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The transboundary non-renewable Nubian Aquifer System of Chad, Egypt, Libya and Sudan: classical groundwater questions and parsimonious hydrogeologic analysis and modeling

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Abstract Parsimonious groundwater modeling provides insight into hydrogeologic functioning of the Nubian Aquifer System (NAS), the world's largest non-renewable groundwater system (belonging to Chad, Egypt, Libya, and Sudan). Classical groundwater-resource issues exist (magnitude and lateral extent of drawdown near pumping centers) with joint international management questions regarding transboundary drawdown. Much of NAS is thick, containing a large volume of high-quality groundwater, but receives insignificant recharge, so water-resource availability is time-limited. Informative aquifer data are lacking regarding large-scale response, providing only local-scale information near pumps. Proxy data provide primary underpinning for understanding regional response: Holocene water-table decline from the previous pluvial period, after thousands of years, results in current oasis/sabkha locations where the water table still intersects the ground. Depletion is found to be controlled by two regional parameters, hydraulic diffusivity and vertical anisotropy of permeability. Secondary data that provide insight are drawdowns near pumps and isotope-groundwater ages (million-year-old groundwaters in Egypt). The resultant strong simply structured three-dimensional model representation captures the essence of NAS regional groundwater-flow behavior. Model forecasts inform resource management that transboundary drawdown will likely be minimal—a nonissue—whereas drawdown within pumping centers may become excessive, requiring alternative extraction schemes; correspondingly, significant water-table drawdown may occur in pumping centers co-located with oases, causing oasis loss and environmental impacts.

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Introduction

Overview

The Nubian Aquifer System (NAS) is a key water resource within Chad, Egypt, Libya and Sudan. Water availability is a problem and there are concerns about transboundary impacts of water use. Large quantities of NAS groundwater are presently available; Egypt and Libya are the primary current users. Transboundary concerns among these neighboring countries include excessive depletion of shared groundwater by individual countries and spread of water-table drawdown across borders causing shallow wells to dry and oases to disappear. There are also local concerns, including excessive drawdown within pumping centers, contamination by untreated recharge, and disappearance of oases where most pumping centers are co-located. Water quantity is not a limiting factor for long-term pumping, except in the southeast part of NAS; rather, the cost of lifting water from the ever-deepening water level, which declines as a result of pumping, may eventually make groundwater production uneconomical in some locations. Where NAS is thin in the southeast (Sudan), groundwater quantity is more limited.

NAS (Fig. 1) is one of the largest aquifers in the world, about 1,600 km wide in both north–south and east–west directions, with an area of more than 2.6 million (M) km^2 and thickness of permeable water-saturated sediments varying from hundreds of meters at its southern peripheries to several kilometers in its center and in the north. NAS groundwater is non-renewable on a practical timescale, having been recharged during previous pluvial periods thousands to millions of years ago. At present, groundwater predominantly discharges from the aquifer, naturally, in areas of relatively low topography and in pumping wells. There is little practical recharge, so the availability of this water resource will be time-limited (see Salem and Pallas 2004, for an overview).

Crucial NAS management issues revolve around classical questions about drawdown. A key concern involves transboundary impacts of water use, primarily water-table drawdown that may cross a national border

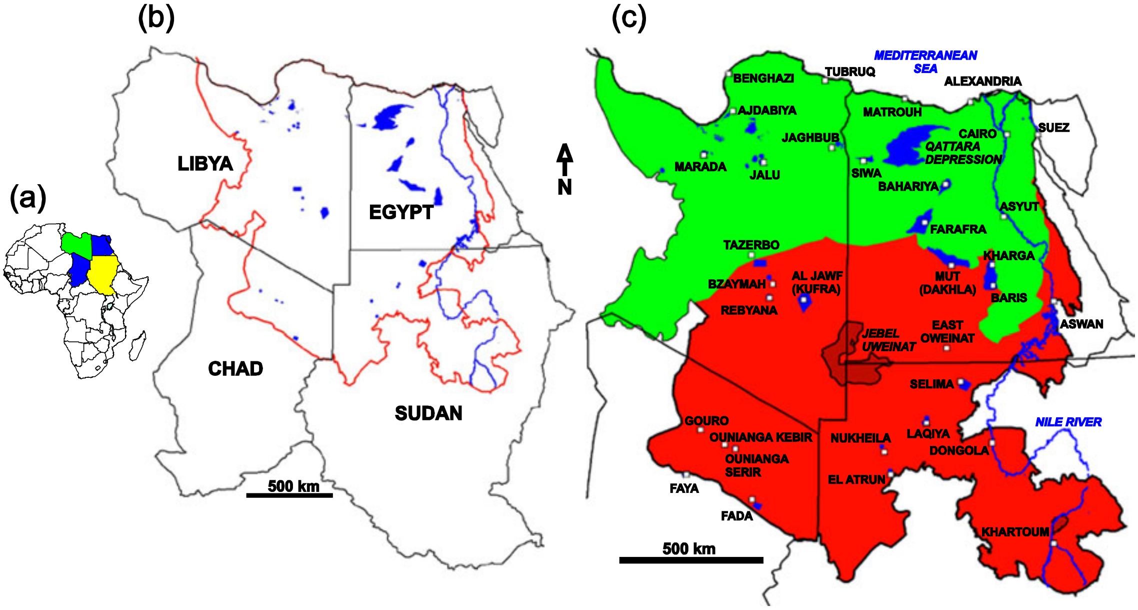

Fig. 1 Overview of Nubian Aquifer System (NAS) region. **a** location in Africa. **b** extent of NAS (*red line*), political boundaries (*black lines*), and surface waters (oases, sabkhas and Nile River; *blue areas*). **c** NAS hydrogeologic regions and towns: Nubian sandstone region in the south (*red*); Post-Nubian/Nubian region in the north (*green*); oases/sabkhas/river (*blue*). Towns and oases are labeled. Areas *shaded gray* in central location (Jebel Uweinat) and near Khartoum are areas of bedrock outcrop where NAS is absent

from a pumping center in one country, adversely impacting water availability in a neighboring country. Related concerns include more use of the resource by one country than another, bringing into question equitable apportioning. Another concern is environmental preservation; oases co-located with pumping centers may disappear as a result of groundwater abstraction. Concerns also include practical questions of local groundwater management—how each country can most-effectively employ the resource and how local groundwater availability (pumping lift and water quality) may evolve or degrade with time as a result of continued water use.

This study develops hydrogeologic insight into the aquifer-wide behavior of hydraulic head changes and groundwater flow, via the process of developing a three-dimensional (3D) groundwater model. The resultant model is intended to be shared by the NAS countries (see “Acknowledgements” section for a description of the project), allowing transboundary and local management concerns to be discussed and evaluated in as quantitative and as scientifically sound a manner as possible. This study also provides a model-based evaluation of possible ranges of regional and local drawdown in NAS to inform management of NAS groundwater resources.

Due to its location in an arid region, where deep drilling only exists in a few spots (primarily in oases), there is little quantitative data available for definition of the lateral and vertical boundaries and hydrogeologic and hydrologic properties of NAS. Available data are limited to a few wells and wellfield locations; thus, data are exceptionally sparse in relation to the great spatial scale of NAS. To develop a robust and effective regional model of NAS, parsimonious model representation is employed, based primarily on proxy data for regional aquifer response.

Previous NAS evaluations and models

Many local models have been created for development areas but these do not provide information about regional response—see electronic supplementary material (ESM). Most important of previous regional-scale modeling studies is the 1980s pioneering work at the Technical University of Berlin, Germany. Heinl and Holländer (1984) presented the conceptual hydrogeologic underpinnings of what would become the first groundwater model of the entire NAS. These authors reviewed previous modeling efforts from 1968 to 1981, (all of which had been local models) and presented the case for modeling the entire system at once. They pointed out the sparseness of hydrogeologic data and showed that steady-state conditions could not exist in this system because current groundwater recharge is non-existent. They argued that groundwater must have been recharged in past pluvial periods and groundwater levels were still dropping from the last recharge event (ca. −20 ka, i.e. 20,000 years ago). During a pluvial, aquifers were full with water levels following the ground surface; thus, simulation would be in transient mode, following the decline of groundwater levels after recharge stopped. These authors pointed out that groundwater currently discharges only at low points in the terrain, including oases and sabkhas (evaporite salt

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flats) via springs and evapotranspiration. Moreover, these authors realized that the recent advent of pumping had not disturbed overall NAS groundwater levels, implying that pumping could be ignored when considering how the aquifer system reached its present-day state in its post-pluvial evolution. This is a landmark paper, though hidden from international view in the university's transactions book series, in which the main concepts regarding the functioning of this aquifer system were first presented. This paper provides the hydrogeologic conceptual foundation for the current work. For a complete discussion of the subsequent NAS work by these authors and their colleagues, Brinkmann and Heinl (1986); Brinkmann et al. (1987); Heinl and Brinkmann (1989); Heinl and Thorweihe (1993); and Thorweihe and Heinl (2002), see ESM. Many results and concepts from these studies are used in the present effort, and important conclusions and speculations of these authors are confirmed.

A comprehensive effort was undertaken by CEDARE (2001) under the guidance of M. Bakhbakhi (General Water Authority, Libya) to develop a model to be used as a technical reference for discussions among the four NAS countries. A two-dimensional (2D) finite-element model was developed, generally following conceptual and modeling procedures set out by the Technical University of Berlin group. A second aquifer was included, the Post-Nubian aquifer, above the Nubian aquifer in the northernmost portion of the region, separated by a confining unit. The extended system was referred to as the Nubian Sandstone Aquifer System (NSAS), and a shorter version of this name, Nubian Aquifer System (NAS), referring to the entire stratigraphic sequence, not only the sandstone, is employed in the current work. The most important contribution of CEDARE (2001), with respect to the current effort, was to describe and organize all of the existing data and to store it in ARC^{TM}-GIS databases. CEDARE brought their NAS model much closer to the point of reproducibility than previous efforts by providing full data and 1960–1998 NAS pumping coverages. Such transparency is a critical feature of any model intended to inform international discussions. Results reported by CEDARE (2001) include 2D finite-element model-based predictions of drawdown, flow field and water balance for a variety of future development scenarios.

The first 3D NAS models (both finite-difference and finite-element) were presented by Gossel et al. (2004), highlighting the use of GIS in developing the model. These authors reiterated the previous hydrogeologic conclusions of the Technical University of Berlin group. Sefelnasr (2007) developed a regional finite-element model of both Nubian and Post-Nubian sediments as a basis for local studies of Dakhla and Lake Nasser areas of Egypt. Here, the primary effort was invested in technological infrastructure to generate the model and populate its 3D parameter field, by creating consistent aquifer-wide stratigraphic sequences and kriging interpolation of surfaces separating units and lateral hydraulic conductivity (and other parameter) distributions within units. Gossel et al. (2010) presented an interesting 3D model study of salinity origins in the northern parts of NAS, with simulations of the past 140 ka (140,000 years) and a 120 m change in the level of the Mediterranean Sea.

Previous modeling and the present study

Except for the most-recent efforts, previous regional models were 2D representations of NAS (or quasi-3D, a stack of connected 2D aquifers). In 2D areal models, NAS groundwater flow occurs in a horizontal sheet and no vertical flow can occur. However, for NAS, three-dimensionality is important. NAS is an extremely thick aquifer and wells withdraw water at distinct limited depths. Past recharge occurred on the aquifer top, not uniformly throughout its thickness. NAS is a stratified stack of high- and low-hydraulic conductivity units that causes a great drawdown difference between the top and bottom of the aquifer and at the depth of well screens. Flow paths from point of recharge to point of discharge near the top of the aquifer tend to be short and flow paths near the bottom of the aquifer tend to be long. All of these aspects of NAS violate the conditions required for meaningful 2D areal model representation. 2D representations are not appropriate for evaluating local effects of pumping (i.e. wellfield drawdown) and will not allow flowpaths of groundwater and capture zones of wells to be properly represented in either local or full regional models.

Furthermore, no single calibrated groundwater model representation can be relied upon to give a reliable prediction of aquifer response because models generally fail to provide a full accounting of the underlying hydrogeologic complexity. Each previous NAS study resulted in only a single model representation of NAS and model predictions of drawdown were generated from this single representation. The more-recent efforts had more-complex spatial structure of aquifer parameters, requiring many values, though there were very few and uncertain data upon which to base the choice of these values. The model structure and parameter values in the single model NAS representations must be considered to be highly uncertain. Although each effort provides one possible mode of aquifer behavior, sensitivity analyses that elucidate the magnitude of uncertainties are lacking.

Adding all available data without understanding which model factors are important controls on the aquifer behavior of interest (in the present case, drawdown) is a modeling approach that results in a model of uncertain value (Voss 2011a, b). This approach is based on the questionable premise that when more details are included, the model becomes a better representation of system functioning. Data are rarely available for calibration of parameter values for each such detail. A more practical-effective approach relies on the realization that only a few particular structural or parametric details are important in controlling the behavior of an aquifer. The most vital result of a modeling study is the determination of these controlling parameters, and, if possible, estimation of their values. Furthermore, a key part of a modeling study is an investigation of the impact of uncertainty in model features and parameter values on predicted groundwater behavior, including sensitivity analysis. This parsimonious approach is employed in the present study, providing insight into the strength and possible ranges of model predictions, given what (little) is known about ranges of controlling features and parameter values at the regional scale for NAS.

