

Three-dimensional groundwater flow modeling approach for the groundwater management options for the Dakhla oasis, Western Desert, Egypt

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Received: 14 July 2013 / Accepted: 31 December 2013 / Published online: 10 January 2014
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Abstract In Dakhla oasis, Western Desert of Egypt, groundwater is the only resource for all anthropogenic activities. During the last 50 years, the Nubian Sandstone Aquifer System (NSAS) has been undergoing serious stress through withdrawing its storage. Plans for expanding the agricultural areas in Dakhla oasis were given by the government. This article is an attempt to investigate the best management option that meets development ambitions and groundwater availability. Based on a calibrated regional three-dimensional groundwater flow model for the NSAS using FEFLOW, a refined (high resolution) local scale model was developed to simulate and predict the impact of applying the actual and planned extractions rates on Dakhla oasis. Five management scenarios were suggested. The application of the actual extraction rate of 1.2×10^6 m³/day for the oasis for the next 90 years resulted in a drawdown of 75 m and a depth to groundwater up to 75 m with an annual change in hydraulic head of 0.57 m. At the end of this simulation, only a few wells at the west of the oasis will still be free flowing. The application of the planned extraction rate (1.7×10^6 m³/day) resulted in great depths to groundwater (>100 m) and formed huge cones of depressions that connected together to cover the whole oasis and extend further beyond its borders. It was found that the best option for groundwater management in the oasis is the implementation of an extraction rate of 1.46×10^6 m³/day, as the depths to groundwater will never exceed the 100 m limit.

Keywords Dakhla oasis · Groundwater modeling · Egypt · Management options · Scenarios

Introduction

The populated areas in Egypt constitute only 6 % of Egypt's total area. Some 99 % of all Egyptians live in the Nile valley. Therefore, the quickly growing development in Egypt has required big movements of investments and people from the Nile valley towards the Western Desert. In that case, fresh water supply is an essential and feasible option that can cover the wide gap between the available capacities and the accelerating demands. The Western Desert of Egypt suffers from severe aridity and scarcity of rainfall. In addition, these small rainfall events occur in winter, in the form of scattered showers, and cannot be relied on for extensive agricultural activities. Thus, reliable availability of irrigation water is an absolute necessity for agricultural development.

The Dakhla oasis lies in the Western Desert of Egypt, which is a hyper arid zone with very scarce rainfall events. The groundwater is the only water resource for all activities in this oasis. However, the potentiality of this water resource is very promising. Dakhla is the biggest oasis in the Western Desert of Egypt and lies farthest away from the main settlements of Egypt with about 82,000 inhabitants (2010 estimate) who live in 17 different settlements (Fig. 1). The whole depression of the Dakhla oasis comprises a number of smaller oases, separated by hills or desert, but never far in between. Dakhla is situated above sea level, as high as an average of 122 m (Knetsch and Yallouze 1955; Mitwally 1953; Euro and Pacer Consultant 1983). The lowest point of the Dakhla oasis, about 88 m (amsl), lies in the west of the oasis (Fig. 1), and the oasis'

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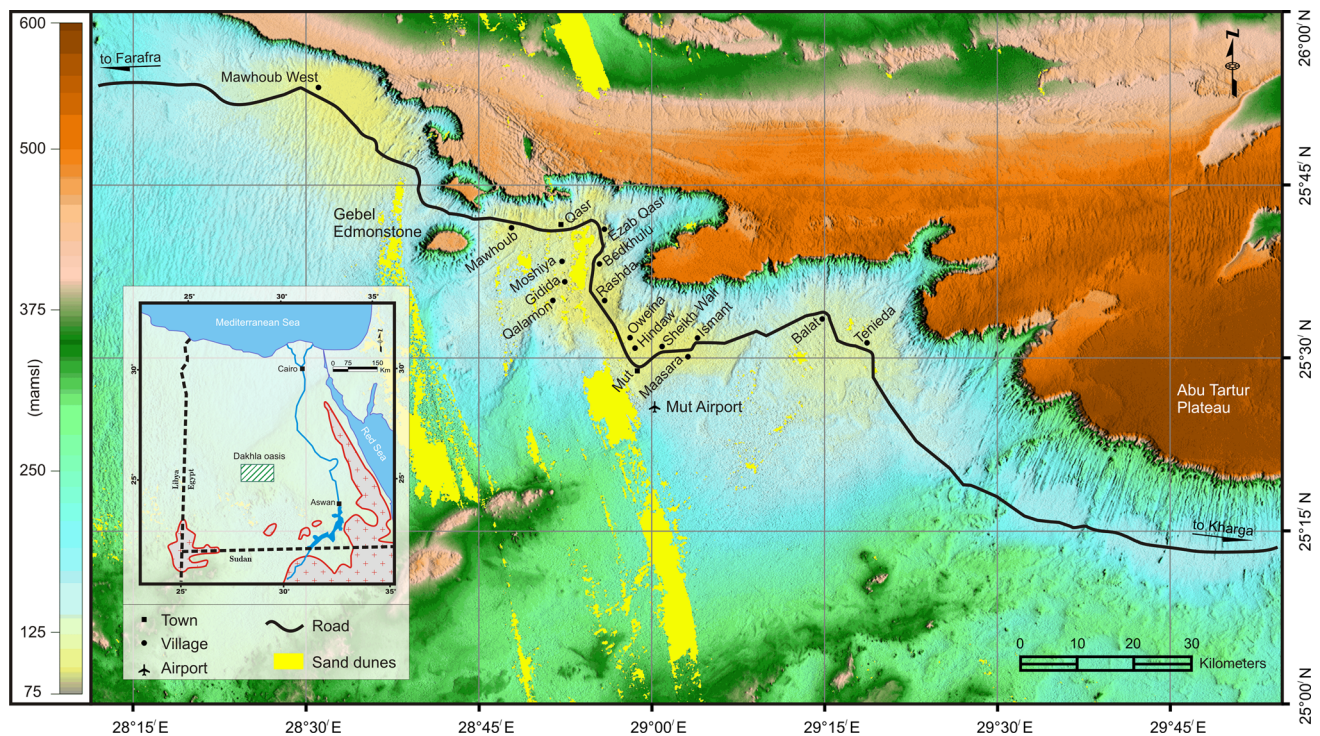


Fig. 1 Location map of the Dakhla oasis showing the depression, settlements, and topography. The topography is obtained from the DEM of the SRTM-03 (USGS 2004; NASA 2005)

surface rises gradually southeastward. Altitudes range from 110 to 140 m above sea level (Murray 1952; Ambroggi 1966; Mansour 1973; Kleindienst et al. 1999).

Originally, Dakhla was fed by about 520 springs and ponds, but in modern times many have dried out, and others only work with electric pumps (Sefelnasr 2002). The economy of Dakhla is based on agriculture, production of handicrafts, and some tourism.

A three-dimensional groundwater flow model (Figs. 2, 3a, b) for the whole Nubian Sandstone Aquifer System (NSAS) was developed and calibrated (Sefelnasr 2007, 2008; Sefelnasr et al. 2013) using the groundwater modeling system FEFLOW (Diersch 1996). This model was valuable on account of the following:

- The boundary conditions for the whole system were precisely defined.
- The regional model was calibrated to serve as a base model for the local modeling interests.
- A refined local model (high resolution meshing) was developed based on this model.
- The boundary conditions of the local model are obtained from the regional model.
- The input and output data could be presented spatially as accurate as it is needed.
- Results from local models can be analyzed and displayed independently.

