day for five small-diameter pumping bores (average 72 m^3/day). These are used for irrigation of date palms and filling trucks for sale to local communities and Quwayiyah township.

Numerical modelling

Hydrogeological numerical models have become a frequently used tool for predictions related to water in mine operations. Application of hydrogeological numerical models include groundwater flow model for mine water supply. A numerical model was used to assess groundwater availability for the proposed mine and associated works and facilities. Groundwater flow models are often used in water resource evaluations to assess the long-term productivity of aquifers. This study presents the development and application of the numerical modelling of the Saq Sandstone and associated groundwater system. It includes model calibration and simulation of long-term groundwater extraction (1.5 MCM/year) from the Saq Sandstone underlying the Outside Borefield. Modelling was undertaken using MODFLOW-SURFACT code (HGL 2013), an advanced MODFLOW-based code (Harbaugh 2000) that handles complete desaturation and resaturation of grid cells, within the framework of Visual MODFLOW version 4.6.

Model design

Spatial discretization and layering

The model covers an area of approximately 357 km^2 (model area), with the Al Quwayiyah and Labkha Borefields located to the north and northeast of the model area, respectively (Fig. 2). The model was designed for steady state and transient state simulation of groundwater flow.

An approximate 500 × 500 m grid was applied across the model area, with refinement of the grid to 20 × 20 m around the proposed borefield to allow for the steeper hydraulic gradient near the 'Outside Borefield'. In the vertical direction, deformed model layers were used to represent the hydrogeological framework in the model (Fig. 6). Vertical discretisation using deformed model layers allows horizontal continuity to be maintained with fewer cells (Reilly and Harbaugh 2004). The model grid is presented in Fig. 7.

The model is based on a conceptual model with three layers corresponding to the main geological units illustrated in Table 3 and Fig. 6. Non-uniform (100 m thickness) basement bottom layer was assigned. The layers are Khuff Formation (layer 1), Saq Sandstone (layer 2) and basement (layer 3).

Boundary and initial conditions

The extent of the model domain was based on the appropriate site-specific geological and hydrogeological boundaries. The model domain was designed to reflect the extent of the Saq Sandstone that is expected to significantly control the major groundwater flow.

The model area is located between a series of no-flow boundaries,

- West—following the outcrop of basement (impermeable);
- South and east—inferred absence or thinning of Saq Sandstone; and
- North—coinciding with the current groundwater divide line (Fig. 4).

The northern boundary is set to be sufficiently far from the proposed borefield (~10 km) to minimise impacts from the northern groundwater extraction area. This boundary coincides with the
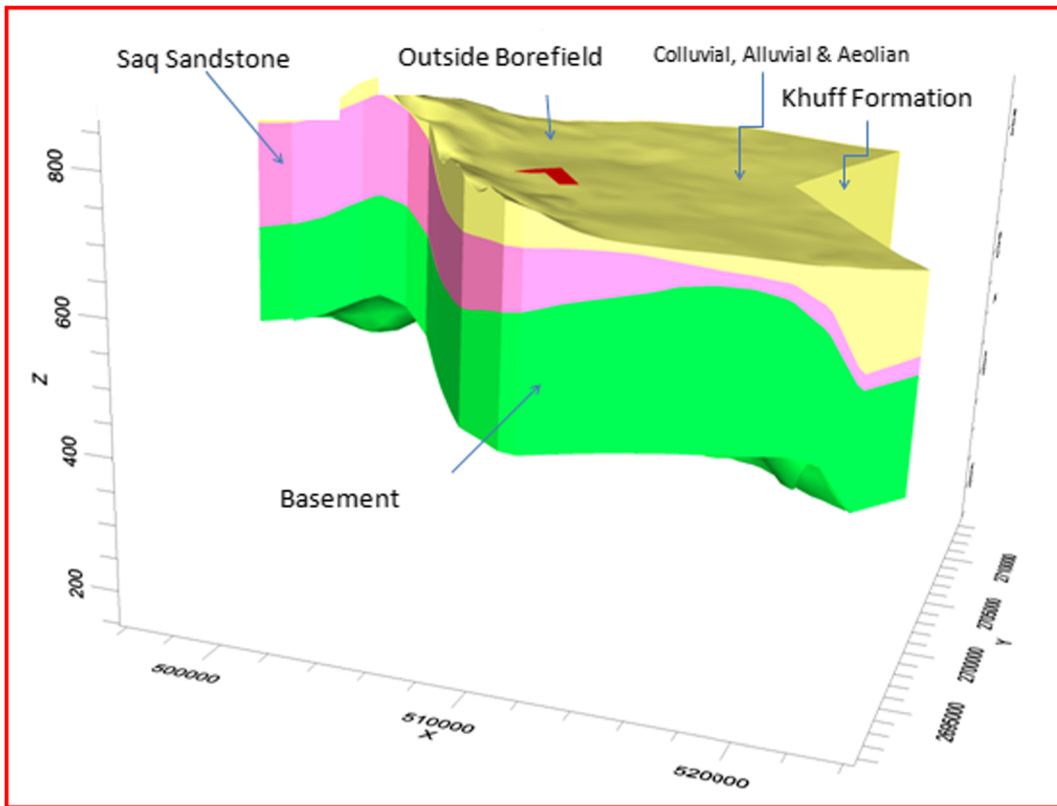
Fig. 6 Hydrostratigraphic units in the groundwater model

induced hydraulic boundary formed by the current groundwater divide line following the RL 718 m above sea level (asl) contour line (Fig. 4).

Recharge conditions

Upland recharge volume into the model area was transformed into grid-cell value recharge rate together with recharge zonation shown in Fig. 5.