Description of NAS and available data

Hydrogeology and hydrology

NAS consists of highly permeable continental sandstones containing layers of siltstones, shallow marine shales and clays of much lower hydraulic conductivity and unknown lateral continuity. The sandstone ends where crystalline Precambrian basement outcrops in the west, south and east. Towards Chad, Nubian sandstones end in the Faya-Largeau oasis area, but against permeable formations of the Chad basin. In the central higher-elevation area where borders of Libya, Egypt and Sudan meet, Nubian sandstones also end where basement outcrops in the Uweinat Mountain, located centrally in the region (Jebel Uweinat, Fig. 1). In the north, the Nubian aquifer dips northward, reaching an unknown extension below the Mediterranean Sea. In the south, the Nubian sandstones are unconfined, but north of approximately the 25th parallel, the northward dipping Nubian sandstones are overlain by stratified permeable continental deposits and low hydraulic conductivity shales and carbonates. Bakhbakhi (2004) gives an overview of NAS hydrogeology. The low hydraulic conductivity units are believed to locally confine the deeper Nubian sandstones, but can also be considered as strongly reducing the overall vertical hydraulic conductivity of NAS where they exist above the Nubian sandstones. In the NAS conceptualization used here, even the northern region of NAS is considered unconfined, with deeper parts of the aquifer naturally behaving as confined because of the low vertical hydraulic conductivity. Stratification within Nubian sandstones also reduces overall vertical hydraulic conductivity even where these extend to the surface in the south, though likely not to the extent of reduction in the north.

Isotope data

Groundwaters below oases in Egypt have interpreted ages on the order of 1 Ma (i.e. one million years), based on ^{36}Cl and ^{81}Kr studies by Du (2003), Sturchio et al. (2004), and, Patterson et al. (2005). Patterson et al. (2005) provided a thorough analysis of these data, including cross-sectional groundwater modeling supporting the supposition that the great ages are due to long travel time from recharge areas near Uweinat Mountain (Jebel Uweinat) in Egypt to deeper aquifer zones in the oasis areas. Available stable and ^{14}C isotope data were compiled by the International Atomic Energy Agency (IAEA) and were reported by Froehlich et al. (2007), but most ^{14}C sampling in NAS was flawed via contamination of samples by atmospheric carbon or mixing of older with younger waters entering boreholes, and only a few of the many non-zero ^{14}C values in the IAEA NAS database available to this study are now considered reliable (P. Aggarwal, IAEA, personal communication, 2009). For the present analyses, the ^{36}Cl and ^{81}Kr data of Sturchio et al. (2004) are the key isotope data employed; additionally there is one ^{14}C age (in Sudan) considered reliable (P. Aggarwal, IAEA, personal communication, 2009).

Hydrologic history of NAS

To explain 1 Ma ages of NAS water samples, NAS hydrologic history must be reconstructed for at least as long. During this time (Quaternary period, 2.8 Ma), earth underwent both glacial and interglacial periods with approximate length of 100 ka for the past 1 Ma, and with length of about 40 ka for the earlier part of the Quaternary period; these are similar in periodicity to the Milankovitch eccentricity and tilt cycles (cf. review of Quaternary glaciations by Ehlers et al. 2011). In the NAS region, glacial periods were pluvial-humid periods and interglacials were arid. For the current analysis, in view of many other simplifications required to elucidate hydrological behavior in a data-sparse system, it suffices to consider a highly generalized representation of Quaternary hydrologic climate history. A periodicity of 100 ka is employed for repeated periods during the past 3 Ma, each containing a 50 ka glacial and 50 ka interglacial phase. During pluvial periods in NAS, there were likely significant surface-water bodies (lakes and rivers) and a shallow water table that received recharge from both rain and surface waters. During arid periods, there was likely little or no groundwater recharge once surface waters disappeared. One major paleodrainage channel (the 'Kufra River') of possible Miocene age (>5 Ma) has been identified in NAS by remote sensing, connecting Kufra oasis in Libya to the Mediterranean Sea (Paillou et al. 2009). Paleolakes and marshes with drainage systems have been identified: some existed from −10 ka to −5 ka (i.e. from 10,000 to 5,000 years ago) in western Sudan (Pachur et al. 1990). NAS has been in an arid-zone state, the natural situation during the current Holocene interglacial period, for the past approximately 5–10 ka.

Two climate histories are represented in current modeling. First, the assumption made is that for the past 3 Ma (approximately the entire Quaternary Period) there were repeated pluvial periods with groundwater recharge and arid periods of little or no recharge on a 100-ka cycle. This allows the possibility that simulated present-day water ages could be up to 3 Ma. This long-term climate pattern is used for the model analyses of groundwater flowpaths and ages. Second, for the more recent (Holocene) period, it is assumed for simulations of long-term water-level declines and drawdown due to pumping, that the last pluvial phase ended at −10 ka (or alternatively at −5 ka) with no recharge occurring thereafter.

In the past, the Mediterranean Sea level changed, with some impact on coastal position in Libya and Egypt. A 120 m lower sea level during the Holocene glacial maximum, as considered by Gossel et al. (2010), would have moved the coast seaward, but not a significant distance relative to the scale of NAS. Coastal migration would affect the location and type of boundary conditions in a

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groundwater model of the same period, but this is less important than other factors and is not included in the current effort.

Predevelopment state of NAS

Prior to significant groundwater production from NAS in about 1960, NAS was in a natural state that evolved from the most recent pluvial and current arid period that began approximately 5–10 ka before present. NAS is a water-table aquifer and, during pluvial periods, the water table was likely shallow in most areas, as it is in most areas with humid climate. Over the recent 5–10 ka arid period, the NAS water table has been dropping. Initially, decline was due to natural spring discharge and evapotranspiration over much of the surface. Later, as the water table retreated to greater depths, evapotranspiration decreased to near-zero and discharge could only occur where it met the ground surface. Today, the remaining discharge locations comprise oases, sabkhas, and the Nile River (Figs. 1 and 2, and Figure 1 of the ESM). In these places, discharge occurs by evapotranspiration and direct groundwater flow to surface-water bodies. Thus, the NAS predevelopment state (i.e. before significant pumping began) in 1960 may be described as a water-table aquifer, in which the water table is mostly deep and meets the ground surface in very limited areas. The water table in 1960 was still dropping as a result of natural water loss from NAS; thus, it was in transient state before pumping began. Even without pumping, water levels in NAS decrease naturally with time, tending towards a low stand at some point in the future, equivalent in elevation to the lowest discharge point, the Qattara Depression in Egypt.

Water-resource development

Development of pumping centers from 1960 to 1998 was detailed by CEDARE (2001). Primary abstraction occurred in Libya and Egypt during this period with more-significant abstraction beginning in Sudan later. Little groundwater is abstracted from NAS in Chad. Data used here for 1960 to 1998 were compiled from volume II, Table 5.5 and Table 5.11 of CEDARE (2001). These data include location and yearly pumping rates from pumping centers. Approximate indicators are provided for depths of typical well screens. Data for 1999–2009 for Sudan and Libya were provided by their governments. Chad had no significant pumping to report and although Egypt continued significant pumping, only incomplete data were provided to this project and rates had to be estimated (see ESM). Future projections were also provided by Libya and Sudan, based on the areas planned for

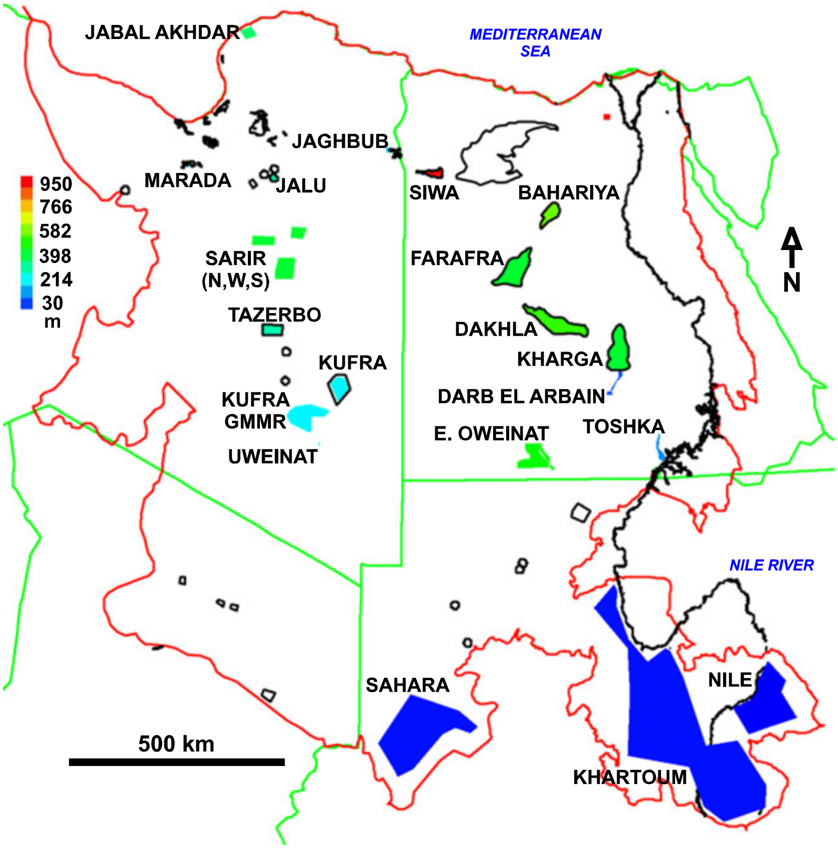

Fig. 2 NAS groundwater development areas (labeled with their name and shown as *solid colors* with *rainbow color scale* representing depth of top of well screen in m, as implemented in the model). *Black outlines* (some co-located with development areas) indicate areas of surface water (oases and sabkhas) and Nile River. Country borders are *green lines*. NAS boundary is *red line*

development. (All past, present and future pumping rates are reported in Table 2 of the ESM.) Groundwater development areas in NAS are shown in Fig. 2. Total extraction from NAS has approximately doubled every 10 years during the period 1970–2010. Measured drawdowns in three development areas are shown in Fig. 3.

A few possible future development scenarios considered in this study are intended to give a general indication of how NAS water levels would react to future pumping. These include: simple continuation of estimated 2009 pumping rates, arbitrary doubling of these rates after 2060, and doubling of rates plus addition of new hypothetical pumping centers after 2060 in Sudan and Libya. These are described in detail later.

Model development

Software

The groundwater modeling software is the three-dimensional (3D) U.S. Geological Survey (USGS) MODFLOW-2000 code (Harbaugh et al. 2000) with a few of its utilities, including MODPATH, a flowpath postprocessor (Pollock 1994) (for details see ESM). More-recent versions of MODFLOW exist, however, MODFLOW-2000, has all of the hydrological processes required for modeling NAS and of all MODFLOW versions, it is the only one that has inverse modeling included as an internal process (Hill et al. (2000), so this version was deemed easier to apply in the brief model construction period (see "Acknowledgements").

Model volume

The NAS model domain (Fig. 1) was extended beyond that defined by CEDARE (2001) to locations of more-natural NAS boundaries (see Figure 2 of the ESM). The domain extends from the Mediterranean Coast in the north to the locations where permeable NAS sediments end against less-permeable formations, except in Chad where a groundwater divide delimits the domain. The top of the NAS domain was set at ground surface topographic elevation and the bottom elevation was interpreted from several data sources (see ESM for detailed descriptions).

A map of NAS thickness, obtained as the difference between the top and bottom elevations (see Figure 3 of the ESM), is shown in Fig. 4. Thickness ranges from 500 to 5,000 m throughout, with the thickest regions in Libya and in the north, and the thinnest in the southeast, particularly in Sudan, where NAS thickness decreases to 100 m or less (see

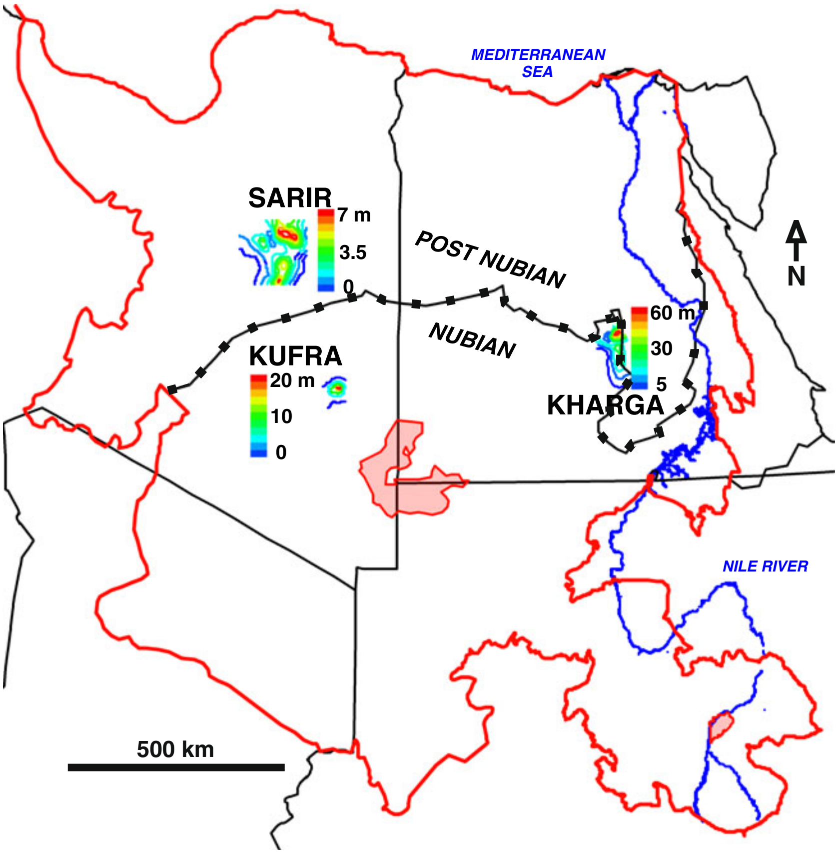

Fig. 3 Available drawdown data (1998) in NAS from CEDARE (2001). *Colors* represent drawdowns (in m) as measured from 1960 predevelopment conditions. It is assumed that the drawdowns are representative of head conditions at the depths of pump screens (depths from which water is extracted) and not at the water table. The border of the Post-Nubian/Nubian (north) zone and Nubian (south) zone is shown as a *black line with blocks*. Country borders are *black lines*

Figure 4 of the ESM). Here, hardly any basement data exist and improving water-resources management may require additional basement measurements and possible adjustment of the current model. The grid used for most analyses is comprised of 3D cells that appear in map view as 20-km × 20-km squares and there are 20 layers of cells vertically (see Figures 5 and 6 of the ESM). (See ESM for details of model setup, discretization, time-stepping, and data coverages used).