Based on this model, a refined local scale groundwater flow model for Dakhla oasis was developed to examine the natural and anthropogenic stresses on the Nubian system within this area and to investigate the best groundwater management options for this system under the given actual and planned activities taking into account the groundwater availability and the socio-economic effects. The local modeling procedure was considered to involve all the detailed data for the study area and get clean and trusted boundary conditions from the regional model. In addition, the local model will give a detailed image on the reaction of the aquifer to the different stresses.

Taking into account the actual and planned extraction rates, the groundwater availability and the development ambitions, as well as the economic lifting depth, five scenarios were suggested to present the most feasible management option that meets these aspects. The results from the first, third and fifth scenarios are presented and discussed in this paper for the comparison purposes and introducing the optimal scenario that meets the best conditions of water demand and availability.

Physical and geological setting

The Dakhla oasis is located in the South Western Desert of Egypt, about 300 km west of the Nile valley, between longitudes 28°15' and 29°40'E and latitudes 25°00' and 26°00'N

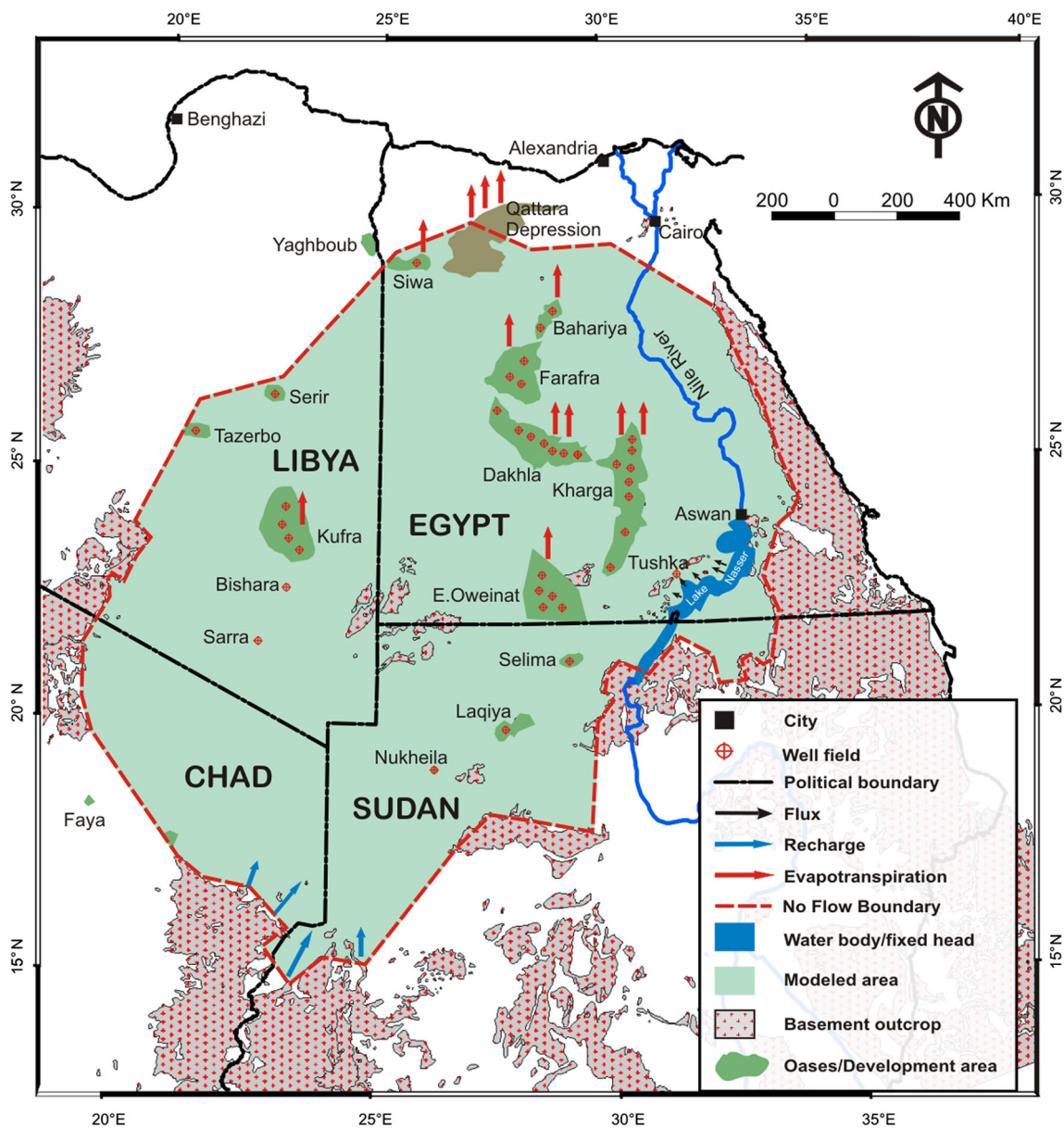


Fig. 2 A map showing the location, extent, and boundary conditions of the regional model for the Nubian Sandstone Aquifer System

(Fig. 1). The oasis is about 155 km long from southeast to northwest, with a maximum width of about 60 km. As to climate, the Dakhla oasis belongs to the rainless part of Egypt (Brookes 1993; Kleindienst et al. 1999). The hottest months are June, July, and August (with a mean maximum temperature of 37.7 °C). The coldest month is January (with a mean minimum temperature of 4.0 °C).

The main topographic feature of the Dakhla oasis is the steep scarp, which bounds and overlooks the depression of the oasis on its northern side (Ibrahim 1956; Wycisk 1987, 1990, 1993). It is irregular in its outline, but generally it extends in a WNW-ESE direction for more than 250 km (Hermina et al. 1961). It is broken into a number of promontories by well-marked indentations, the most important of

which occur to the east of Qasr, northeast of Balat, and to the east of Tenieda. A gradual slope is formed up to the plateau at these indentations (Said 1961; EL-Younsy 1978, 1984; Brookes 1993). The face of the scarp is essentially composed of Upper Cretaceous to Paleocene shale and mudstone and is generally capped by limestone and chalky limestone (Awad and Ghobrial 1965; Klitzsch and Wycisk 1987; Wycisk 1993; Wycisk 1994). The height of this scarp ranges from 400 m (amsl) to the west and rises gradually to reach about 580 m (amsl) northeast of Tenieda village (Figs. 4, 5a).

Commonly, the successive sedimentary formations within the Dakhla depression dip steadily northward at a very small inclination. Consequently, every formation has a wide outcrop. In general, these formations crop out at the cliff to the