Modelling approach

Modelling was undertaken in a staged approach to allow improved calibration and refinement of the adopted parameters in the CHM. The model was used to simulate four scenarios from the production bore, pumping at 1.5 MCM/year for 10 years (at the Outside Borefield), screened opposite the Saq Sandstone,

- Scenario 1 (with recharge and leakage—best case scenario),
- Scenario 2 (with recharge but no leakage),

- Scenario 3 (no recharge and no leakage—worst case scenario) and
- Scenario 4—same as scenario 3 but water-level simulation extended for 18 years from cessation of pumping (recovery period).

Model calibration

Minimum calibration was done regarding MODFLOW parameters to test whether their values, especially hydraulic conductivity, were independent of the model used. Calibration was mainly related to parameters controlling steady and the transient conditions. A steady state model was developed to assess the regional groundwater flow pattern and to calibrate the recharge and hydraulic conductivity parameters in the model.

A transient model was then developed to assess potential impacts of extraction/pumping on the groundwater flow pattern using pumping test data.
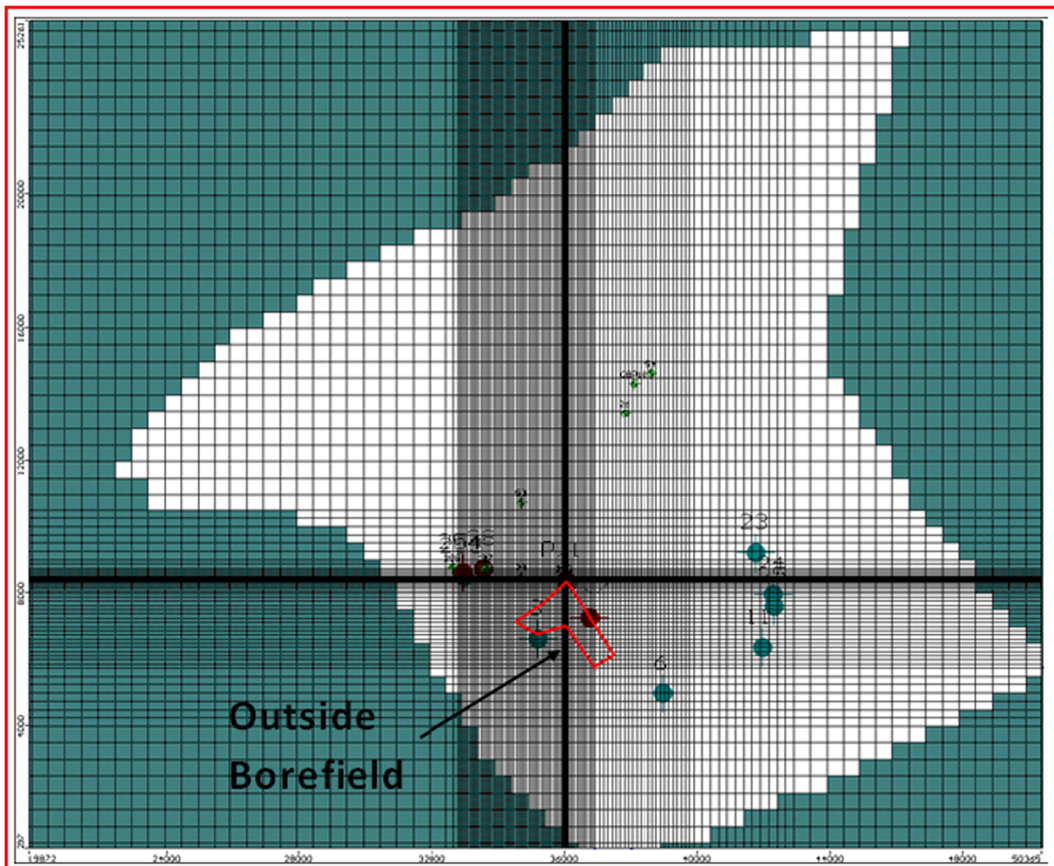
Fig. 7 Groundwater flow model grid (low utilised irrigation bores are shown (*green and red symbols*))

Predictive simulations were then used to assess the hydraulic response of the aquifer. Calibration was accomplished by applying a set of hydraulic parameters, boundary conditions and stresses that produce computer-generated simulated pressure heads (or water-level drawdowns) that match actual field measurement within an acceptable range of error. Model calibration was performed by manual (trial and error) and automatic (inverse model, parameter estimation (PEST); Doherty 1994) methods.

Steady state calibration

The model was calibrated by matching observed groundwater heads against predicted heads in nine bores within the model domain (shown in Fig. 9). To improve calibration, the hydraulic conductivity and recharge zones were adjusted until the modelled head elevations were able to match observed head elevations to an acceptable level of accuracy.

Figure 9 presents the calibration results (that is, calibrated head versus observed head of the target points), with a correlation coefficient of 0.997 (root-mean-squared error is 0.3 m). The figure shows a good correlation between observed and calculated groundwater heads. Residual error ranges between 0.009 m and 0.674 m for model calibration. Analysis of the calibrated steady state model output indicates that the model simulates the groundwater elevation and flow direction across the model area (comparing Fig. 8 with Fig. 4) to an acceptable degree. Given sparse information, model calibration is considered quite acceptable. Such deviations are most likely due to variability of hydraulic conductivity values at a smaller scale than that represented in the simulations. However, it is believed that the model was reasonably calibrated as evident by the reasonable head match and the spatial distribution of hydraulic conductivity values that correlated with various geological features of the study area.