Boundary conditions, water sources and sinks

The model is configured to recreate the long-term decline of the NAS water table (e.g. past 5–10 ka) after a pluvial period. To represent the primary hydrologic response of NAS, the complex paleoclimatic forcing of groundwater recharge sources is distilled and simplified. During pluvial periods (glacials), it is assumed that there is sufficient recharge such that NAS is filled to the top. During arid periods (interglacials), it is assumed that no recharge occurs and there is only drainage/loss of existing groundwater. Thus, the following boundary conditions are implemented (for details, see ESM). All boundaries are closed to flow except the top boundary through which recharge and discharge may occur. A 'drain' is specified to cover the entire model top. The drain discharges any groundwater that rises to the ground surface, such that hydraulic head is always at or below the surface. During pluvials, excess recharge is applied to the model top, raising the head everywhere to the ground surface. During arid periods, there is no recharge and groundwater can only discharge wherever the ever-dropping head (i.e. water table) is still at the ground surface. Discharge areas shrink during the arid period and total discharge decreases.

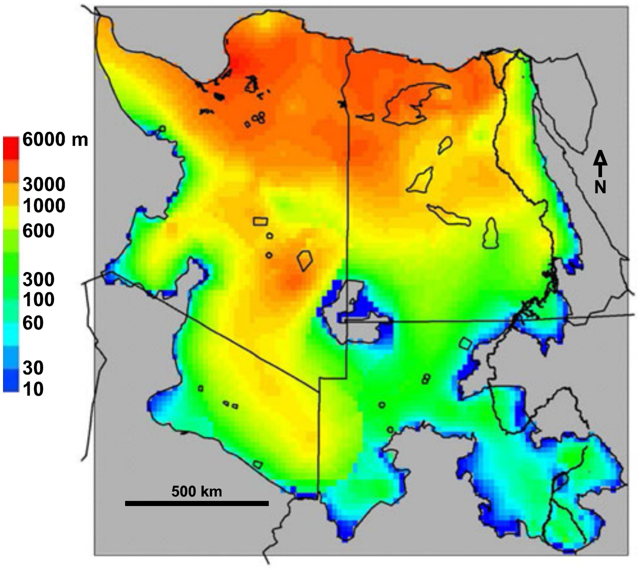

Fig. 4 NAS vertical extent, calculated as difference between NAS model top and bottom (see Figure 3 of the ESM). Thickness of NAS (in m). *Black lines* are country borders, oases, sabkhas and Nile River

Two time progressions of the top boundary conditions are employed, depending on the simulation purpose. A 3-Ma evolution is used to evaluate groundwater age distribution in NAS for comparison with available interpreted ages, and a 5-ka and 10-ka evolution are used for comparing present-day oasis locations to determine values of standard aquifer parameters. The two arid period lengths are considered to investigate impact of assumed period length on estimated parameter values.

The only water source is recharge, applied on the top boundary during pluvial periods. Water sinks, losses of groundwater from NAS, are of two types, natural and pumping. Natural sinks occur at drains at the model top. Pumping is applied over the areas of NAS well fields (Fig. 2). Each wellfield has a schedule of pumping that either consists of pumping data supplied by CEDARE (2001), NAS countries, estimates, or a combination of these. Pump screens in the model are set at particular depth intervals for each wellfield, based mostly on information reported by CEDARE (2001) for a few well types. For each wellfield, the total amount of yearly pumping from the entire wellfield is applied uniformly over the entire wellfield area as though wells are spread throughout; no individual wells are modeled. This is appropriate for regional-scale NAS modeling, but not for evaluating the detailed pattern of drawdown within any wellfield. (Pumping rates and schedules for each area are discussed fully in the ESM and are specified in Table 2 therein).

Procedure for determining aquifer structure and parameter values

For the current hydrogeologic analysis of NAS, the 'simplest possible' model is initially hypothesized to explain existing data and this model is made more complex structurally only if necessary to improve some aspect of fit that is deemed important. This philosophy of modeling may be termed 'parsimonious model development'. Useful and effective simplifications such as described in the following, need to be made in groundwater modeling to produce a model that reliably and robustly represents what is known about aquifer system behavior.

The first model hypothesized describes NAS as a single homogeneous aquifer with uniform value of all hydrologic parameters throughout (one-zone model). Rather than attempting to represent details of stratigraphy and assign each geologic unit a different set of hydrologic parameter values, the overall effect of the stratification is modeled by allowing hydraulic conductivity to be vertically anisotropic, with vertical value lower than horizontal value. The impact of complex layering is initially represented by only one parameter, vertical anisotropy (ratio of horizontal to vertical hydraulic conductivity).

Developing a model intended to evaluate regional behavior requires data at the regional scale (i.e. region-wide drawdown and hydrologic response, ages on long flowpaths). In NAS, the only directly measured response to stress is drawdown in pumping areas; calibration to these

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data will give parameter values only within the pumping area. Measured drawdowns in three development areas are available (Fig. 3), so calibration can be done within only three areas of about 100 km^2 each. In comparison with the NAS area being modeled (over 2.6 M km^2), these data provide little regional information and are merely the regional equivalent of measurement at three single points. A model calibrated mainly to such local data, as has been done in past modeling efforts (e.g. CEDARE 2001; Sefelnasr 2007), can only be expected to predict response only within these small areas—not over the entire regional aquifer.

The realization that measurements of NAS regional-scale aquifer response are lacking motivates a search for less-conventional types of data that will inform estimation of parameters that control regional scale behavior. For NAS, two long-time large-spatial-scale datasets were found: (1) a proxy dataset that represents regional-scale long-time aquifer response to stress in which the predevelopment location of oases indicates the locations where the NAS water table intersects the ground surface after 5–10 ka of natural water table decline from the Holocene pluvial period maximum; thus, a proxy 5–10 ka drawdown map exists for the entire aquifer system providing regional-scale data resulting from a process that occurred over a very long time period; (2) a groundwater ages dataset, interpreted from ^{81}Kr data in Egyptian oases (Sturchio et al. 2004) and from ^{14}C data in Sudan (P. Aggarwal, IAEA, personal communication, 2009), which provides both corroboration of regional model parameter values initially calibrated to water-level decline data (both during the Holocene period and during aquifer development after 1960) and provides the value of an additional regional aquifer parameter that controls groundwater velocity, the effective porosity.

Identifying controlling parameters

The first objective in developing an effective model analysis of NAS is to determine which parameters control the responses of NAS leading to the measured data and behaviors of interest (e.g. drawdown due to pumping). It is desirable to find the fewest possible number of parameters that control the primary response of NAS—even if these are not strictly rigorous in a mathematical sense. There are four candidates in the governing equations: two hydraulic conductivities (K-horizontal and K-vertical with units [m/s]), specific yield (Sy) with units [1] and specific storage (Ss) with units [1/m].

Controls on steady-state and transient groundwater flow

Only hydraulic conductivities, K-horizontal (Kh) and K-vertical (Kv) control the spatial distribution of steady-state hydraulic head. Typically in stratified aquifer fabrics, Kh > Kv; the difference represents the regional effect of continuous and discontinuous low-K layers that block vertical flow more than horizontal flow. Thus, the two controlling parameters are expressed as Kh and vertical anisotropy Kh/Kv. Two additional parameters control time-dependent changes in head and flow: aquifer storage coefficients specific yield, Sy, and specific storage, Ss. To fully evaluate the impact of these four controlling parameters on NAS behavior would require a simulation cross-analysis of several levels of each parameter with all values of each other parameter, which can be a time-consuming task. Some simplifications are sought to reduce the complexity of the problem.

Reducing the number of parameters

The total aquifer storage, expressed as an effective specific storage, Sse, is employed rather than the two individual storage coefficients. Total aquifer storage, S with units [1], is the storage value usually used in 2D models of groundwater flow, and is the sum of water-table storage and compressive storage

$$\mathrm{S} = (\mathrm{Ss})(\mathrm{thickness}) + \mathrm{Sy}$$

or in terms of the equivalent effective specific storage,

$$\mathrm{Sse} = \mathrm{S}/\mathrm{thickness} = \mathrm{Ss} + \mathrm{Sy}/\mathrm{thickness}$$

S and Sse are the true storage values whenever the head change with time is constant from top to bottom of the aquifer at a point. Where head change varies with depth, these only roughly account for total storage, and true effective storage depends on where the transient head changes occur, at the water table or deep. When head change is uniform over aquifer depth, it does not matter what the individual values of Ss and Sy are, only the value of Sse controls transient head change. This is the case for long-term region-wide water-level change over the Holocene period. Controlling parameters are thus determined to be primarily three parameters, Kh, Kh/Kv, and Sse, for controlling the temporal and spatial distribution of modeled head at a regional scale, where vertical head differences are not significant.

It was further found by inspection of the governing equations for groundwater flow, that natural post-pluvial water-level decline in NAS (when there is no pumping in the aquifer), is mainly controlled by only two (approximate) controlling parameters, reduced from the above three:

$$\mathrm{Kh}/\mathrm{Sse}\ \text{(the hydraulic diffusivity) with units}\ \left[\mathrm{m}^2/\mathrm{s}\right]$$
$$\text{and}$$
$$\mathrm{Kh}/\mathrm{Kv}\ \left(\begin{array}{r}\text{the vertical anisotropy of NAS}\\ \text{hydraulic conductivity}\end{array}\right)\ \text{with units}\ [1].$$

Thus, the number of controlling parameters is reduced from four to two, simplifying the predevelopment modeling