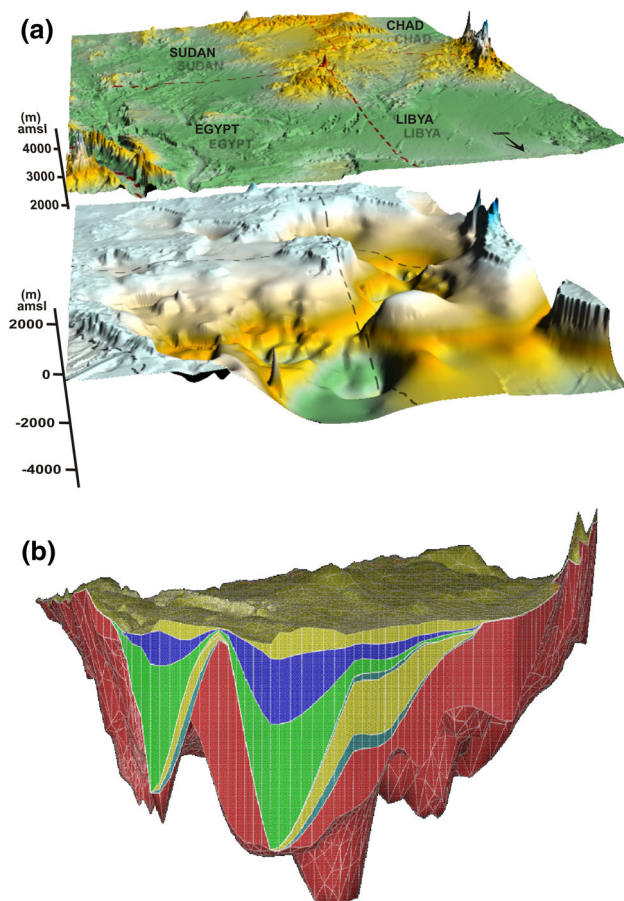


Fig. 3 Geometry of the Nubian Sandstone Aquifer System. **a** Top and base of the aquifer, **b** three-dimensional block showing the modeled layers (colors reflect the hydraulic conductivity for individual aquifers and aquitards, values are shown on Fig. 5)

north of the depression and they do not appear in the oasis depression itself (El Naggar 1970; Ezzat 1974, 1975, 1976; Barthel and Boethcher 1987; Barthel and Hermann-Degen 1981). The late Mesozoic–Early Cenozoic rocks, which build the primary sedimentary cover in the area under discussion, are subdivided into a number of mappable lithostratigraphic units. The units are classified generally into two categories as given in many literatures (Youssef 1959; Issawi 1969; Hermina 1990; Said 1961, 1962, 1990): (a) a Jurassic–Campanian sequence, predominantly continental sandstone but with marine intercalations, and (b) a Campanian–Lower Eocene transgressive–regressive open marine sequence that composed generally from shale, limestone, chalk and phosphate beds (Figs. 4, 5a).

Hydrogeological aspects

The Nubian Sandstone Aquifer System in the Western Desert of Egypt is considered to have a great groundwater

resource potential (Ebraheem 2003; Ebraheem et al. 2002; Gossel et al. 2004, 2006, 2008). It contains large volumes of fresh groundwater (<1,000 ppm) in storage. The aquifer system in Dakhla oasis is composed mainly of thick sandstone reaches 1,800 m thickness and represents very good transmissivity (reaches 15,000 m²/day) and the hydraulic conductivity ranges from 0.85 to 8.5 m/day (Thorweihe and Heini 2002). However, some marine intercalations are present to separate the system into 3 aquifers or locally named “zones” (Sefelnasr 2002; 2008, Sefelnasr et al. 2006). The groundwater flow direction in Dakhla oasis is principally from southwest to northeast, just following the general flow direction of the whole aquifer system (Ball 1927), the aquifer is confined to semi-confined and groundwater used to be free flowing all over the oasis (where groundwater level used to be higher than the ground surface), as the Dakhla shale caps the aquifer at some locations (Figs. 4, 5a). Natural springs and free-flowing shallow wells (35–60 m deep) used to feed the oasis until the project of the New Valley was constructed in 1960 and several deep wells (700–1,200 m) were drilled and are still being drilled (Ebraheem et al. 2004; Sefelnasr 2002; Sefelnasr et al. 2013). Consequently, the hydrodynamic regime has been changing continuously as will be discussed later in this article. From the hydrostratigraphic characteristics, three aquifers could be distinguished in the area and separated by two aquitards and capped at the most top by non-continuous impermeable layer (Ezzat 1975; CEDARE 2002; Ebraheem et al. 2004).

The salinity of groundwater of the NSAS in Egypt changes both horizontally and vertically. The salinity of water increases from SW to NE as well as the hydraulic gradient and usually decreases with depth: e.g., the Kharga and Dakhla oases, where the salinity decreases from about 500 ppm in the upper aquifer to about 200 ppm in the lower one (Dahab 1998; Allam et al. 2002). Generally, the groundwater of the Nubian series of the Dakhla oasis is mainly fresh. The groundwater temperature ranges between 27 and 38 °C, depending on the depth. The TDS (Total Dissolved Solids) of the groundwater in most parts of the Dakhla area is fairly <500 ppm, representing great differences in salinity from one place to another (Idris and Nour 1990; Dahab 1998). It can be concluded that the water in general is marked by low salinity in the eastern part of the oasis (where the TDS has an average of 150 ppm). However, the salinity increases westward until it reaches its maximum value of 2,000 ppm (Diab 1972; Soltan 1999). However, the groundwater at the Dakhla oasis is marked by high concentrations of iron as a result of the nature of water bearing formation and surrounding environment. The values of iron concentrations are estimated to range from 0.001 to 72.04, 0.001 to 13.64 and 0.0009 to 7.66 mg/l, with mean values of 14.6, 6.46 and 4.11 mg/l in the above-maintained