Table 3 Model layer details

Layer	Layer elevation (m asl)		Volume (m^3)	Area (m^2)
	Minimum	Maximum		
Khuff Formation (layer 1)	304	893	3.61×10^{10}	3.57×10^8
Saq Sandstone (layer 2)	296	863	2.81×10^{10}	3.57×10^8
Basement (layer 3)	146	735	5.67×10^{10}	3.57×10^8

Transient state calibration

A pumping test was conducted to evaluate the aquifer hydraulic conductivity and storage coefficient (SMEC 2012). The test was run for 48 h using a production bore discharge at 8.3 L/s (first hour) and 13 to 15 L/s (39 h) and one observation piezometer (50 m from the pumping bore). The model is used to simulate water-level drawdown. The simulation time was 90 h, with 10 time steps and time step multiplier of 1.2. SMEC (2012) reports on the difficulties encountered during this pump-out test.

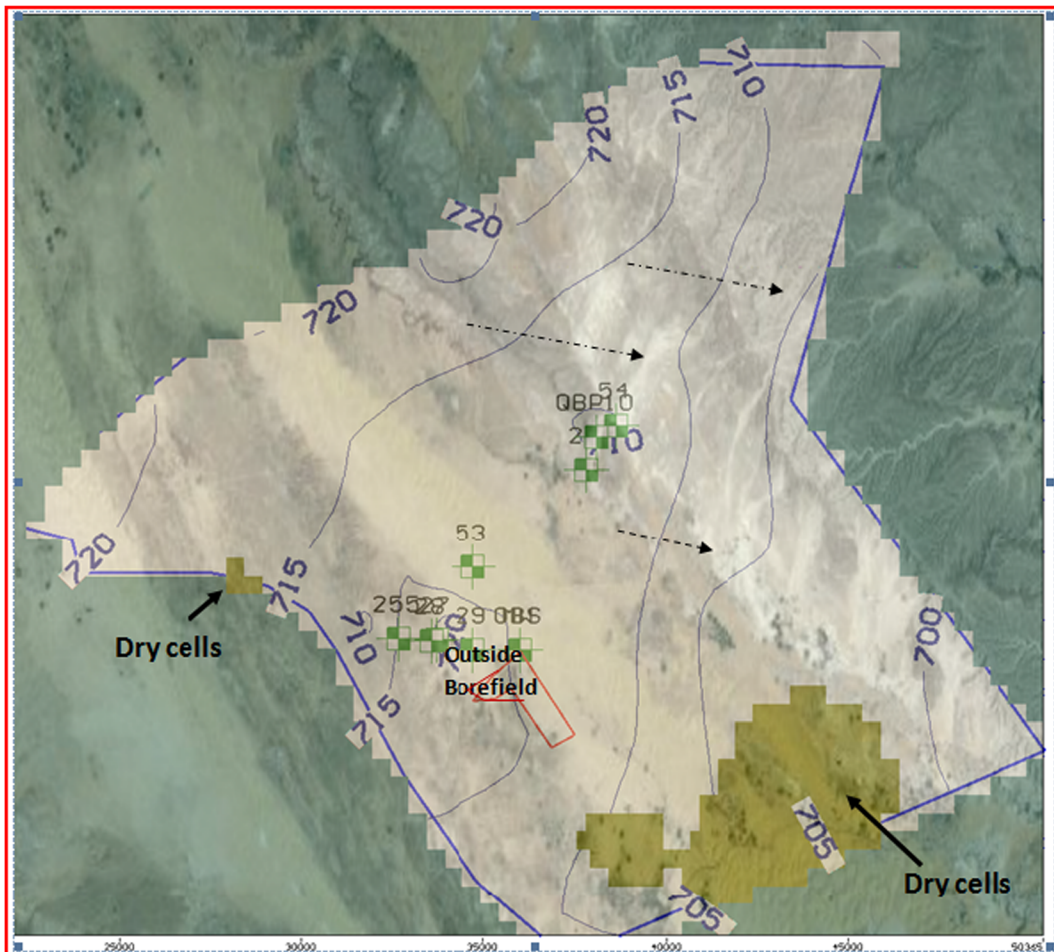Aquifer parameters were adjusted in the model using manual and automatic method (PEST) to match

Fig. 8 Potentiometric surface steady state (*arrow* flow direction) and observation piezometer (*green*)
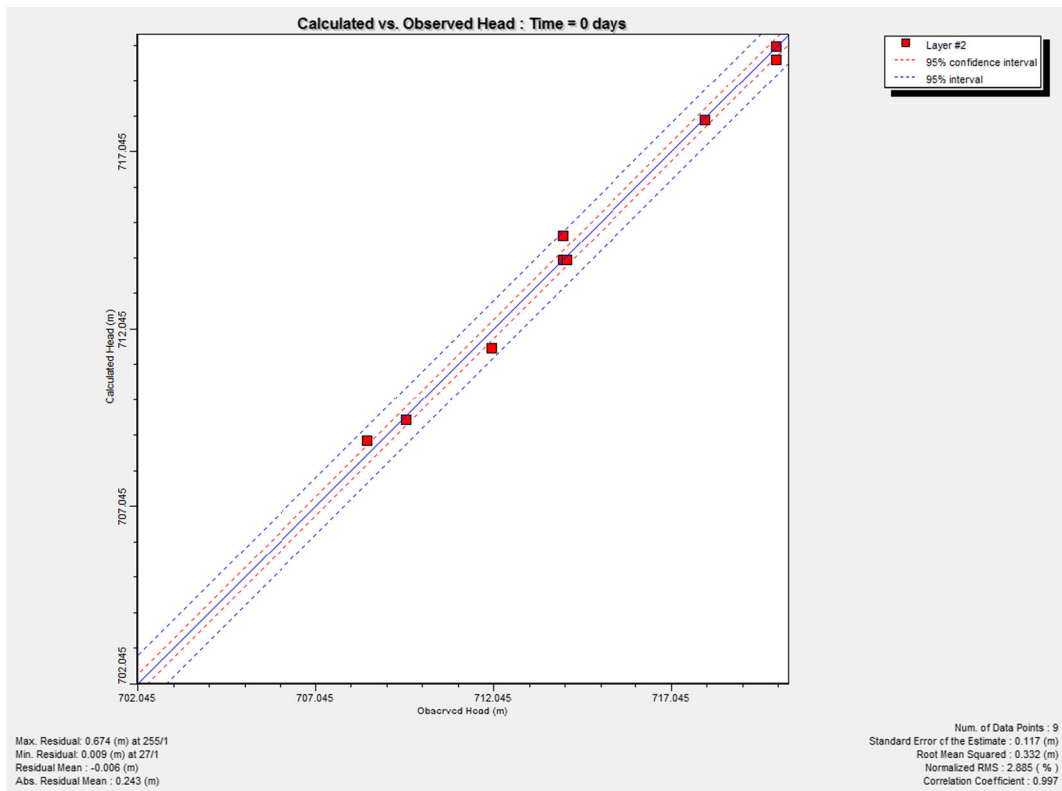
Fig. 9 Comparison of observed head versus calculated head