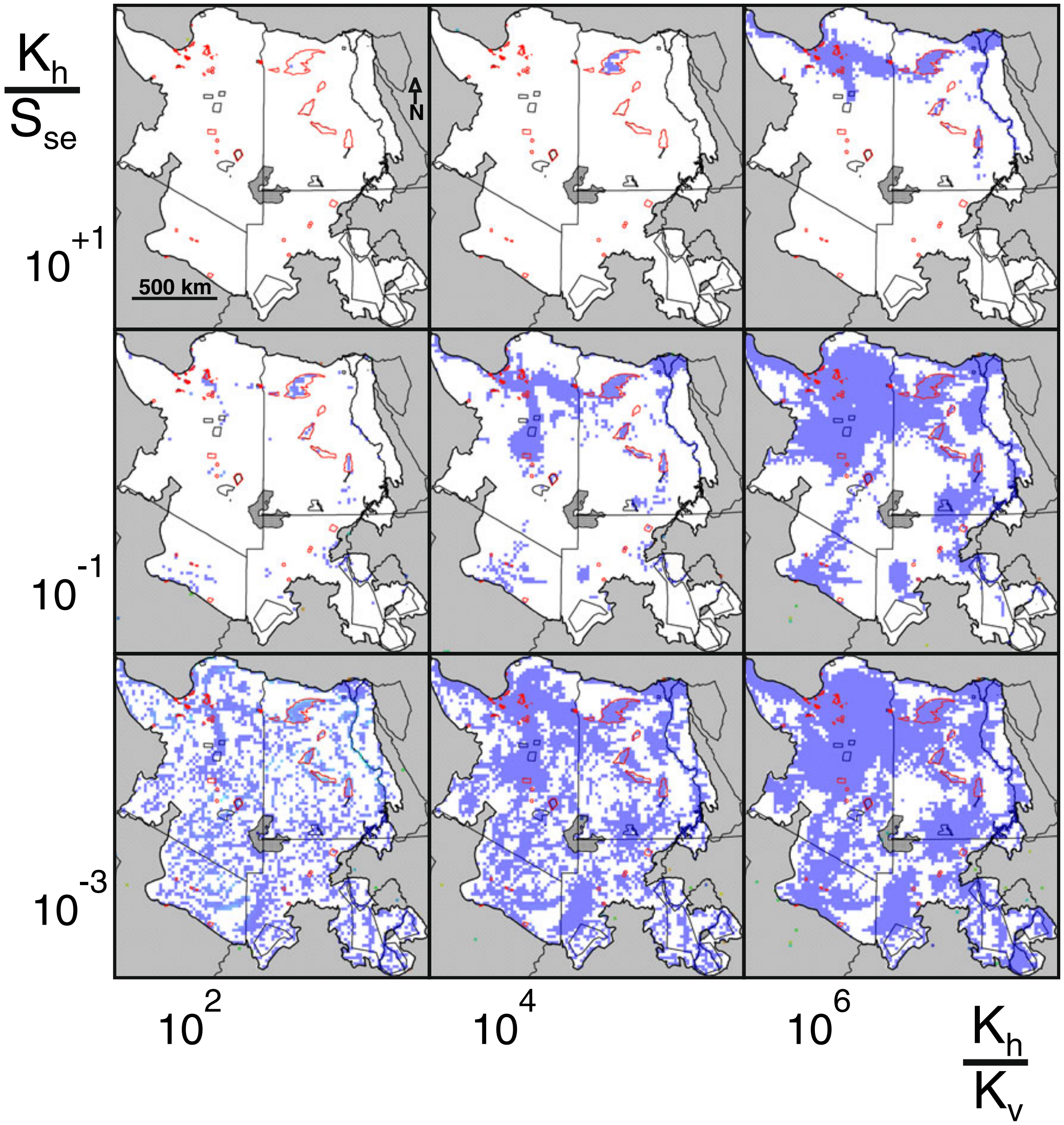

Fig. 5 Sensitivity of predevelopment water-table depths to primary controlling parameters for one-zone NAS model. Examples of simulated oasis locations are shown for a range of hydraulic diffusivity and vertical anisotropy values at a point in time 10 ka after pluvial-period aquifer-full conditions. These result from transient simulations. *Blue areas* are locations where the simulated water table is located at the ground surface, indicating locations of groundwater discharge (e.g. oases/sabkhas). The water table reaches the ground surface (in other words, the hydraulic head is equal to or exceeds the ground surface elevation by at most a few cm) only in the *blue areas* and is below the ground surface elsewhere. Initially, the entire region has full-aquifer conditions at the end of a pluvial period (as shown for simulation 0 a in Fig. 6) with the water table at the ground surface everywhere. (Compare values plotted with range of manually calibrated parameter values shown in Fig. 7.) Oases and sabkhas (mapped in Fig. 1 and Figure 1 of the ESM) are shown with a *red border*. Groundwater development areas (Fig. 2) that are not co-located with mapped oases are shown with a *black border*. Nile River and country borders are shown as *black lines*

analysis. For modeling groundwater travel time, the only additional controlling parameter is porosity, ε.

Controlling parameter ranges

Plausible maximum ranges of NAS controlling parameters are calculated in order to determine the span of values that must be considered. Maximum plausible ranges for the natural post-pluvial water-level decline controls (Kh/Sse and Kh/Kv) were determined from extreme combinations of their three component parameters, Kh, Kh/Kv and Sse. Extremes were selected from ranges derived from data reported by CEDARE (2001), other previous NAS work, and from general knowledge of hydrogeologic properties of similar aquifer fabrics.

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Maximum plausible NAS range of Kh:

$$10^{-6} < \mathrm{Kh}\,[\mathrm{m/s}] < 10^{-2}$$

Maximum plausible NAS range of S:

$$10^{-2} < \mathrm{S} < 1\,.$$

Maximum plausible NAS range of Sse:

$$10^{-5} < \mathrm{Sse} < 10^{-3}$$

(these assume:

$$10^{-2} < \mathrm{Sy} < 1$$

$$10^{-8} < \mathrm{Ss}\,[1/\mathrm{m}] < 10^{-4}$$

$$\text{thickness} \sim 10^{3}\mathrm{m})$$

Thus, the maximum NAS range that must be considered for hydraulic diffusivity is

$$10^{-3} \leq (\mathrm{Kh/Sse}) \leq 10^{+3}\mathrm{m}^2/\mathrm{s}$$

For vertical anisotropy, the maximum NAS range is taken to be as large as the maximum expected conductivity contrast between NAS aquifer layers and NAS confining units

$$1 \leq (\mathrm{Kh/Kv}) \leq 10^{8}$$

The upper value in this extreme range allows for the unlikely possibility that high- and low-conductivity units extend, in an unbroken manner, across the entire NAS.

For porosity, the range of values that must be considered is determined as follows. In fast-moving groundwater, the effective porosity, the value that controls groundwater velocity, is the porosity of well-connected flowpaths (assumed to be 0.01 in NAS) and is usually much lower than the total porosity. For slow-moving (old) groundwater as expected throughout NAS, the effective porosity is likely closer to the total porosity of NAS aquifer fabric (assumed to be 0.4 in NAS). In slow-moving groundwater, isotopes attain uniform concentration across all parts, including patches of high and low hydraulic conductivity, of the aquifer fabric via groundwater flow or diffusion—and isotope concentrations in zones of low hydraulic conductivity have time to equalize via diffusion. In this case, water age is directly proportional to $(1/\varepsilon)$ where ε is the total porosity. The maximum possible range of NAS total porosity to consider is

$$0.01 \leq \varepsilon \leq 0.4$$

One-zone model

One-zone model fits to Holocene water-level decline

Given the previously identified controlling parameters for natural post-pluvial water-level decline, combinations of (Kh/Kv, Kh/Sse) that give plausible oasis/discharge locations at predevelopment (1960), initially assumed to be 10 ka since the last pluvial period, and combinations that give reasonable fits to the regional pattern of measured predevelopment heads were determined. For each combination of controlling parameter values tested, the following procedure was used (see ESM for details).

A steady-state pluvial climate condition (resulting in head at the top surface of NAS equal to the topographic elevation) was simulated to create initial conditions. Recharge was then turned off and transient simulation from the pluvial steady state was run forward in time for 10 ka. The 10 ka transient result for water-table locations at the ground surface was compared with predevelopment oasis locations. Combinations were noted of (Kh/Kv, Kh/Sse) for which all known oasis/discharge locations have near-surface heads, while other locations did not, providing parameter values that reproduce groundwater head dynamics at the largest spatial scale and longest time for which proxy head data are available, i.e. the Holocene. This calibration process is qualitative and was carried out by visual inspection of results.

Examples of results are shown in Fig. 5 for the one-zone model and the time-evolution for one simulation (the final two-zone base NAS model discussed later) is illustrated in Fig. 6. Inspection of the oasis distributions in Fig. 5 reveals that the two controlling parameters have different impacts on the residual 10-ka oasis distribution; roughly speaking, changing vertical anisotropy affects the number of regions with water table at the surface and changing hydraulic diffusivity affects the size of these regions. (The center example in Fig. 5 has properties close to that of the best-fitting one-zone base model discussed later.) After judging results for a series of simulations that covers the plausible ranges of controlling parameters, the pairings of values giving best qualitative matches with oasis locations are reported in Fig. 7. Automatic calibration was also carried out using measured predevelopment heads in 1960 and results (see Figure 7 of the ESM) generally match those of manual calibration. The meaning of this result is as follows. Assuming that reproducing Holocene water-level drop by

Fig. 6 Simulated Holocene water-table decline in NAS. Simulated progression of oasis loss for the case of the pluvial period ending 10 ka before present in the two-zone NAS model (best-fitting 'base model'). Times (0–10000 a) indicate elapsed time in years [a] after pluvial-period recharge ends (i.e. after full-aquifer condition). *Blue areas* are locations where the simulated water table is located at the ground surface, indicating locations of groundwater discharge (e.g. oases/sabkhas). The water table reaches the ground surface (in other words, the hydraulic head is equal to or exceeds the ground surface elevation by at most a few cm) only in the *blue areas* and is below the ground surface elsewhere. Initially, the entire region has full-aquifer conditions at the end of the pluvial period (as shown for 0 a) with the water table at the ground surface everywhere. Oases and sabkhas (mapped in Fig. 1 and Figure 1 of the ESM) are shown with *red border*. Groundwater development areas (Fig. 2) not co-located with mapped oases are shown with *black border*. Nile River and country borders are shown as *black lines* ▶

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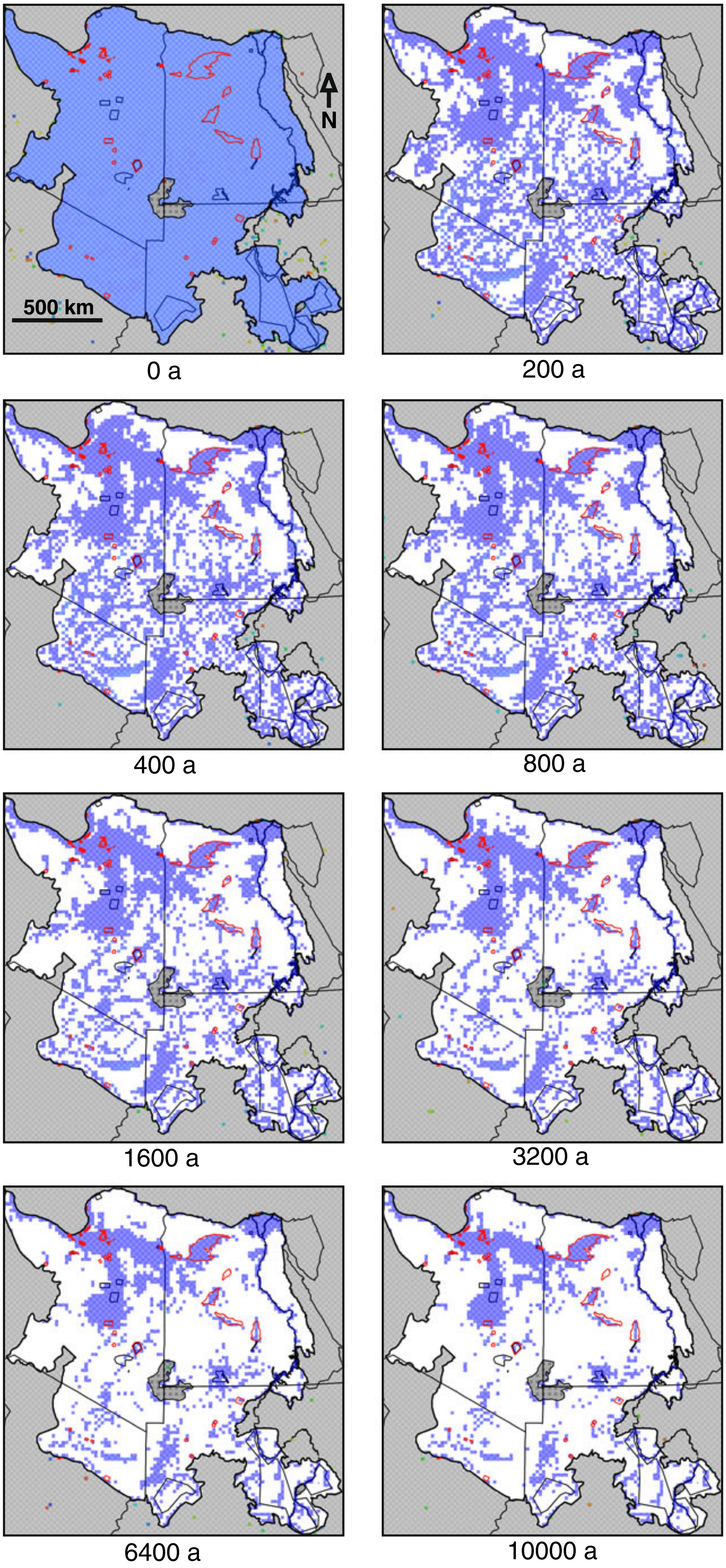

0 a

200 a

400 a

800 a

1600 a

3200 a

6400 a

10000 a

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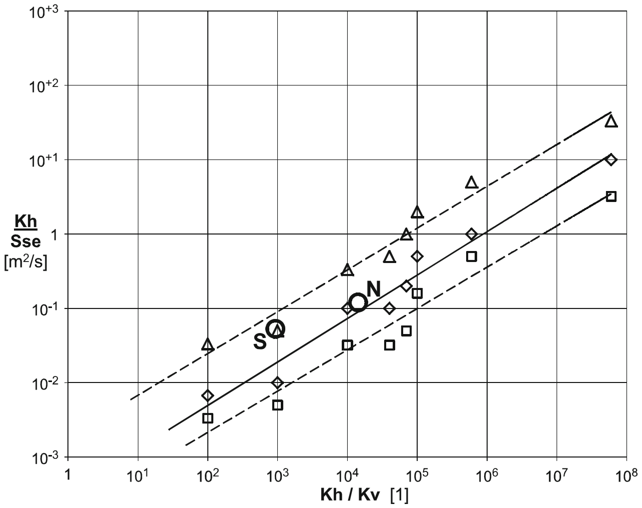

Fig. 7 Controlling parameter ranges and model fits for Holocene water-table decline in NAS. Controlling parameter values for visually selected best matches to oasis and sabkha locations after 10 ka transient simulation using one-zone NAS model with no recharge, starting from pluvial conditions. Shown are extreme high and low parameter values of hydraulic diffusivity (Kh/Sse) that allow rough visual matches to oasis/sabkhas locations for a range of vertical anisotropy (Kh/Kv) values. *Triangles* and *squares* indicate maximum and minimum values, respectively; *diamonds* indicate best-visual match values. *Lines* are least-squares power-law fits to these values: *dashed lines* indicate the extremes of the parameter value range that allows visual matching of oasis locations, and the *continuous line* indicates visual best-fit values. Automatic calibration results for the two-zone NAS model show best-automatic-match results (*circles*) after 10 ka of simulation beginning with pluvial (aquifer full) conditions, thereafter no recharge. Automatic calibration is for a subset of 1960 head data from CEDARE (2001). **N** and **S** indicate fitted controlling parameter values for north and south zones, respectively

matching current oasis location is a good approach that provides proxy head data in 1960, the true NAS regional values of the two controlling parameters must fall somewhere between the extreme lines of Fig. 7, presumably near the best match line.