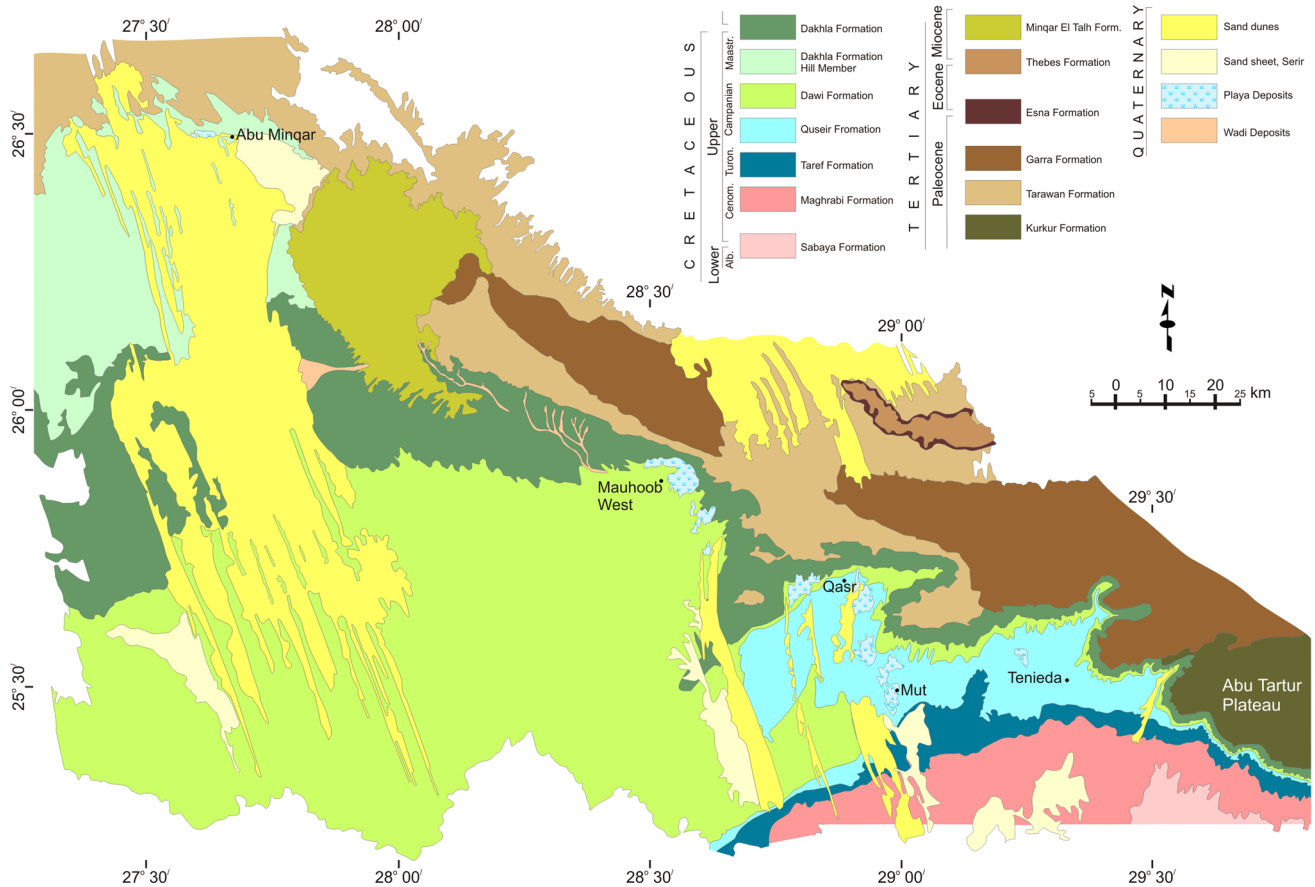


Fig. 4 Geological map of the Dakhla oasis. Digitized from Conoco (1987), lithostratigraphic units adapted from El Khawaga et al. (2005)

three formations, respectively (Sefelnasr 2002; El-Hag Ali et al. 2008). The unusual high iron-content points to a high fluvial input as also suggested by the high phyllosilicate kaolinite contents (Brookes 1993; Tantawy et al. 2001).

Materials and methods

A GIS-database for the NSAS was established from several data sources and formats using ArcMap/ArcInfo. Data included DEM (Digital Elevation Model), geology, topography, hydrogeology, structure, cross sections, pump test, initial head, borehole data (more than 800 shallow and deep wells), parameters, extraction rates, etc. The DEM (Fig. 3a) was derived from the SRTM-3 [Shuttle Radar Topography Mission (Farr and Kobrick 2000)]. Contour maps of potentiometric levels for the aquifer have been derived from the groundwater contour map of Ball (1927) and its modification that was presented by Sandford (1935). In addition, the available individual records of the groundwater levels before or around the year 1960 were also taken into account. As the New Valley project had started first in 1960, these maps are considered representative data inputs for the initial head

records. The data sets, including geometric surfaces and parameters, created in ArcGIS (ESRI 2006) as point data features with their spatial references and appropriate attributes to facilitate the geostatistical analysis procedure. The data were interpolated using kriging (Cressie 1990) with an appropriate variogram for each data set using Surfer software (Surfer® 8 User’s Guide 2002). The exponential (Cressie 1991), spherical (Pannatier 1996), and Gaussian (Pannatier 1996), variograms were the best matching model curves for the interpolated surfaces. The GIS was then used to validate the data and prepare it as in input for the model. The groundwater modeling system FEFLOW (Diersch 1996) was used for the modeling procedure.

Model design and structure

As discussed before, a regional groundwater flow model for the whole NSAS was developed and calibrated to help correctly define the boundary conditions of the area of interest as well as to serve as a base model for the local modeling approach (Sefelnasr 2007, 2008; Sefelnasr et al. 2013). According to the hydrogeological information, the regional

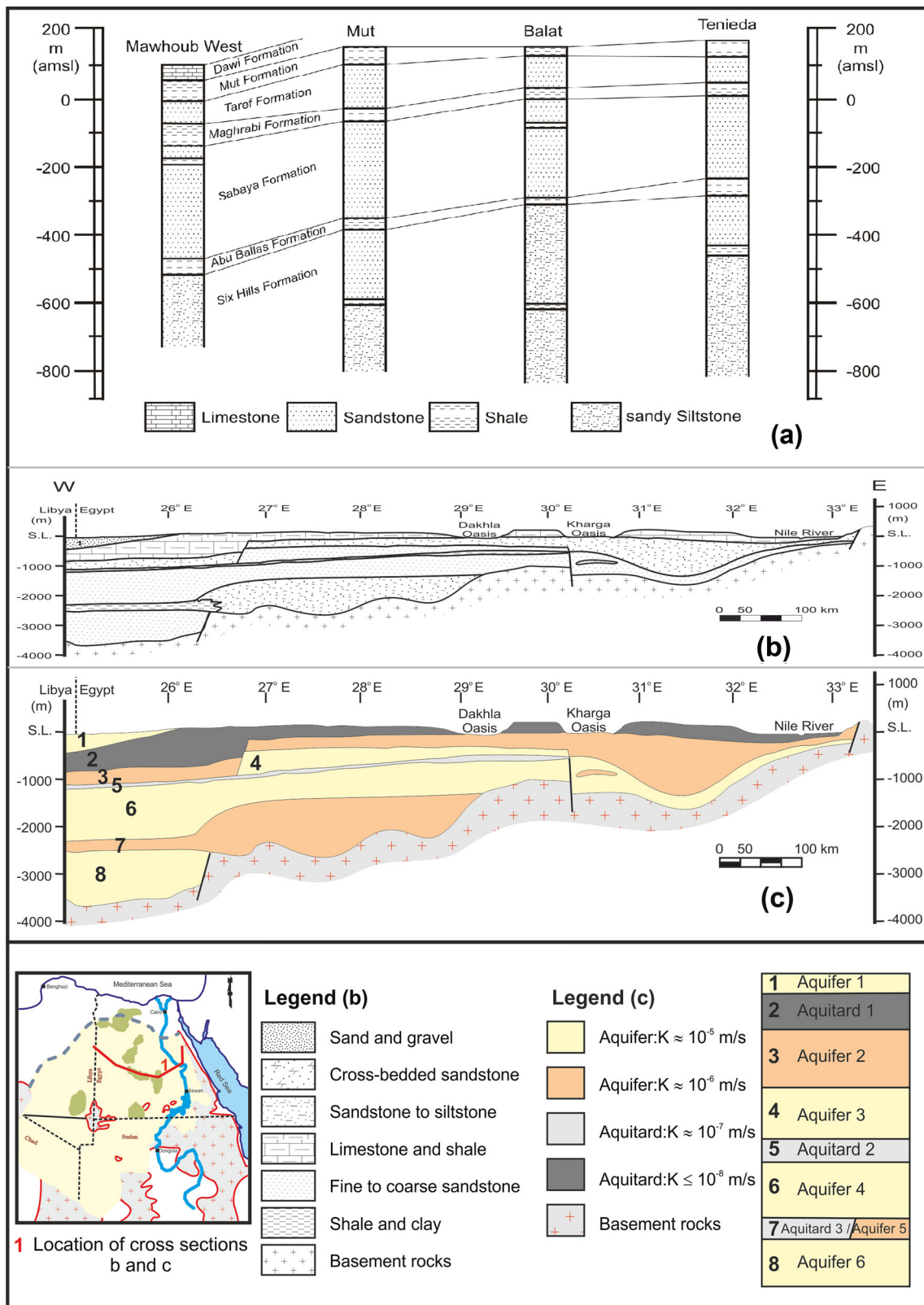


Fig. 5 a Simplified lithostratigraphic correlation of selected wells in the Dakhla oasis (localities on Fig. 2), after Sefelnasr (2002), b a lithostratigraphic section along the domain area of the NSAS,

compiled from Hesse et al. (1987), c hydrogeological concept derived from cross section (b), after Sefelnasr (2007)