observed drawdown from short transient event. Adjustment to hydraulic conductivity and storage coefficient resulted in the match shown in Fig. 10. The curve match is good in late time but not in early time; the latter appears to be the result of the storage properties. A decrease in storage coefficient would have the desired effect of increasing drawdown in early times but would also increase it beyond observed values in later time. A regional model should not be expected to accurately reproduce local-scale changes in head in response to pumpage (Barnet et al. 2012; Middlemis 2004). The model needs to be recalibrated once the pump-out tests from the newly completed production bore in the Outside Borefield is completed.

Sensitivity analysis

Sensitivity analysis was performed using PEST (automatic estimation method), by changing parameter values and examining the effect of these changes on the model results. The scaled weighted sensitivity is plotted against the parameters

- Hydraulic conductivity *(k)*,
- Storage *(ss, sy)* and

- Recharge *(par)*

to compare their effect on the model output (head data). Layer 1 and layer 2 (Khuff Formation and Saq Sandstone, respectively) were considered.

For this purpose, four representative head data (named as *of000029*, *of000045*, *of000085*, *of000100*) were selected from the early to late time series observed at monitoring piezometer during the pumping test.

The sensitivity results are presented in Fig. 11. The more sensitive parameters were storage (specific yield) for layer 1 (Khuff Formation), followed by horizontal hydraulic conductivity (kx_1 and kx_2) of both the Khuff Formation and Saq Sandstone. Recharge parameters are found to be less sensitive.

Model result

Steady state simulation

Table 4 provides a summary of the modelled water balance for steady state condition. It shows that the
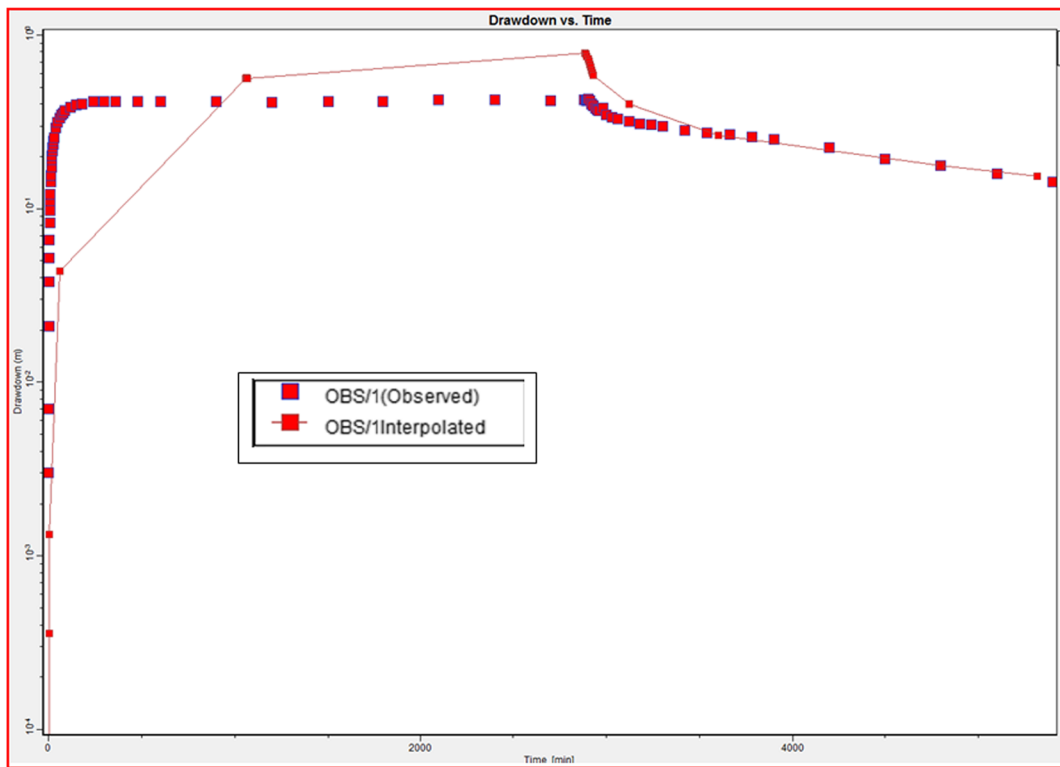
Fig. 10 Comparison of modelled to observed drawdown

model is balanced and that the volume of water entering the Saq Sandstone is mainly through rainfall recharge. The simulation shows that the flow system conserves mass. The volume of water entering the model through recharge equals the volume that leaves the model through extraction and throughflow. The current groundwater extraction from the few existing production bores is around 24 % of potential aquifer recharge. This is reflected in the fairly consistent piezometric

surface in the Outside Borefield of 61 m beneath the surface.