One-zone model fits to post-development period

Next, pumping was added to the model beginning after 10 ka (in 1960) and transient simulation were carried out to determine drawdown by 1998, focusing on areas Kufra and Sarir (north, west and south) in Libya, and Kharga in Egypt (Figs. 2 and 3), where data were available. The objective was to estimate values of the sub-parameters of the controls (Kh/Kv, Kh/Sse), namely, Sy, Ss, Kh and Kv, while maintaining the already-fitted control values. The result of this manual calibration is that it is not possible to fit drawdown at all three pumping centers, Kufra, Sarir and Kharga using the same four sub-parameter values. The meaning of this result is as follows. Although it is possible to find values of Kh, Kv, Sy and Ss that allow simulated drawdowns to separately fit measured drawdowns in each local area while the ratios of these parameters still agree with their ratios determined from the regional 10 ka analysis, it is not possible to use the same four parameter values for Kharga as for Kufra and Sarir. Additional regional model complexity is required in the form of an additional zone of parameter values in order to fit all three simultaneously.

Two-zone model

The simplest rezoning of the model was sought that might allow fitting of both 10 ka water-level drop and 1960–1998 drawdown in three pumping centers using the same parameter values. Perhaps the greatest deficiency of the homogenous one-zone model in representing NAS hydrogeology is in restricting both northern and southern portions of the system to the same parameter values. The northern region, identified by CEDARE (2001) as containing the Post-Nubian sequence of sediments overlying the Nubian sandstone sequence, is more-strongly layered with low-conductivity units. To represent this north–south difference, the entire NAS within the CEDARE (2001) Post-Nubian boundary extended for the current larger model (as shown in Fig. 1) is designated as the northern zone with its own values of parameters that are constant from top to bottom of the entire aquifer (including deep Nubian and shallower Post-Nubian sediments). The southern zone remains representative of the Nubian sandstone sequence with its own parameter values. Presumably, if the layering is truly stronger in the north and hydraulic data support its effect, the vertical anisotropy of this zone will calibrate at a higher value than the southern zone. Thus, one possible two-zone model was defined (Fig. 8).

Two-zone model fits to Holocene water-level decline

For this two-zone model, Holocene water-level decline was evaluated by simulating 10 ka of head decline beginning with pluvial (full aquifer) conditions. Regarding the objective for the one-zone model that simulated water level should be at ground surface only where current oases and sabkhas exist and below ground everywhere else, it was assumed for the two-zone model that values of hydraulic diffusivity and vertical anisotropy ratios for each zone should fit within the maximum feasible ranges determined for the one-zone model; thus, this step was not repeated. Calibration was achieved by matching simulated hydraulic heads after 10 ka against the measured predevelopment heads in 1960. For these calibrations, values of (Kh/Sse) and (Kh/Kv) were automatically estimated for each zone

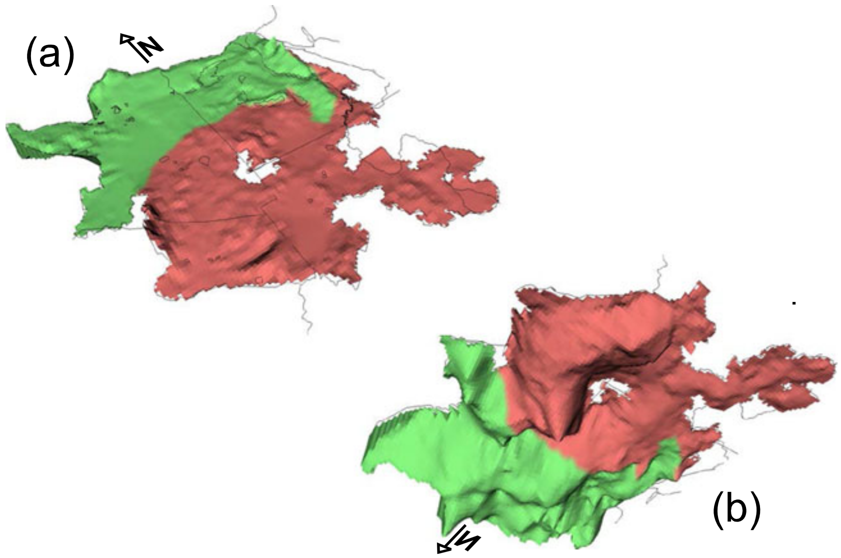

Fig. 8 Two-zone 3D NAS model; views from southwest are from above the model **a** and from below the model **b**. North zone is shown in *green* and south zone is shown in *red*. Each zone has its own set of aquifer parameter values that are spatially constant within each zone. Zone volumes are vertical extrusions through the model from the Post-Nubian/Nubian and Nubian zones shown in Fig. 1c

using the MODFLOW-2000 calibration utility. As for the one-zone model, several different fits were obtained, depending on the subset of 1960 hydraulic heads selected. The same subsets used for the one-zone model were used for the two-zone model (see ESM). Two subsets were selected in an attempt to enhance the information provided for estimating possible vertical anisotropy differences between zones. This involved selecting pairs of nearby observations at two depths in the north zone to provide vertical head differences to the automatic estimation process.

One estimation used all non-duplicated 1960 heads (the head data provided had much duplication) reported by CEDARE (2001) resulting in no significant difference between north and south zone parameter values. A second set used a subset of the latter in the form of pairs of Nubian and Post-Nubian 1960 heads at the same location but at different depths, to allow better estimation of vertical hydraulic conductivity in the northern zone. This provided a difference in zone parameters:

$$\begin{aligned}&\mathrm{North}:\mathrm{Kh/Kv}=2661,\ \mathrm{Kh/Sse}=1.07\times10^{-2}\mathrm{m^2/s}\\&\mathrm{South}:\mathrm{Kh/Kv}=1012,\ \mathrm{Kh/Sse}=1.11\times10^{-1}\mathrm{m^2/s}\end{aligned}$$

A third selection of observations used the already mentioned paired 1960 heads, plus all available (non-duplicated) values except those deemed to be in error due to unusual values of 1960 head above or below the local topography. The parameter values for this result:

$$\begin{aligned}&\mathrm{North}:\mathrm{Kh/Kv}=14330,\ \mathrm{Kh/Sse}=1.18\times10^{-1}\mathrm{m^2/s}\\&\mathrm{South}:\mathrm{Kh/Kv}=937.2,\ \ \mathrm{Kh/Sse}=5.26\times10^{-2}\mathrm{m^2/s}\end{aligned}$$

are shown in Fig. 7. This result is considered the best possible fit using the 1960 data. The assumption that the north zone has greater vertical anisotropy (layering) than the south zone is borne out; it is about 15 times more anisotropic. The latter inverse was re-simulated using a 5 ka time from the previous pluvial (see ESM). The result was that estimated Kh/Sse values were exactly doubled, as expected from an understanding of groundwater-flow mathematics.

Two-zone model fits to post-development period

Next, post-development water-level decline was evaluated by simulating 1960–1998 pumping with the objective of matching simulated drawdowns in the three pumping centers with 1998 drawdown data. Values of the four individual parameters were constrained to give the values of the two controlling parameters, determined from long-term water-level decline data. Good fits of drawdown were obtained for all three areas, Kufra, Sarir (north, west and south) and Kharga, with the following values of the four parameters that control drawdown in each zone:

North

$$
\begin{aligned}
&\text{controlling parameters:}\\
&\mathrm{Kh/Kv} = 14330\\
&\mathrm{Kh/Sse} = 1.18 \times 10^{-1}\ \mathrm{m^2/s}\\
&\qquad \mathrm{Kh} = 1.5 \times 10^{-5}\ \mathrm{m/s}\\
&\qquad \mathrm{Kv} = 1.05 \times 10^{-9}\ \mathrm{m/s}\\
&\qquad \mathrm{Sy} = 0.005,\ \mathrm{Ss} = 1.2 \times 10^{-4}\ 1/\mathrm{m}\\
&\qquad\quad \text{giving}\\
&\qquad\quad \mathrm{S} = 0.125\\
&\qquad\quad \mathrm{Sse} = 1.25 \times 10^{-4}\ 1/\mathrm{m}\\
&\qquad \left(\text{assuming} \sim 10^3 \mathrm{m}\ \text{thickness of the aquifer}\right)
\end{aligned}
$$

South

$$
\begin{aligned}
&\text{controlling parameters:}\\
&\mathrm{Kh/Kv} = 937.2\\
&\mathrm{Kh/Sse} = 5.26 \times 10^{-2}\ \mathrm{m^2/s}\\
&\qquad \mathrm{Kh} = 2.2 \times 10^{-5}\ \mathrm{m/s}\\
&\qquad \mathrm{Kv} = 2.35 \times 10^{-8}\ \mathrm{m/s}\\
&\qquad \mathrm{Sy} = 0.365\\
&\qquad \mathrm{Ss} = 5.0 \times 10^{-5}\ 1/\mathrm{m}\\
&\qquad\quad \text{giving}\\
&\qquad\quad \mathrm{S} = 0.415\\
&\qquad\quad \mathrm{Sse} = 4.15 \times 10^{-4} 1/\mathrm{m}\\
&\qquad \left(\text{assuming} \sim 10^3 \mathrm{m}\ \text{thickness of the aquifer}\right)
\end{aligned}
$$

Assessment of two-zone parameter values

The most reliable value-fitted aquifer-storage value is the effective specific storage, based on water-table decline during the past 10 ka. For the fitting process, given data at only three sites where NAS is very thick and pumping is relatively deep, apportioning this total between compressive (Ss) and water-table (Sy) storage can be difficult. Where short-term drawdowns are isolated from the water table (because well screens are deep and vertical hydraulic conductivity is relatively low), estimation of specific yield is not possible, because drawdown is not sensitive to its value. For the two north-zone sites with local drawdown data, Kharga and Sarir, drawdown does not reach the water table and so the fitted value reported here is arbitrary. In these locations and in thinner parts of NAS (e.g. in Sudan), fitting of Sy could be improved if hydraulic tests on wells screened near the water table were carried out. For Kufra in the south zone, drawdown reaches the water table (cf. modeled drawdown at this site in Fig. 11a), and it is possible to estimate specific yield. A comparison of fitted values with results of field tests at a few pumping centers in NAS shows values generally in agreement (see Figure 8 of the ESM).

The meaning of this result is as follows: With the fitted values for the two zones, the NAS model is able to reproduce the presumed water-table decline over 10 ka (considering both oasis locations and 1960 measured heads) and the 1960–1998 drawdown in three pumping centers. This two-zone model is thus sufficient to represent all available data. No additional zones or complexities are required in the model to allow it to represent long-term or short-term responses of NAS hydraulic heads to natural stresses and to pumping. This two-zone model with the parameter values listed previously is considered the best-fitting “base model” for NAS.