Table 1 The different extraction scenarios (Mill m³/year) for Dakhla oasis

Area	Scenario 1 (actual)	Scenario 2 (simulated)	Scenario 3 (simulated)	Scenario 4 (simulated)	Scenario 5 (Planned)
Dakhla	439	485.5	532	578.5	625

Sources: MPWWR (1999), RIGW (1999), Pallas and Salem (2001), CEDARE (2002) and Bakhbakhi (2006)

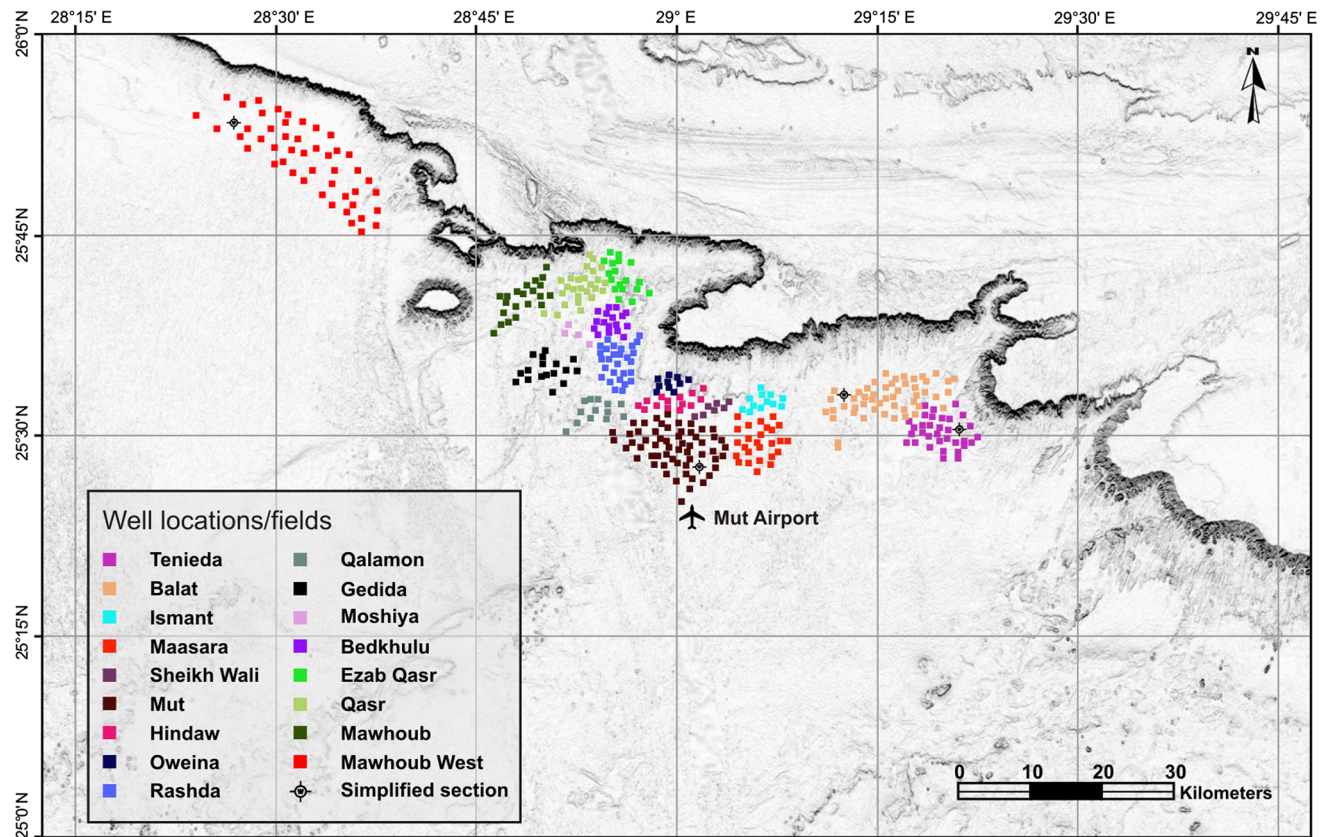


Fig. 6 Location map of the Dakhla oasis showing the distribution of pumping wells and well fields

aquifer was conceptualized vertically into eight (Fig. 5b, c) hydrogeologic layers (five aquifers and three aquitards). These layers were further discretized numerically into three layers each to enhance the vertical distribution of the hydraulic conductivity to contain a total of 22 numerical layers or 23 slices (Sefelnasr et al. 2013). Consequently, the detailed data for Dakhla oasis is also further used for the local modeling with appropriate adjustments and refinement (Leake and Claar 1999) for the Dakhla area according to the locations of the pumping wells and other stresses. This approach allowed precise analysis of the pumping and the resulting drawdown in the Dakhla oasis during the simulation period 1960–2100.

Five extraction scenarios were considered for the modeling purposes. The scenarios were based on the given actual and planned extraction rates and in between there were other three scenarios looking for the most feasible management option in the oasis (Table 1). There are 523

private and/or shallow wells and 313 deep wells extracting the upper and lower aquifers, respectively, in the Dakhla oasis (Fig. 6). These wells are entered into the model based on their horizontal and vertical coordinates. For the wells that numerically overlap (when they are too close to each other) or fall in the same numerical cell, their extraction rates are summed up and gathered to one pumping center. If a certain well is tapping both the shallow and the deep aquifer, then it is divided into two numerical wells at the same node. The actual extraction rates are given to the model for scenario 1 and the extraction rates from the other scenarios are shared out on the wells proportionally. Figure 6 illustrates the spatial distribution of the pumping wells/pumping centers within the Dakhla oasis.

The local prediction simulation was used to evaluate the given five future development plans for the NSAS in the Dakhla oasis in an attempt to explore the hydrologic

feasibility of these plans and the sustainability of the aquifer under each extraction scheme. In this article, the results from the first, third and fifth scenarios will be presented. The prediction period extended from year 2005 to 2100. The assumed groundwater extraction rates for each scheme are presented in Table 1.

Results and discussion

Scenario 1

In this scenario, the actual extraction rate of $1.2 \times 10^6 \text{ m}^3/\text{day}$ for the Dakhla oasis (Table 1) are considered constant during the prediction simulation. As can be seen from the initial hydraulic head (Fig. 7a), the original groundwater flow direction in the Dakhla oasis was generally from southwest to northeast and followed the regional trend of groundwater flow direction in the whole NSAS. This general trend is still roughly kept by year 2005. However, cones of depression (COD) have appeared just around the well fields in the east, middle, and west of the oasis. This change in the flow direction is obviously noticed from the 120-m contour line of hydraulic head. It shows that the flow direction changes and new locally closed contour lines with lower head values of 110 and 100 m appear around the well fields (Fig. 7a).

These changes in the hydraulic head pattern will be further developed by year 2050 and 2100, (Fig. 7b, c) as the hydraulic gradient changed from 4.6×10^{-4} by year 2005 to 2.0×10^{-3} by year 2100 in the middle of the oasis, which induces the COD to be wider and deeper with time.