Inaccuracies also are evident in the high-elevation area due to the assumption of no-flow conditions along the boundary treated as divides. Certainly, as was the case with the MODFLOW's simulation, additional calibration could have produced closer results. However, in the absence of a clear basis for parameter adjustments, calibration by refining
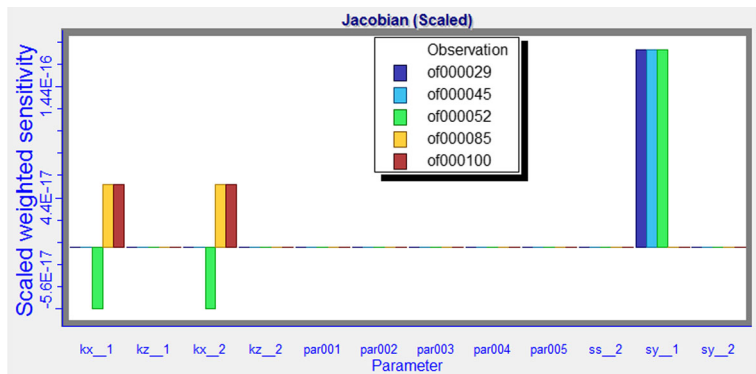
Fig. 11 Sensitivity analysis

Table 4 Modelled mass water balance summary (steady state)

Component	Inflow (m³/day)	Outflow (m³/day)
Recharge	1510	0
Extraction	0	360
Throughflow		1150
In–out	0.0 m³/day	
Discrepancy	0.0 %	

spatial distribution of parameters is merely a fitting process.

Transient state simulation

A transient simulation was carried out to estimate the effects of project groundwater extraction on the Saq Sandstone beneath the Outside Borefield. The model was used for a prediction run for 10 years, using the monthly time-varying recharge rate from 1995 to 2005 (that is, a percentage of monthly precipitation was assumed in both outcrop and upland areas), with the value of hydraulic conductivity and storage coefficient obtained in calibration.

The scenarios are

- Scenario 1—borefield operation for 10 years at 1.5 MCM/year (with precipitation recharge and leakage from the Khuff Formation),
- Scenario 2—borefield operation for 10 years at 1.5 MCM/year (with precipitation recharge and no leakage),
- Scenario 3—borefield operation for 10 years at 1.5 MCM/year (with no precipitation recharge and no leakage) and
- Scenario 4—borefield operation for 10 years at 1.5 MCM/year (scenario 3) and no pumping afterwards for 18 years (recovery period).

The water-level drawdowns in the model cell containing the monitoring piezometer (50 m far from the pump bore) are presented in Figs. 12, 13 and 14.

The predicted water-level drawdowns within the monitoring piezometer model cell at the end of 10-year continuous pumping are around 7.5, 11.5 and 12 m for scenarios 1, 2 and 3, respectively. The cumulative volumetric budget for the entire model area at the end of the simulation (after 10 years) is shown in Table 5.

Scenario 1 shows that with both rainfall recharge and leakage from the overlying Khuff Formation conditions imposed, water-level drawdown is minimal and commences to recover over time because the radius of influence created due to the pumping contributes to generate significant amount of recharge.

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Scenarios 2 and 3 indicate that water-level declines continue over the pumping interval without reaching an equilibrium/steady state condition. Under scenario 2 imposed conditions, project groundwater extraction (1.5 MCM/year) exceeds precipitation recharge (assuming no vertical leakage from the Khuff Formation) and groundwater is being taken from aquifer storage. There is a slight difference between scenarios 2 and 3 (Figs. 13 and 14, respectively), indicating that recharge is relatively insignificant compared to leakage.

Under 'worse case' scenario 3 condition, the predicted water-level drawdown in the monitoring piezometer does not exceed the available drawdown in the Saq Sandstone and the aquifer remains under confined hydrogeological conditions. The results indicate that the Saq Sandstone should be capable of yielding the mine water demand (1.5 MCM/year) over a 10-year duration. Note that the cells in the west and south of the model area went dry as a result of pumping (Fig. 15).

MODPATH package (Pollock 1994) was employed to define the radius of influence contributing to the groundwater extraction using particle-tracking method (Fig. 15). The determination of the flow path aids in conceptualising and quantifying the sources of water in the modelled area due to pumping bore (particles tracked backwards towards the recharge location). Under scenario 3, the radius of influence from the Outside Borefield is of the order of 10 km after 10 years of pumping at the design. The shape reflects the multiple barrier boundaries surrounding the Outside Borefield.

Assessment of potential impacts

Numerical modelling indicates that the cone of depression created around the borefield may extend beyond the northern model area boundary, where interference from the Quwayiyah and Labkha Borefields and irrigation bores to the north of the model area is highly pronounced. Cumulative water-