Two-zone model fitting to age

Ages interpreted from ^{81}Kr and ^{14}C isotope data were used as a manual calibration target in the two-zone base model. For travel time, the porosity is an additional controlling parameter. The porosity parameter does not affect hydraulic heads so did not need to be considered earlier in the analysis. Porosity can therefore be estimated independently of parameters that control hydraulic head, which are already estimated for the two-zone model. The approach used was to keep the two-zone model with its parameter values constant and a single value of NAS porosity was sought that allows the simulated ages comparable to the isotope-interpreted ages. Should a single porosity value for the entire NAS not suffice, additional zonation of porosity might be required. The following procedure was used to calibrate the porosity value:

1. Simulate groundwater flow with MODFLOW for 3 Ma, with glaciations and interglacial periods. The typical climate evolution in the Nubian area for the past 1 Ma consists of 10 cycles per 1 Ma; one climate cycle includes a 50-ka pluvial period and a 50-ka arid period (see Figure 9 of the ESM).
2. From the specific well locations and screen intervals in Egypt used by Sturchio et al. (2004) and IAEA (P. Aggarwal, IAEA, personal communication, 2009 for ^{14}C) (see Fig. 9), use MODPATH to *backward track* flow paths from these well screens for the 3-Ma MODFLOW simulation. Backward tracking determines the full flowpath from the point of recharge to the point specified as an end point for the tracking. This provides ages of groundwater that discharge under present-day conditions at the Egyptian oases and Sudan discharge areas for a selected porosity value.
3. Compare simulated ages at all measurement locations with isotope-interpreted ages. If simulated ages do not fit, adjust the porosity value appropriately and make another 3 Ma simulation. Repeat until all simulated and interpreted ages match, or until all plausible porosity values have been tested and no single value allows all (or most) ages to match. This is an approximate manual calibration process. Many flow paths converge to the screen interval at the sampled locations and each flow path has a different travel time from its initial recharge point. The mean and median and standard deviation of travel times for all flowpaths arriving at the screened interval of a well were calculated (for details, see ESM) to obtain

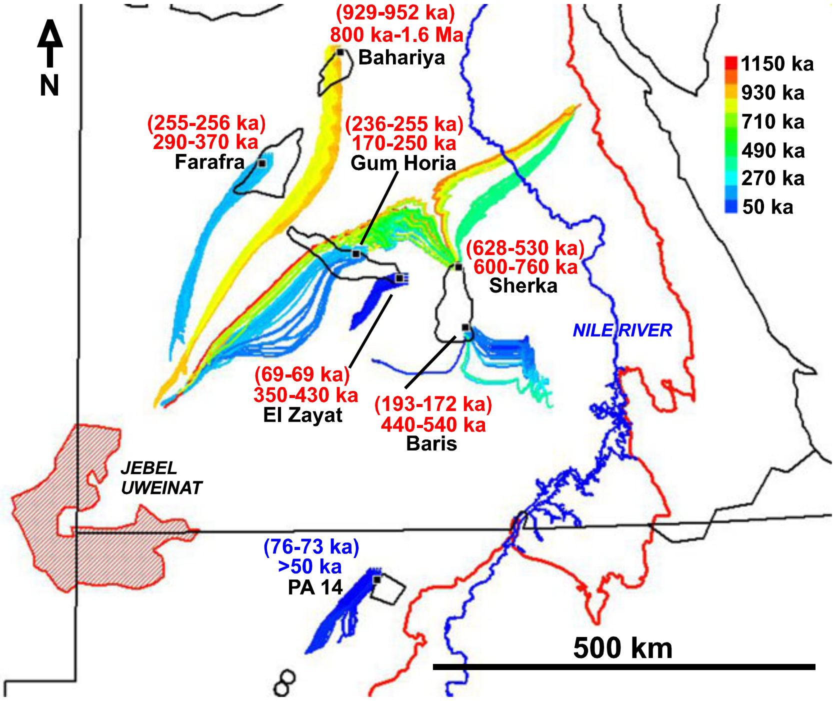

Fig. 9 Simulated 3D flowpaths to isotope sampling locations in the best-fit two-zone base model of NAS. Flowpaths illustrated are those captured at well screens where water samples for isotope analysis were collected. Flowpaths are tracked backwards to their recharge location from their ending location in the sampled well screens for a transient simulation period of 3 Ma with 100-ka glacial cycles. Isotope-interpreted ages and NAS groundwater model simulated ages are compared. Age ranges were interpreted from isotope samples analyzed for ^{81}Kr and ^{36}Cl in Egypt (by Sturchio et al. 2004) (*labeled in red*) and for ^{14}C in Sudan (P. Aggarwal, IAEA, personal communication, 2009) (*labeled in blue*). Small *black squares* indicate well locations. Simulated age ranges are given in *parentheses* indicating (mean–median) travel time from recharge point to capture point of all flowpaths captured in modeled well interval. These simulated age ranges are obtained with a uniform porosity value (0.35) throughout NAS. NAS boundary shown as a *red line*

the modeled age range that would be compared with the interpreted range of ages from Sturchio et al. (2004) and the ^{14}C interpreted age provided by IAEA.

Results of two-zone model age fitting

The result of the manual fitting is that the ages of groundwater interpreted in Egypt (except El Zayat, see discussion in ESM) and Sudan can all be approximately matched by using a single porosity value for the entire NAS as follows:

Porosity = 0.35

Flow lines for the water captured in the age samples and resulting modeled age ranges that match the interpreted age ranges are shown in Fig. 9. The quantitative fits and related data are given in Table 1. Screened intervals used in the modeling (for details, see ESM) are given in Table 1. Locations of sampled wells are also shown in Fig. 9.

Simulated flowpaths to the sampling regions (Fig. 9) are not simple. Some sampling regions collect simulated flowpaths that all were recharged in one relatively small-limited area (e.g. Bahariya, Farafra). Others collect flowpaths from disparate (e.g. Sherka, north Kharga) or irregularly shaped (e.g. PA14, Sudan) recharge areas. Large standard deviation of the ages collected at a sampling point can be indicative of multi-modal simulated age distributions such as for Sherka. Interpreting ages of samples that mix waters from different recharge areas is not straightforward and this difficulty is superposed on that caused by the range of ages of flowpaths arriving even from small-limited recharge areas. Future work might consider evaluating the sensitivity of the fitted NAS porosity value to various measures of simulated age (other than mean and median of flowpaths collected in a sampling region), and the sensitivity of groundwater age predictions when porosity is varied (much as the sensitivity of NAS drawdown was evaluated by varying other controlling parameter values).

Not only flow velocities, but also actual flowpaths depend on the porosity value because the points of discharge to which groundwater flows changes with time as the water table drops (see ESM). The effect of oscillating heads and changing patterns of discharge areas can be observed in the flowpaths of Fig. 9. Regular undulations can be seen in the flowpath patterns and some paths change direction more drastically, sometimes in an apparently erratic manner. This behavior confirms the need for an individual simulation for each porosity value tested (i.e. age does not scale with porosity). Some paths travel smoothly toward a unique discharge area, not vacillating between different areas; this likely occurs when the discharge

Table 1 Interpreted isotope ages and modeled ages

Location	Interpreted ^{81}Kr Age	Interpreted ^{14}C Age	Mean–median simulated age	Simulated paths: number and (standard deviation) of simulated age	Sampling interval (depths below land surface)
Bahariya (Egypt)	800 ka–1.6 Ma	–	929–952 ka	80 (42) ka	1,100–1,200 m
Farafra (Egypt)	290–370 ka	–	255–256 ka	112 (10) ka	600–800 m
Gum Horia (Dakhla, Egypt)	170–250 ka	–	236–255 ka	80 (34) ka	1,100–1,200 m
El Zayat (Dakhla, Egypt)	350–430 ka	–	69.4–68.8 ka	112 (7) ka	620–720 m
Sherka (North Kharga, Egypt)	600–760 ka	–	628–530 ka	96 (231) ka	650–750 m
Baris (South Kharga, Egypt)	440–540 ka	–	193–172 ka	64 (79) ka	500–600 m
PA14(DW2) (Sudan)	–	> 50 ka	75.7–73.1 ka	192 (14) ka	100–200 m

area prevails and is the dominant water outlet in the region, despite climatic fluctuations.

Age of groundwater at the Sudan location, PA14 (DW2), estimated from a ^{14}C value of about 1 % modern carbon (pmC), indicates waters older than 50 ka (P. Aggarwal, IAEA, personal communication, 2009); referring to data stored in IAEA RAF/08/036, NAS, Sudan). This is not contradicted by simulated age of about 75 ka (Fig. 9; Table 1).

The meaning of this result is as follows: With a single value of porosity for the entire NAS (both north and south zones), a reasonable fit of groundwater travel time to interpreted ages is obtained with no other changes required to the model zonation or parameter values. The calibrated value of porosity therefore becomes part of the 'base model' of NAS. (Note that the porosity value is truly determined only in the region through which the flowpaths of sampled waters passed, roughly the northeast quadrant of NAS.) The calibrated value of effective porosity that allowed matching of ages is plausible for the NAS geologic fabric. The porosity parameter does not affect the water levels in the aquifer, so this value is not important for prediction of long-term water-level decline or drawdown.

Model-based forecasts

The two-zone NAS model, the 'base model', fits all available data sufficiently well with nine fitted parameter values and, with its sensitivity analysis to variations in parameter values, describes the large-scale long-term response of NAS to changes in climate and the local-scale short-term responses to pumping. The model also provides some insight into the large-scale groundwater flow pattern that may occur in NAS. The base model is used here for forecasting impacts of future pumping. There are three major questions regarding impacts of existing and future ground-water development in the NAS: (1) What are the future lateral expansions of drawdown cones generated by development centers? Will these extend across national boundaries? (2) What are the maximum future drawdowns within these development areas at the depth of the well screens? Greater local drawdown implies higher pumping costs, and eventually drawdown may increase to the extent that pumping becomes economically infeasible; (3) What are the future water table drawdowns in these development areas? Dropping water tables may imply severe environmental impacts should springs and oases dry and disappear. Where the aquifer is relatively thin, large drops in the water table may imply insufficient groundwater availability, or equivalently, over-pumping the local resource.

Two-zone model flow field

Figure 10 shows all flowpaths for the entire NAS using base model parameter values (up to 3-Ma travel time) to groundwater at the top of the aquifer, from the recharge point to the discharge point. Interpreted predominant deep NAS regional groundwater bodies are delineated in this image. The water within each body defined by continuous lines in Fig. 10 all derives from a single spatially contiguous recharge area. Each body may have a distinct geochemical-isotopic signature, at least for some species, deriving from differences in recharge situation and geology-geochemistry encountered along flowpaths. Some of the groundwater bodies meet in mid-aquifer. For example, in southern Libya and northern Chad, modeled groundwater flowpaths converge from high-elevation former recharge areas in the east and west along a roughly northeast trending line in mid-aquifer. At some discharge areas (e.g. sabkhas and Qattara Depression in north, Kufra oases in Libya, Kharga and Dakhla oases in Egypt), waters from different groundwater bodies converge, giving the possibility of wide differences in geochemical-isotopic signature within a small sampling area. Local hydrogeologic structural details would control where each water type discharges within the discharge area; the current homogeneous model gives only the general pattern that might be expected. Dotted *pink lines* in Fig. 10 divide the groundwater bodies into sub-bodies that have different discharge areas. The dotted lines indicate where groundwater from the same historical recharge area has different discharge regions; thus, some similarity in geochemical-isotopic signature might be expected in waters discharging at widely separated discharge areas. (Other visualizations of flow fields are shown in Figure 10 of the ESM.) There are several smaller-scale shallower groundwater bodies that are apparent in the 3D flow field (e.g. surrounding some oases in Egypt), but these have not been delineated in Fig. 10. The shortest flowpaths (shown in black) recharge and discharge within one simulated pluvial period of 50 ka. These are generally the shortest flowpaths in NAS and these are shallow (see Figure 10d of the ESM).

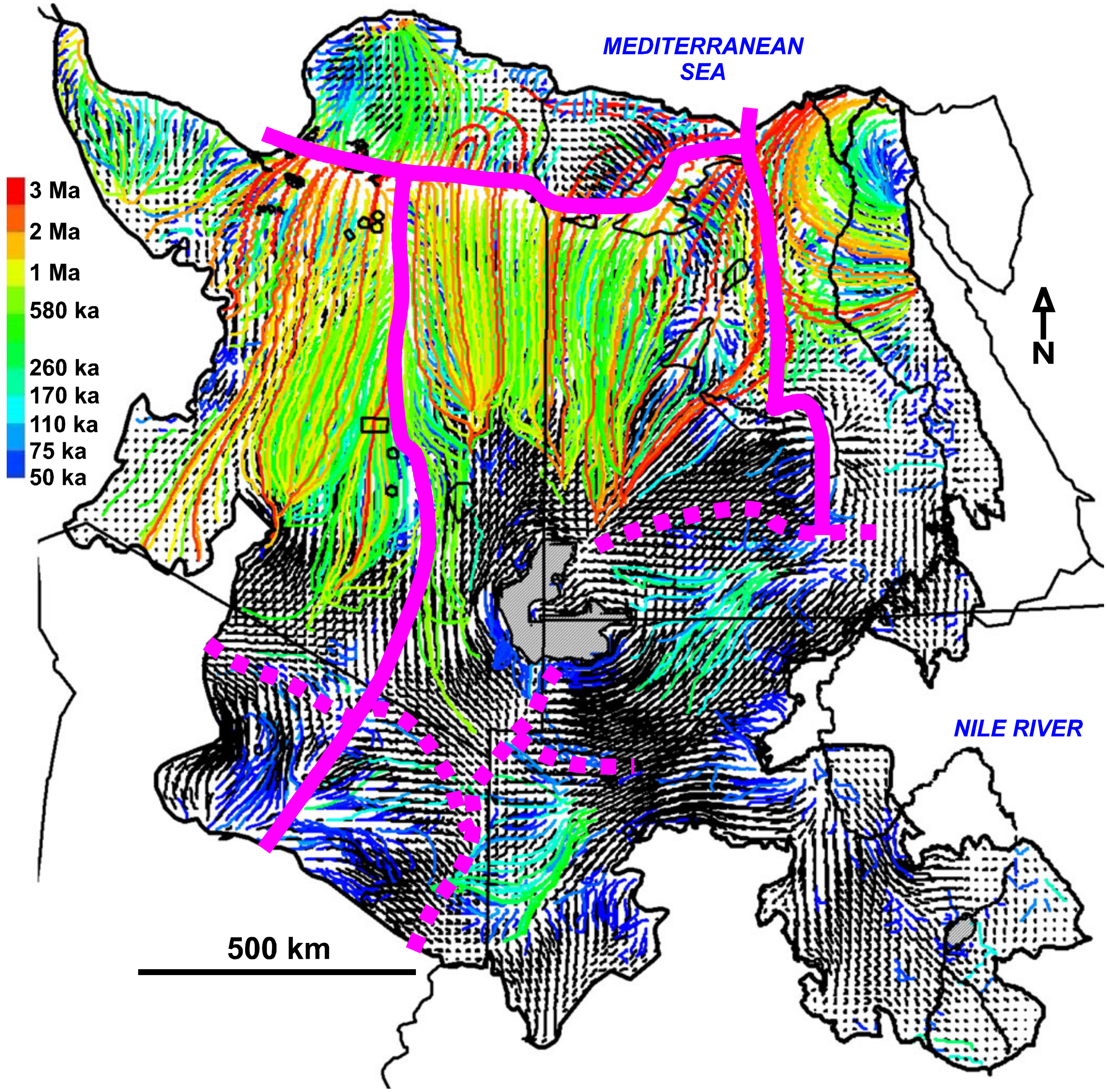

Fig. 10 Groundwater flowpaths and interpreted deep groundwater bodies in the two-zone NAS base model. Map view of 3D flowpaths where rainbow coloring illustrates travel time from point of recharge to discharge at top of aquifer (*color legend* shows travel time). *Black flowpaths* have travel time of less than 50 ka. Flowpaths are tracked backwards to their recharge location from their ending location on the aquifer top (one path for each model grid cell on aquifer top) for a transient simulation period of 3 Ma with 100-ka glacial cycles. The shortest *black lines* have travel time of less than 50 ka, recharging and discharging within each 50-ka pluvial period. The *red lines* have travel times of 3 Ma, and some of these have not reached their recharge points by the end of the 3-Ma simulation. NAS groundwater bodies are interpreted primarily using longer flowpaths. The *thick continuous pink lines* indicate locations to which flow converges from different recharge areas. *Thick dotted pink lines* indicate areas of flow divergence from the same recharge area; these separate waters that travel to disparate discharge areas—see Figure 10 of the ESM for more details on flow field