The COD are centered on the well fields (around major population communities), forming an elongated shape from northwest to southeast following the general depression trend of the Dakhla oasis. By year 2005, the 3 m drawdown line lies about 30 km away from centers of the COD. The major decline in potentiometric surface is observed around the well fields of Teneda, Balat, and Mut, where the drawdown reaches 35 m at the center of the COD. Nevertheless, it is only about 12 m at Mawhoub West (Fig. 7d). This indicates that the groundwater potentiality in the Dakhla oasis is rather good at the eastern side of the oasis and gets obviously better westward, especially at the area of Mawhoub West. Further simulation shows the decline of potentiometric surface increases to reach 50 m at the east of the oasis, 60 m at the middle, and 20 m in the west by 2050 (Fig. 7e). The COD developed further by 2100 to overtake the oasis boundaries. The maximum drawdown of 75 m is recorded at Maasara village, whereas the 50 m COD covers the whole east and middle of the oasis from Teneda village to Qasr city (Fig. 7f). With an

average drawdown of 55 m for the oasis, the average annual change in hydraulic head of the entire simulation period would be 0.57 m per year. Most of the wells in the middle and west of the oasis were still free flowing by year 2005 (Fig. 8a). This case changes completely at the end of the simulation, as only a few wells in Mawhoub west will still be free flowing and the rest will have different depths to groundwater (Fig. 8b).

However, the depth to groundwater in all the cultivatable areas within the oasis will be still less than 75 m. At present, the depth to groundwater less than 100 m is considered economical; hence, the application of this scenario is affordable for the groundwater development in the Dakhla oasis. Yet this scenario is still under the permissible potentiality of the NSAS in the Dakhla oasis.

Scenario 3

This scenario was considered to predict the consequences of the future development when the artificial discharge is increased by half of the full capacity planned extraction rates. An extraction rate of $1.46 \times 10^6 \text{ m}^3/\text{day}$ was subsequently applied.

Figures 9a, b represent the successive changes in hydraulic head during the simulation by years 2050 and 2100, respectively. The core of COD reached the maximum value of 80 m around Mut city by year 2050, as shown in Fig. 9a. At the same time, it did not exceed 30 m at Mawhoub West and an average decline of the potentiometric surface of 45 m over the whole oasis. The abstraction at the current pumping scheme was found to balance the local inflow at the end of the simulation with a 75 m average decline in the potentiometric surface in Dakhla oasis (Fig. 9b) and a maximum drawdown of 105 m at the middle of the oasis. Nevertheless, the drawdown did not exceed 30 m at the Mawhoub West area.

At the end of the prediction, depth to groundwater at Mawhoub West area will mostly be around the ground level at all well fields and will not exceed 25 m. In the Mawhoub area the maximum depth to groundwater will be 50 m. However, between Qasr city and Mut city the average water depth ranges from 50 to 75 m below ground level. To the east of Mut city the water level lies a little bit deeper, as the water depth ranges from 50 to 100 m below ground level (Fig. 9c). The productivity of the aquifer at implementation of this abstraction scenario is still high to very high, as it reaches $19,500 \text{ m}^3/\text{day}/\text{m}$ of drawdown. Based on the groundwater potentiality and development ambitions in the Dakhla oasis, this scenario was found to be the best development option for the domestic, agricultural and industrial activities for the coming 100 years.

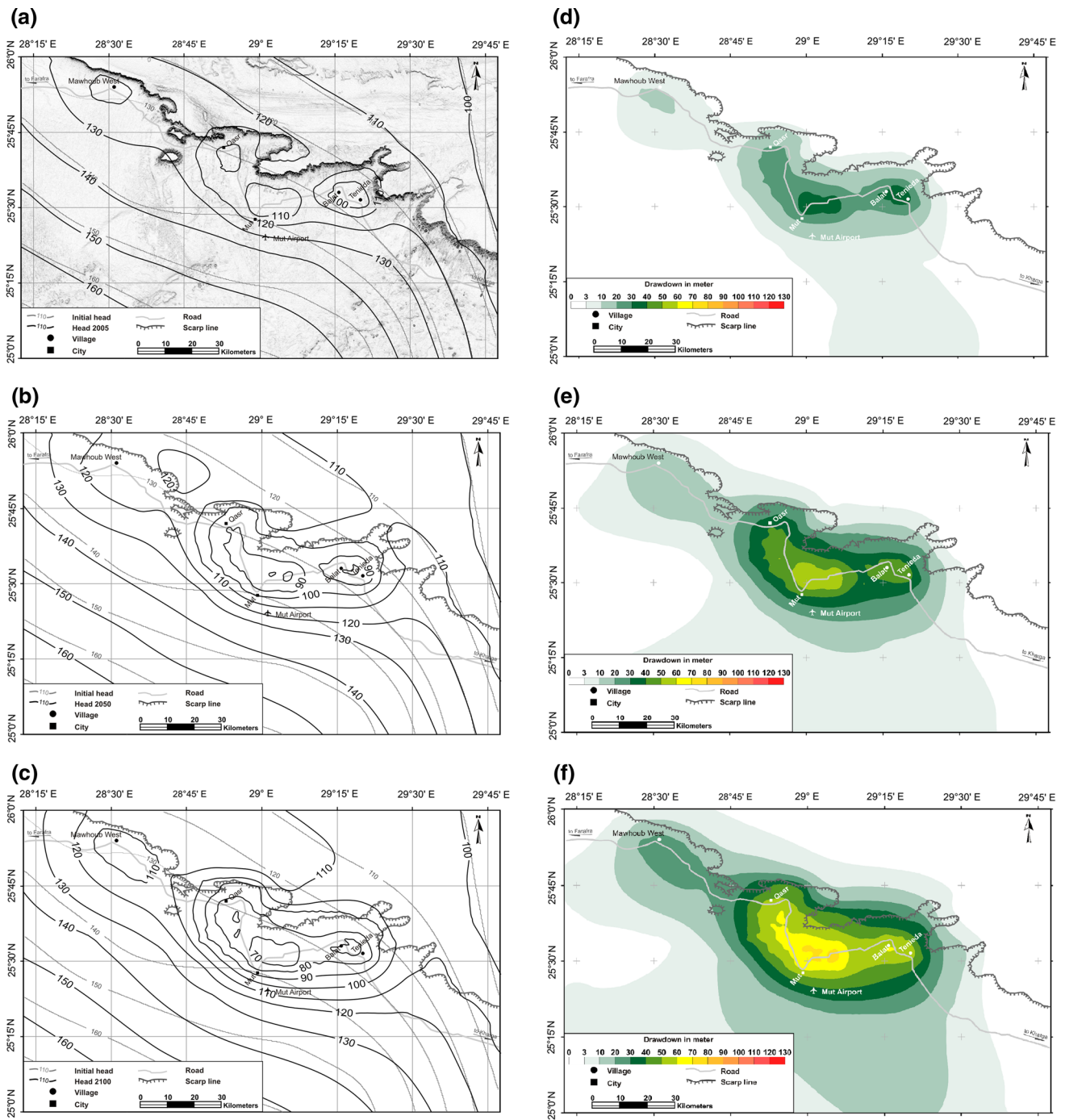


Fig. 7 Simulated hydraulic head m (amsl) for the NSAS in the Dakhla oasis in years **a** 2005, **b** 2050 scenario 1, **c** 2100 scenario 1. Simulated decline in potentiometric surface in years **d** 2005, **e** 2050 scenario 1, **f** 2100, scenario 1

Scenario 5

The attempt to simulate this scenario is to investigate the consequences of expanding the groundwater abstraction rates in the Dakhla oasis to their full capacity planned rates of $1.7 \times 10^6 \text{ m}^3/\text{day}$. It is already expected from the

simulation results of scenario 3 and 4 (scenario 4 is not included in this article) that results would not be pleasant with the application of this scenario concerning the decline in potentiometric surface and depth to groundwater.