Fig. 12 Drawdown versus time
at the monitoring piezometer
(scenario 1)
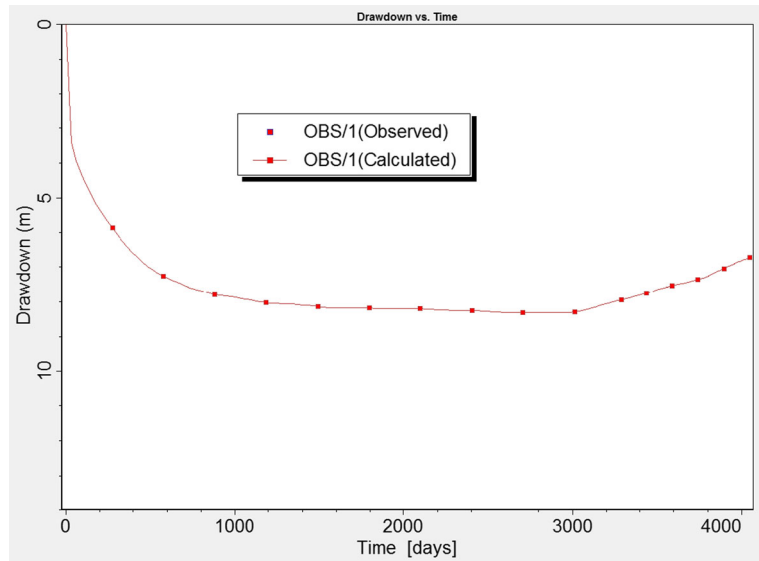
level drawdown is likely to occur over time. Water-level monitoring in the Outside Borefield and along the northern model area boundary should occur to update the numerical model over time.

Groundwater extraction from the Outside Borefield will impact on water-level behaviour in surrounding bores. Figure 16 indicates the simulated impact of groundwater extraction from the Outside Borefield over 10-year pumping at 1.5 MCM/year. Water levels in neighbouring bores may decline by up to ~12 m (bore 28).

The water level in the production bores is estimated at ~20 m (Fig. 17). However, no multistage

tests have been carried out on bores in the Outside Borefield. Water-level drawdown in production bores depends on many factors, including the number of production bores, bore separation, pumping rate, screen length, bore diameter and bore efficiency.

Scenario 4 (Fig. 17) shows that, in the long term, there will be a recovery of around 8 m out of the 12-m drawdown due to the 1.5-MCM/year pumping over 10 years. Water recovery will be around 70 %, implying that the aquifer will be stressed and a large percentage of water is taken from Saq Sandstone aquifer storage.

Fig. 13 Drawdown versus time
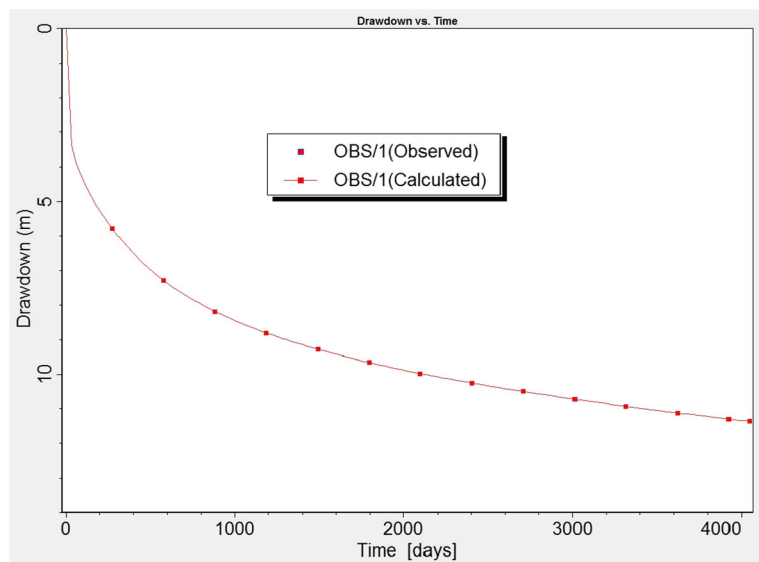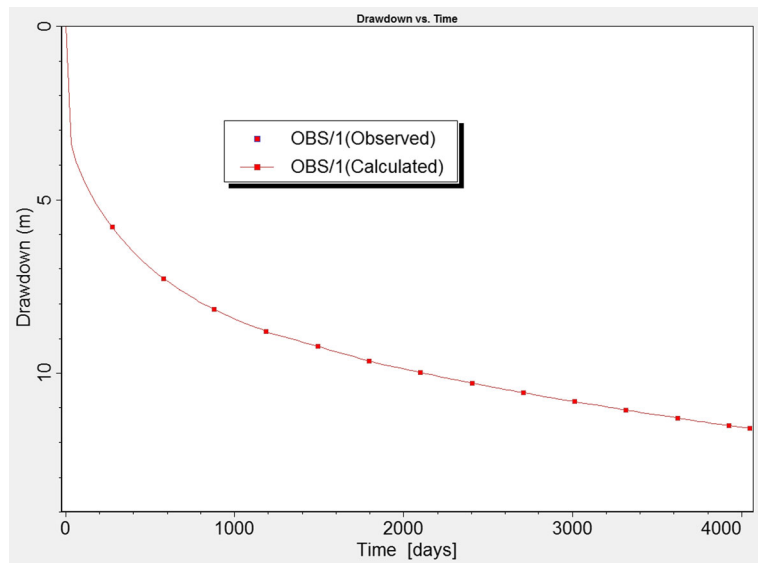at the monitoring piezometer
(scenario 2)

Fig. 14 Drawdown versus time at the monitoring piezometer (scenario 3)

Discussion and conclusion

A three-dimensional numerical model has been constructed to allow simulation of groundwater response to pumping for the design mine water demand. The model has been constructed based on limited data and water-level measurements. It is thus designed to provide a preliminary assessment of water supply potential from the target aquifer. The model needs to be refined as new data becomes available. A very good calibration for the steady state model appears to have been achieved. A new production bore and pump-out tests are required to better calibrate transient conditions. Using the numerical model developed, several important conclusions have been obtained for the management of these units.