Drawdown forecasts to 2060

Pumping was simulated from 1960 to 2060 in the base model. In this 'scenario 0' simulation, pumping occurs only at development sites already in operation in 2009 (annual discharge rates applied from 1960 to 2060 are tabulated in Table 2 of the ESM). The base model forecast for total drawdown in 2060 from 1960 predevelopment conditions is shown in Fig. 11a. This is an aerial view of 3D drawdown, for values 1 m and greater, displayed as a solid 3D region in which colors represent the drawdown values. The highest drawdown in each development area occurs at the depth of the well screens, so cannot be seen in this image type. A surface of 1 m drawdown (shown in dark blue) envelops each drawdown region, hiding the interior, unless the

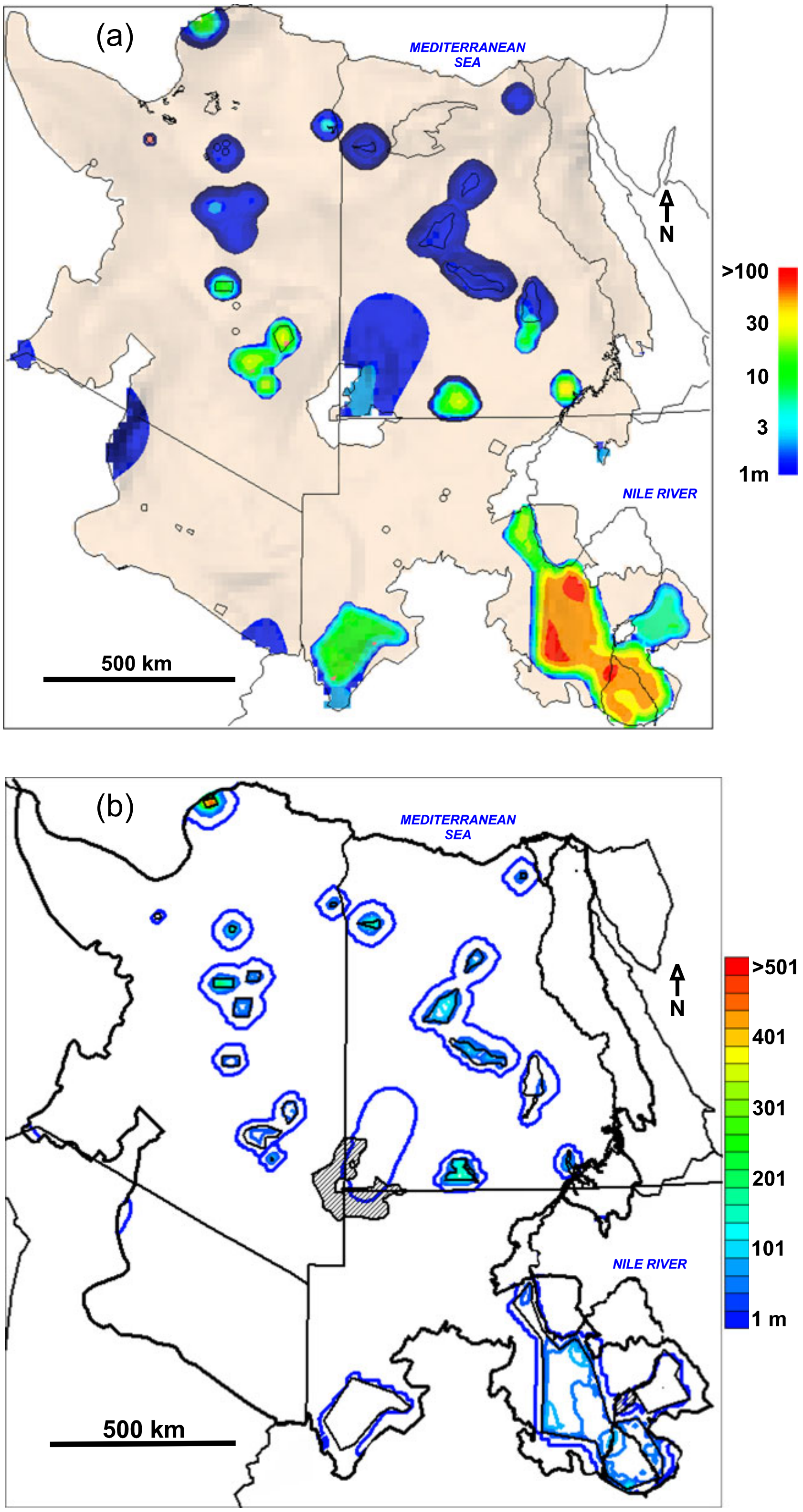

Fig. 11 Drawdown in 2060 from 1960 predevelopment conditions (forecast with two-zone base model) for currently planned extraction rates. **a** 3D drawdown viewed from above showing 3D volumetric regions of drawdown enclosed by a minimum value of 1 m. Colors range from 1 to 100 m, with drawdowns greater than 100 m colored *red* (maximum modeled drawdown is 464 m). Where the drawdown volume reaches the aquifer top, higher drawdowns within the drawdown volumes are visible. Highest drawdowns are centered within each 3D drawdown volume, and are not visible in this image. **b** Maximum simulated 2060 drawdown among all depths in NAS. Drawdown scale in m

drawdown reaches the ground surface, in which case higher drawdown values are visible (as other colors) where they intersect the ground surface. Where the 3D region surrounding a pumping area does not reach the surface, drawdown is forecast to be less than 1 m at the ground surface.

Forecast 2060 drawdown of more than 1 m generally does not cross national boundaries from development areas. Between Libya and Egypt (Jaghbub and Siwa), drawdowns between 1 and 2 m are forecast to cross the border in both directions, and at the Egypt-Sudan border south of East Oweinat, forecast drawdown is between 1 and 2 m crossing the border. In both areas, the predicted drawdown intrusion distance across the border is small compared with NAS scale. Drawdown at the aquifer top is discussed later.

Figure 11b shows maximum simulated drawdown among all depths at each map location. Forecast maximum drawdowns for some areas are reported in Table 2, which also lists maximum drawdown as a percentage of total aquifer thickness at locations where this value is forecast to be high. (The highest 2060 drawdown is forecast to reach 464 m, but this occurs at Jabal Akhdar, located against the closed northern model boundary, which exaggerates modeled drawdown.) Drawdown at well screen depths may be much higher than at the water table and because aquifer dewatering requires drawdown to reach the water table, the listed percentages should only be considered as indicative of potential dewatering problems.

Higher-elevation areas near Uweinat Mountain, Egypt, and Tibesti mountains, Chad, are forecast to experience drawdown; although no pumping is applied in those areas, continuing water-level decreases result from natural flow and discharge. Water-level declines are forecast to be on the order of 1–2 m in these areas between 1960 and 2060, but due to the model assumption of a constant-thickness aquifer, the magnitude of this drop is not a strong forecast.

Table 2 Simulated maximum drawdown among all depths (from 1960 predevelopment conditions) for selected development areas, for forecasts in 2060 (scenario 0) and 2110 (scenario 1 and scenarios 2 and 3). Drawdowns in m. Percentages are given for areas with excessive drawdown relative to aquifer thickness. The value gives the drawdown as a percentage of local NAS thickness. 50% means that drawdown equals half of local aquifer thickness, 100% means drawdown is projected to be equal to or greater than local aquifer thickness

Development area	2060 scenario 0	2110 scenario 1	2110 scenarios 2 and 3
Jabal Akhdar	464	538	921
Jalu	157	183	324
Sarir West	207	264	463
Siwa	178	210	356
Farafra	129	170	287
Dakhla	97	109	192
Kufra	52	69	114
Uwienat	84	110	193
Toshka	103 40%	152 60%	250 100%
East Oweinat	169 27%	237 36%	409 62%
Khartoum	95–140 50–100%	195–254 100%	309–411 100%

Sensitivity of drawdown forecasts to 2060

Drawdown is the most reliable model forecast; however, because this is a simply structured model calibrated to only few data, a sensitivity analysis is required to assess the range of forecast drawdowns that results from parameter value uncertainty. Extreme values of each of the four parameters for each of the two zones are selected and drawdown in 2060 is forecast using each combination. The two storage parameters are combined into a total storativity as described earlier, and so there are only three parameters for which extremes need to be tested. The extreme values selected for each zone in the two-zone model are: for Kh and Kv, five times higher and lower than the base model value, and, for Sse, two times higher and lower than the base model value. Equivalently, in terms of the two primary controlling parameters, the tested extreme values are, for hydraulic diffusivity Kh/Sse, 10 times higher and lower, and for vertical anisotropy Kh/Kv, 25 times higher and lower than base model values for each zone. (Tested values are compared with the region of values that allow the model to fit Holocene drawdown resulting in present-day oasis/sabkha locations in Figure 11 of the ESM). These ranges are arbitrarily selected, to demonstrate sensitivity of the model forecasts to the values of its parameters.

Considering simulated drawdown for all eight combinations of the three parameters, two drawdown extremes would cause practical management problems, high local drawdown and laterally extensive drawdown crossing borders. Maximum local drawdown is obtained for low values of Kh, Kv, and Sse. Maximum lateral extension of drawdown is obtained for high values of Kh and Kv, with a low value for Sse. The forecast 2060 drawdown distributions in NAS for these worst-case situations are shown in Fig. 12 and may be compared with the base model forecast (Fig. 11b). The extreme combinations give a truly wide range of extreme drawdowns; maximum drawdown exceeds 500 m in some areas, and maximum lateral extension exhibits significant drawdown crossing international borders (for details, see ESM). These wide ranges can be used in aquifer management to focus evaluation of unknowns and simplifications underlying model construction.