The drawdown will reach 95 m and cover the area between Ismant to Qasr by year 2050, whereas this area

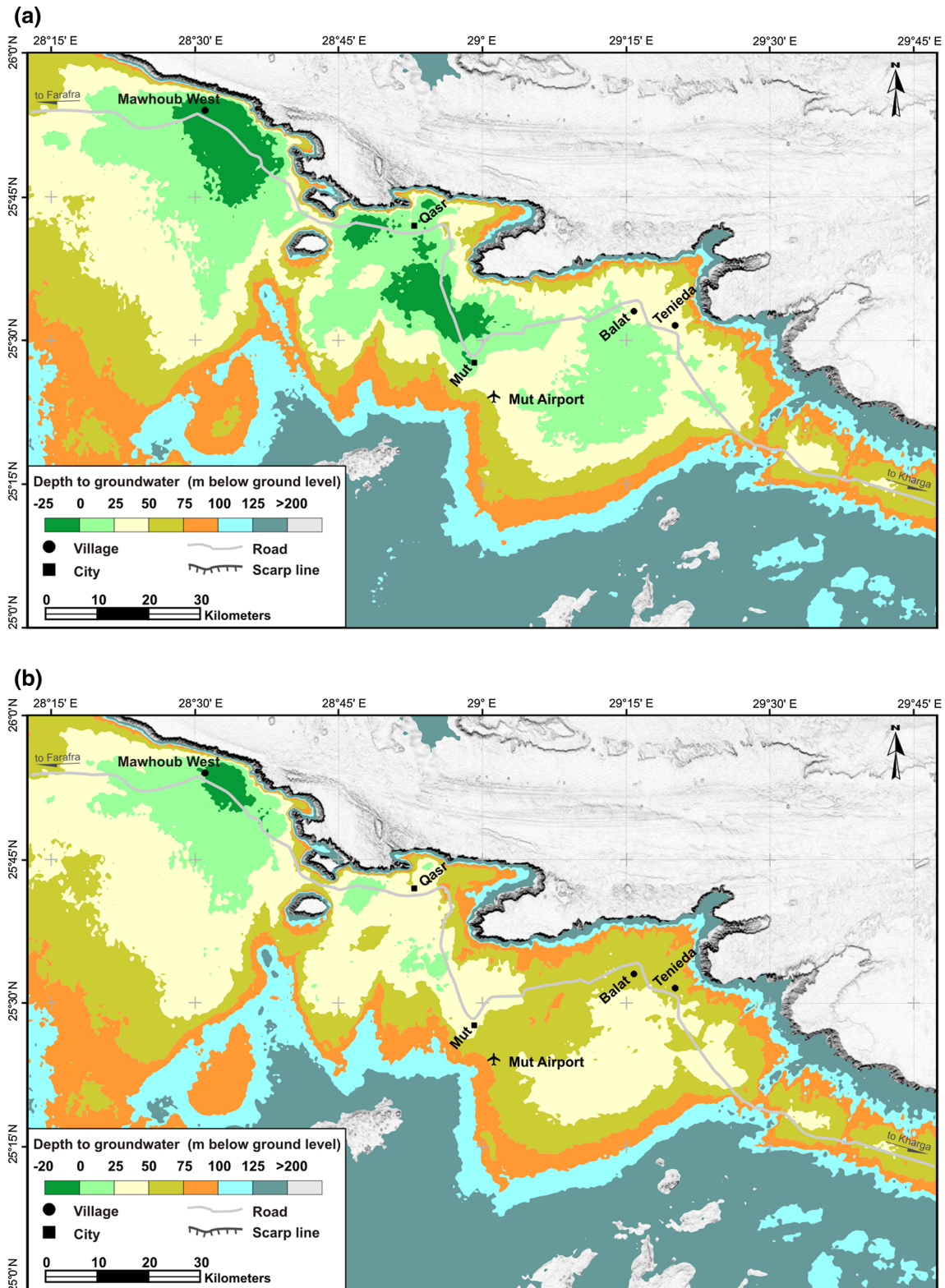


Fig. 8 Calculated depth to groundwater for the NSAS in the Dakhla oasis by year **a** 2005, **b** 2100, scenario 1

will be covered by a 125 m drawdown by year 2100. The average drawdown over the oasis at the end of the simulation will then be about 85 m, which means that the

average annual decline in hydraulic head is about 0.90 m/year (Figs. 10a, b). A huge cone of depression will be formed at the end of the simulation, covering the whole

Fig. 9 Simulated decline in potentiometric surface for the NSAS in the Dakhla oasis by a 2050 scenario 3, b 2100, scenario 3. c Calculated depth to groundwater by 2100 scenario 3