The models were calibrated against hydraulic head data. Reasonable matches were obtained despite uncertainties in the model data. A steady state model was developed to assess the regional groundwater flow pattern and to calibrate the recharge and hydraulic conductivity parameters in the model. The model was calibrated with a correlation of coefficient of 0.997 and root-mean-squared error of 0.3 m. A transient model was developed to assess potential impacts of groundwater extraction on the aquifer flow pattern using pumping test data. A transient simulation model was used to predict the impact of 1.5-MCM/year extraction for 10 years on the Saq Sandstone hydrogeological regime.

The simulated water-level drawdown at the monitoring piezometer for the *worst case* scenario 3 (that is, no leakage and no recharge) indicates that the Saq Sandstone Aquifer beneath the Outside Borefield should be capable of supplying the mine water demand (1.5 MCM/year) for 10 years. However, the long-term water-level drawdown shows a continuous decrease without achieving steady state conditions; thus, the majority of water is being taken from aquifer storage; the aquifer appears to go dry along the southern and western boundaries where the Saq Sandstone terminates; the Saq Sandstone Aquifer is located on a bedrock high; and in

Table 5 Cumulative volumetric mass water balance summary (transient state) at the end of the simulation period (after 10 years)

Component	Scenario 1 (m^3)	Scenario 2 (m^3)	Scenario 3 (m^3)
Recharge	76,627,016	76,627,016	0
Discharge	17,803,482	17,803,482	17,803,482
Storage in	60,465,744	71,717,832	42,049,956
Storage out	119,220,512	130,505,296	24,267,538
In–out	0.0	36,081	−21,064
Discrepancy	0.0 %	0.02 %	−0.05 %

Fig. 15 Source of water for the
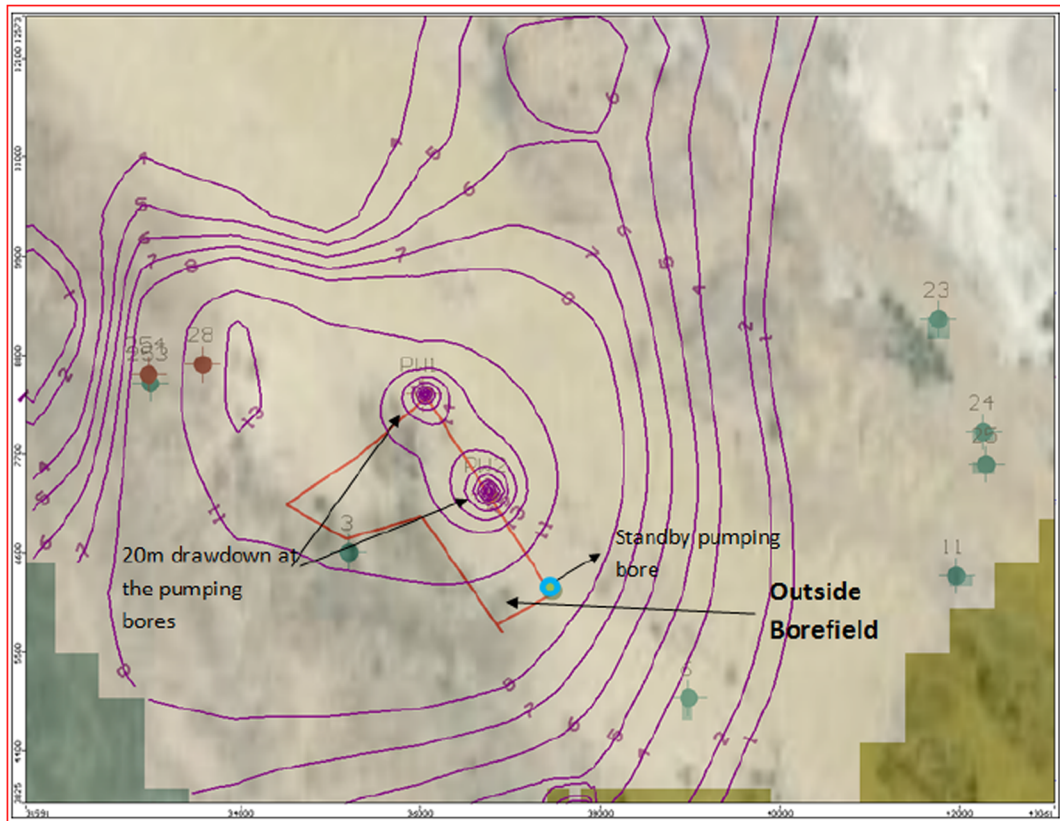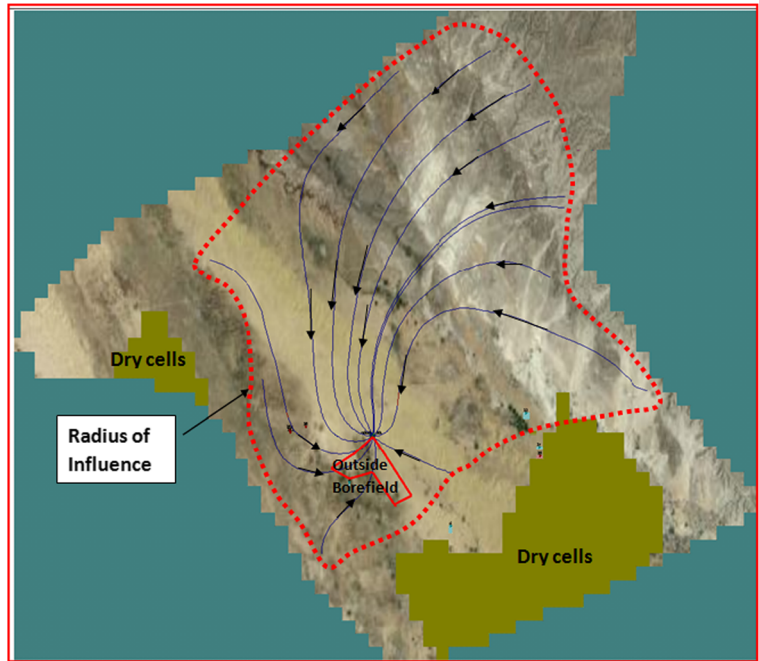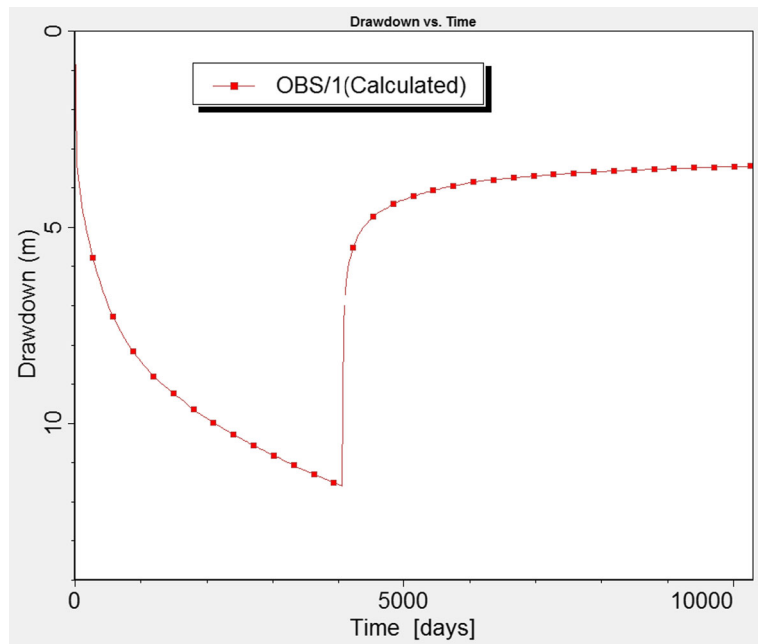pumping bore (scenario 3)

Fig. 16 Drawdown (metres) map of the area surrounding the outside borefield (scenario 3). Low utilised irrigation bores (*green*)

Fig. 17 Water-level drawdown and recovery (metres) at the monitoring piezometer (scenario 4)

the long term, there will be a mutual interference from the Al Quwayiyah Borefield located to the north of the model area. In this area, the hydraulic gradient is relatively steep because of over-pumping for more than 28 years.

In the case of the study area, an increase is foreseen in the groundwater storage deficit, due to the reduction of the recharge, although the management option considered for the future would accelerate the process of depletion (Fig. 14). For this reason, in the groundwater management planning, a general decline should be considered in the piezometric level, even without abstractions; such that, restrictive and unpopular policies would not be capable of achieving positive effects on the water level.

As with any modelling studies, it should be stressed that the results are subjected to uncertainty due to model and data limitations. In addition, calibration was done using a snapshot of hydraulic head; therefore, and considering the non-uniqueness inherent in modelling, such a calibration should be considered incomplete.

Scenario 4 shows that there will be a recovery of around 8 out of the 11.6-m drawdown, implying that the aquifer will be stressed and a large percentage of water taken from aquifer storage. To obtain a more accurate assessment of current groundwater conditions and the potential impacts on groundwater by extraction, it is recommended that the following further works be

undertaken, construct a new production bore and carry out a multistage and long-term pump-out test; establish a nested piezometer in the Khuff Formation and Saq Sandstone aquifers to define the inter-aquifer flow system in the model area. Currently, the vertical hydraulic gradient of the model output has not been cross-checked for its reliability; and establish a groundwater monitoring network in various aquifers (Khuff Formation and Saq Sandstone) for future update of the calibrated model.

To minimise hydrogeological impacts, it is recommended to laterally spread out production bores (at least 500 m apart); bores should be located along the eastern boundary periphery, where the Saq Sandstone is deepest; and operate the bores at low extraction rates. As an alternative, it might need to increase the size of the borefield that is to purchase another block of land north of the Outside Borefield in the deeper parts of the aquifer system.

Limitations exist with respect to aquifer recharge rates and spatial distribution of aquifer recharge areas, hydrogeological properties of Khuff Formation and basement rock units, structural influence on groundwater flow (faults, fractures and joints), groundwater monitoring for the shallow aquifer and the hydraulic connection between the Saq Sandstone and Khuff Formation; there is little historical information relating to groundwater extraction from the northern bores, except

recent data, and some of the hydraulic parameter values were obtained from locations outside the model area (Al Quwayiyah and Labkha Borefields). The data obtained from these pumping tests are assumed to be representative and in line with that expected in the model area. The KMC provided aquifer test is used for transient calibration purposes. Additional confidence in the calibration was obtained through a steady state history match to water level. When the new production bores are constructed, pump-tested additional calibration of the model should occur; the active model domain northern boundary was defined by making model limits coincide with the groundwater divide resulted from the pump effect over the past 28 years. There is still a degree of uncertainty in flow exchanges between the Outside Borefield system modelled and mutual interference resulting from the neighbouring Al Quwayiyah and Labkha Borefields.

Results of this study provide guidelines towards the sustainable management of groundwater resources on Outside Borefield area. Future management decisions should take into consideration the fact that long-sustained drought and climate change has serious adverse effects on sustainability indicators. In the case of the study area, the importance of the recharge under changing climate conditions should be studied in more detail, as it is the most important inflow in these systems. Consequently, a more complete analysis of the uncertainty introduced in the climatic change would be required to reduce the existing uncertainty to improve the conceptual model, the numerical model or the parameter values to obtain a reliable tool for supporting decision-making.

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