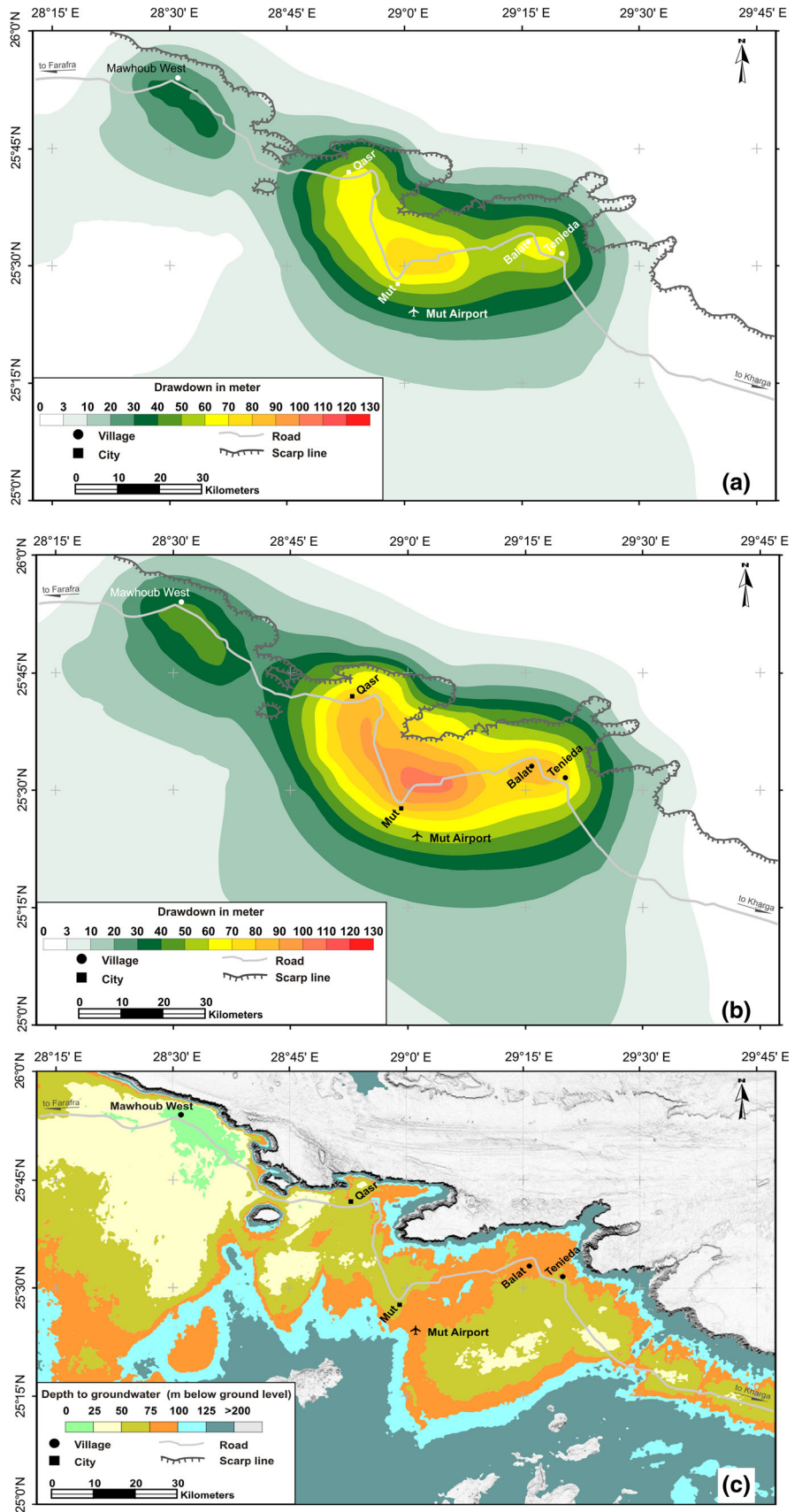
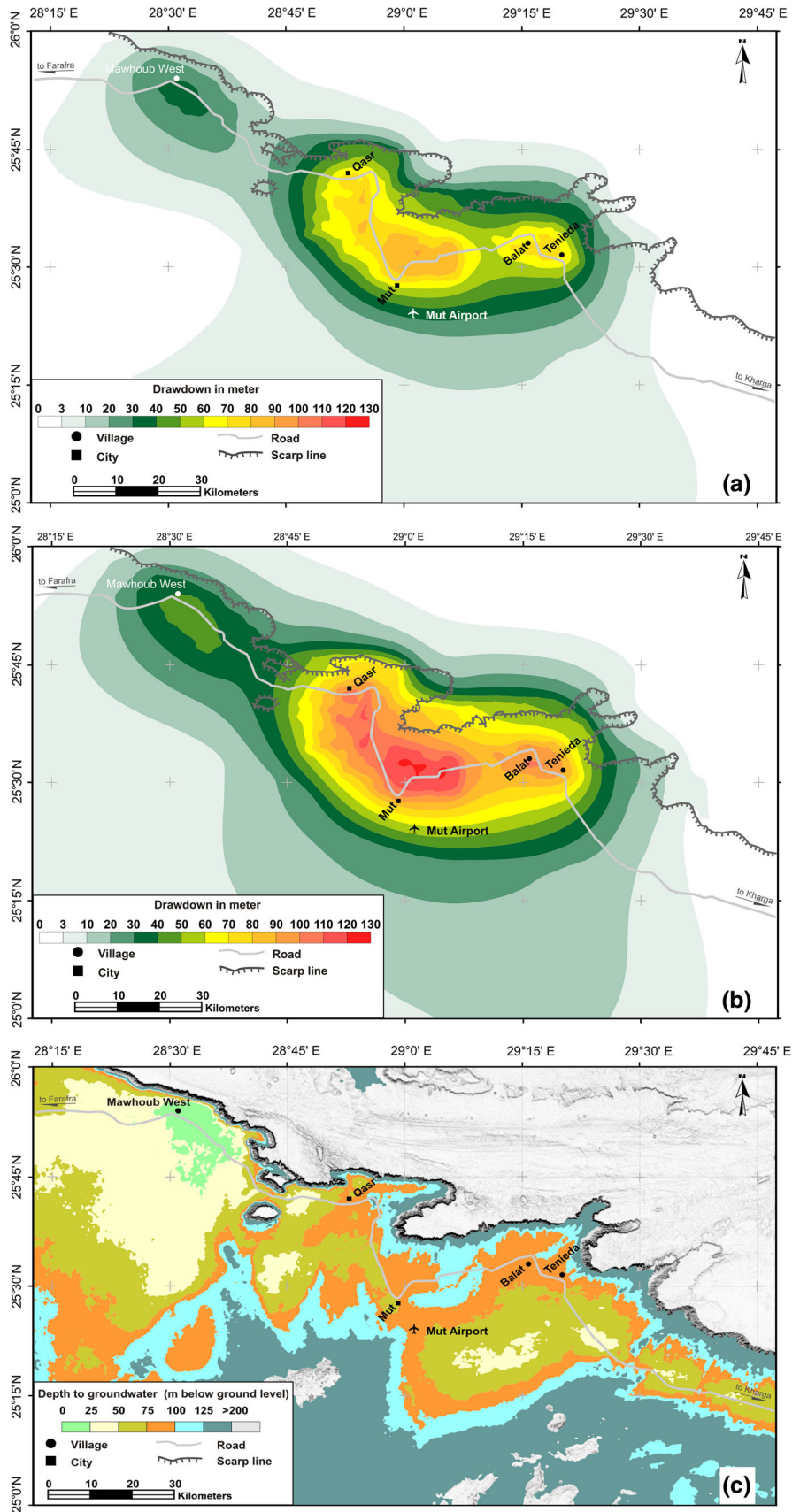


Fig. 10 Simulated decline in potentiometric surface for the NSAS in the Dakhla oasis by a 2050 scenario 5, b 2100, scenario 5. c Calculated depth to groundwater by 2100 scenario 5



oasis and extending further beyond its boundaries. The areas of depth to groundwater exceeding 100 m due to this scheme of abstraction will expand to cover most of the villages east of Mut city. Figure 10c illustrates the depth to groundwater from ground level by year 2100.

Conclusion

In spite of the promising potentiality of the NSAS at the Dakhla oasis, the groundwater extraction there is considered, by definition, a groundwater mining. Any development plans for this aquifer should be based upon an aquifer depletion concept, as the major part of groundwater extraction will be from aquifer storage. As, by definition, when the groundwater level in an aquifer over 5 years period, endure an average annual lowering by 1 percent or more of the initial saturated thickness is considered excessively declining, hence the NSAS at Dakhla oasis will undergo an excessively declining situation when applying either of scenarios 4 or 5. On the long term, the groundwater level will severely decline in that the current techniques and pumping facilities will not be valid any more to lift the groundwater from those great depths, at least not economically any more. In case of the planning to establish new developments or expansion of the cultivated area, the “sustainable” extraction rate of scenario 3 should not be exceeded, however, choosing appropriate crop types and irrigation methods that adequate these conditions (aridity and groundwater non-renewability) could be the best option to maintain the designed withdrawal rate on one hand and to meet the development ambitions on the other hand.

A depth to groundwater up to 100 m is considered economical. Based on this contemplation and the results from this work, it is concluded that the best option for groundwater management in the Dakhla oasis in terms of groundwater extraction is the implementation of an extraction rate of $1.46 \times 10^6 \text{ m}^3/\text{day}$ as introduced by scenario 3. The results of this scenario emphasize not only that the economic depth to groundwater could be retained during the simulation period and maybe beyond but also that the potentiality of the aquifer could be better utilized to meet the proposed development plans. The implementation of scenarios 4 and 5 will be responsible for creating a huge cone of depression that extends far away beyond the oasis borders, and the depth to groundwater will exceed 100 m (bgl). Besides, the potentiometric head will drop below the bottom of the first aquifer. This, in turn, will affect the phreatic water levels and springs. Therefore, the wells extracting the first aquifer will dry out. Since the current groundwater flow model is GIS-supported, it can easily be used for any further simulation purposes. It can also be updated to match the newly situations or to be improved

when new data are obtained. A post audit modeling approach will be also considered.

Acknowledgments This work is derived from the first Author's dissertation that funded by the German Academic Exchange Service, DAAD (Deutscher Akademischer Austausch Dienst), and held and granted at Martin Luther University, Halle Wittenberg, Germany.

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