Drawdown forecasts to 2110

Using the base model, three future development scenarios are considered, and drawdown forecasts to 2110 are developed for each. These serve as examples of how the NAS model may be exercised to evaluate impacts of planned new development. These are not real plans provided by any NAS countries. *Scenario 1*: Pumping rates in all existing areas (assumed in drawdown forecast

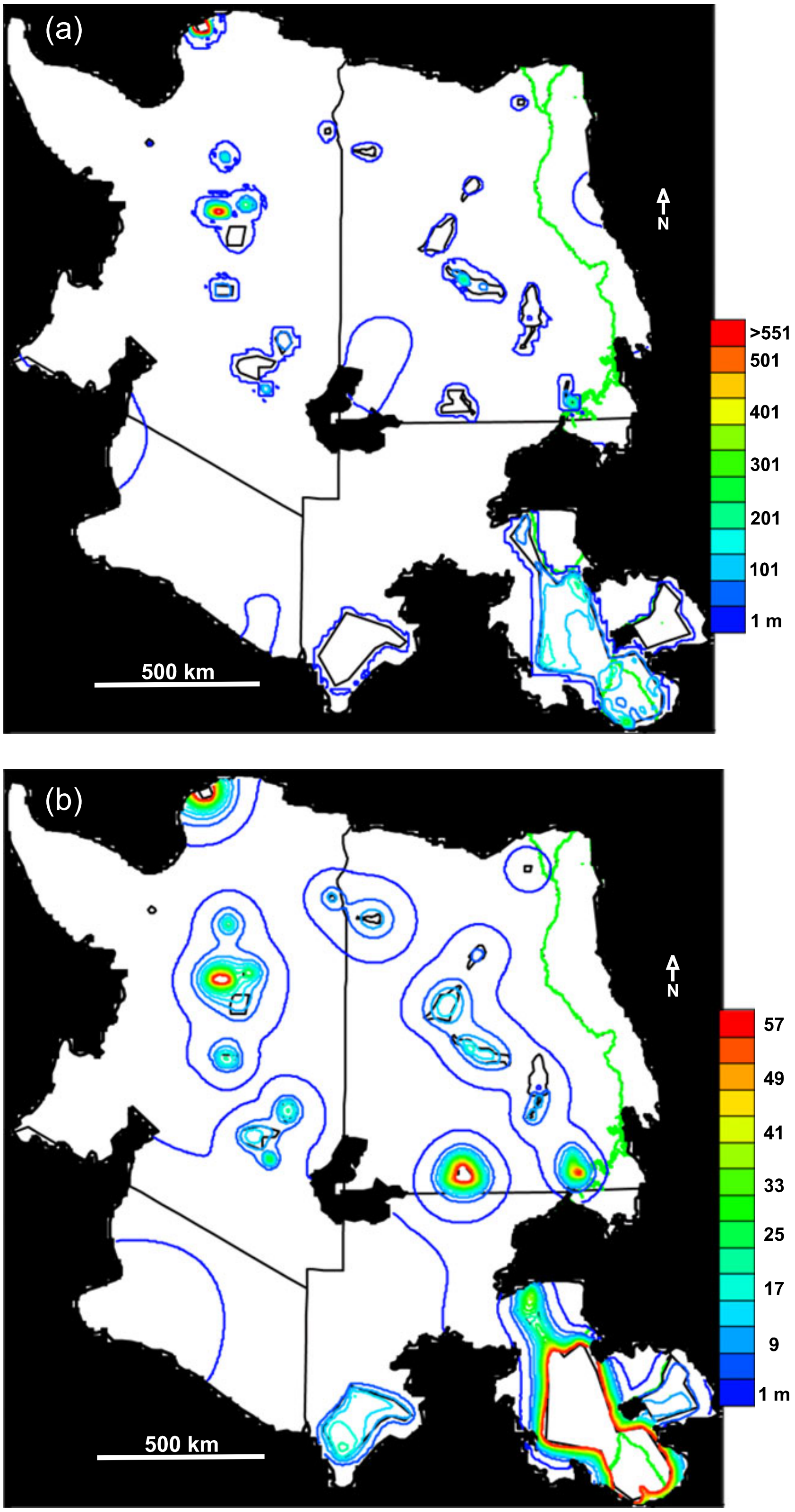

Fig. 12 Sensitivity of NAS base model forecasts to uncertainties in model parameter values. **a** Maximum 2060 drawdown magnitude for changes in controlling parameters that most increase modeled drawdown: 5 times lower for Kh and Kv and 2 times lower for Sse than two-zone base model values. Drawdown in m. Minimum value shown is 1 m. Nile River shown in *green*. **b** Maximum lateral extent of 2060 drawdown for changes in controlling parameters that most increase modeled lateral extent: 5 times higher for Kh and Kv and 2 times lower for Sse than two-zone base model values. Drawdown in m. Minimum value shown is 1 m. Nile River shown as a *green line*

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for 2010 to 2060, Fig. 2) are held constant at their 2060 rate from 2061 to 2110 and no new development areas are added. Drawdown in 2110 is shown in Fig. 13a,b. *Scenario 2*: Pumping rates in all existing areas are set to double their 2060 rate from 2061 to 2110 and no new development areas are added. Drawdown in 2110 is shown in Fig. 13c,d. *Scenario 3*: Pumping is applied as in scenario 2, but three new hypothetical development areas are added, gradually beginning pumping in 2010. Drawdown in 2110 is shown in Fig. 13e,f. The new areas are as follows: The hypothetical 'Oweinat Mirror' area is in Sudan, directly across the border from Egypt's East Oweinat area (see Fig. 2) maximizing drawdown along the border. A second 'Sahara' hypothetical area is in Sudan north of the true Sahara area. Both Sudan additional areas are assigned the shape of East Oweinat. Both areas are assigned the following pumping development: 2011–2020 5 m^3/s, 2021–2030 10 m^3/s, 2031–2040 20 m^3/s, 2041–2050 20 m^3/s, 2051–2060 20 m^3/s, 2061–2110 20 m^3/s. The hypothetical 'Southern Libya' area is in Libya, near the Libya-Chad border and with lateral area and extraction similar to that of Kufra-GMMR (Great Man Made River), to illustrate potential impact of new southern Libya pumping on groundwater levels below near-border oases in Chad. This area was arbitrarily assigned the following pumping development: 2011–2020 0 m^3/s, 2021–2030 2 m^3/s, 2031–2040 5 m^3/s, 2041–2050 8 m^3/s, 2051–2060 10 m^3/s, 2061–2110 20 m^3/s.

Scenario 1 (continued 2060 pumping) drawdowns in 2110 (Fig. 13a) are forecast to spread laterally and to be greater than in 2060 (Fig. 11a). Transboundary drawdown is still of quite limited extent spatially, but 2110 water-table drawdown at the Egypt-Libya and Egypt-Sudan borders is forecast to increase to about 10 m. Figure 13b shows maximum drawdown for all depths at each lateral location (some forecast maximum drawdowns are reported in Table 2). Drawdowns in the Khartoum valley of Sudan increase to more than 100 m with a 250 m maximum. Forecast local maximum drawdown in 2110 at East Oweinat, Siwa and Sarir West exceeds 200 m, and at Toshka, Farafra and Jalu exceeds 150 m.

Scenario 2 (doubled pumping after 2060) results in a lateral extent of the 1 m drawdown envelope (Fig. 13c) not visibly greater than for scenario 1, but local maximum 2110 drawdown is much greater in the groundwater development areas (Fig. 13d; Table 2), exceeding 400 m at East Oweinat and Sarir West, 300 m at Siwa and Jalu, and is nearly 200 m or more at Toshka, Farafra, Dakhla, and Uweinat. In the Khartoum area, maximum forecast drawdowns are widely as great as 300–400 m. The modeled aquifer thickness here is less than 250 m, so the drawdown result indicates that the applied pumping rates are not sustainable. Thus, in the 50-year time frame considered (2060–2110), the primary impact of doubling pumping is a significant increase in local drawdown within each area. Moreover, significant water-table declines in 2110 of tens to more than 100 m are forecast for Jaghbub, Sarir West, Tazerbo, Kufra, Kufra GMMR, Uweinat, Darb al Arbain, Toshka, East Oweinat Khartoum and Sahara.

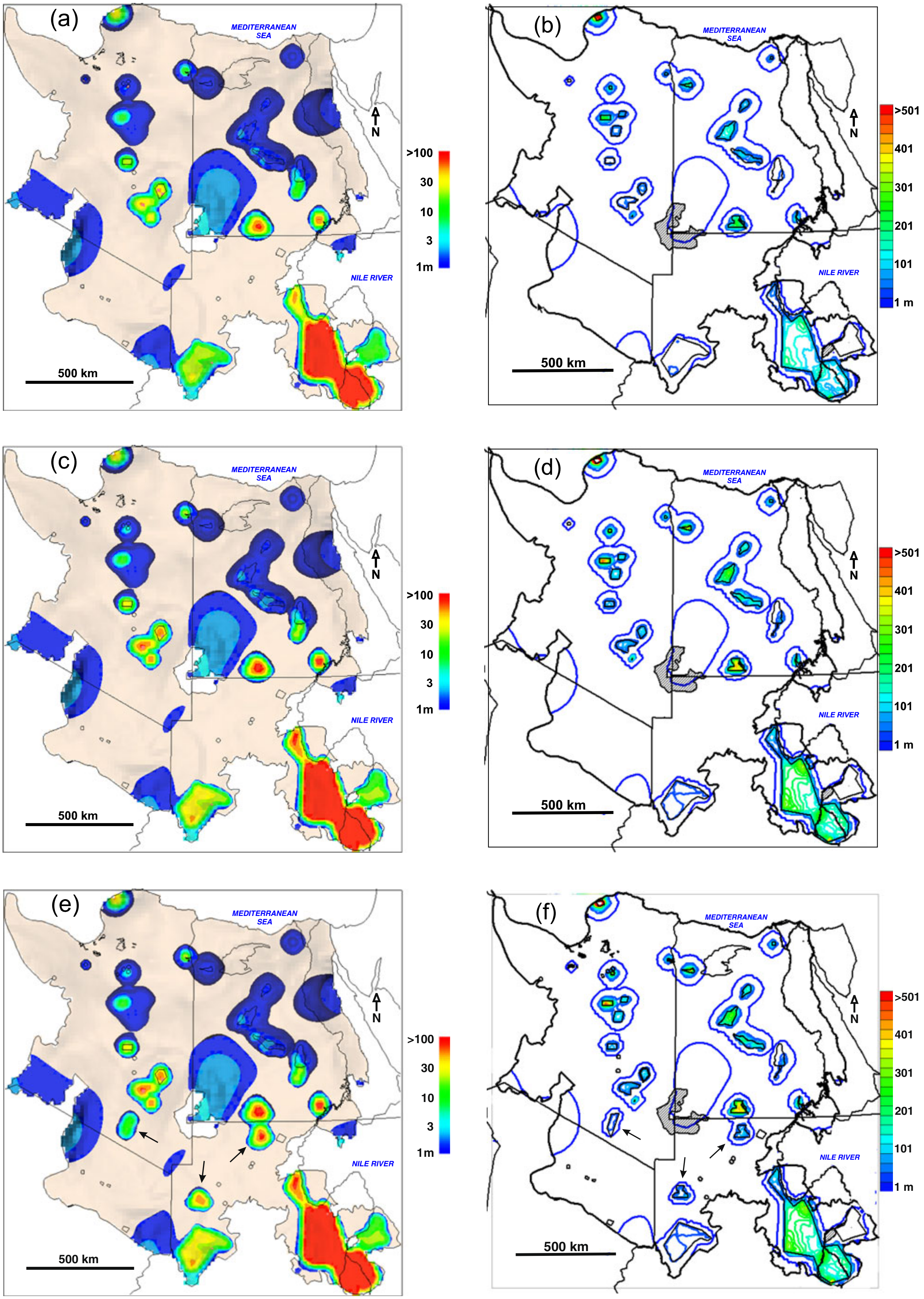
Scenario 3 (doubled pumping after 2060 plus hypothetical new areas) drawdowns in 2110 are forecast to be exactly the same as for scenario 2, with the addition of a new disconnected area of drawdown at each new area (Fig. 13e and f). This indicates that the predominance of groundwater pumped at each new area comes from local drawdown alone—not from other more-distant areas. Drawdown from the 'Oweinat Mirror' area just reaches the Egypt-Sudan border, but does not significantly increase drawdowns there. There is no transboundary Libya-Chad drawdown from to the hypothetical 'Southern Libya' development area; thus, the Chad oases are forecast to be unaffected by such development in Libya. Similarly to scenario 2, high drawdown reaches the aquifer top (tens of meters in several areas, exceeding 100 m in some).

Hydrologic budget

The modeled total groundwater discharge for NAS over the past 10 ka is shown in Fig. 14a. This curve shows how natural discharge (through springs and evapotranspiration) decreases with time due to lowering groundwater levels. Also shown in Fig. 14a is a forecast of how natural discharge quantity would decrease in the future 10 ka, assuming there is no pumping. Immediately following the cessation of pluvial recharge (at −10 ka), natural discharge halved each 2–3 ka. In the future tens of thousands of years, natural discharge is predicted to halve each 10–12 ka, with the rate slowing even more thereafter. All discharge results in depletion of stored groundwater. The modeled water balance (hydrologic budget) for NAS over the past and future 10 ka is shown in Fig. 14b. Pumping has an immediate impact on the budget, but results in only minor decrease in overall discharge, as most water pumped comes from loss of storage due to local drawdown. Total natural NAS discharge is forecast to decrease only about 7 % from 1960 to 2060 (approx. 86 m^3/s in 1960 to 80 m^3/s in 2060). The pumping rate surpassed the natural discharge rate in roughly the year 2000. Despite the minor impact of pumping on the overall natural discharge rate, pumping may strongly decrease local discharge rates within development areas, impacting the fate and existence of oases, as discussed in the following.

Loss of oases

Loss of oases is a natural process during an extended arid period in the NAS region. Groundwater levels drop causing decreased area of contact of the water table with the ground surface and groundwater discharge areas decrease. This process is accelerated wherever pumping causes the water table to drop below the ground surface. Because most NAS development areas are co-located with groundwater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◀**Fig. 13** Drawdown in 2110 from 1960 predevelopment conditions (forecast with base model) for three development scenarios. Drawdown scale in m. For **a**, **c** and **e**, 3D drawdown is viewed from above showing 3D volumetric regions of drawdown enclosed by a minimum value of 1 m. Colors range from 1 to 100 m, with drawdowns greater than 100 m colored *red*. Highest drawdowns are centered within each 3D drawdown volume, and are not visible in these images. Where the drawdown volume reaches the aquifer top, some higher drawdowns are visible. For **b**, **d** and **f**, maximum drawdown among all depths is plotted. **a** 3D drawdown for scenario 1 (2060 pumping rates continue after 2060 in currently existing areas). Maximum modeled drawdown is 538 m. **b** Scenario 1, maximum 2110 drawdown among all depths in NAS. **c** 3D drawdown for scenario 2 (double 2060 pumping rates after 2060 in currently existing areas). Maximum modeled drawdown is 920 m. **d** Scenario 2, maximum 2110 drawdown among all depths in NAS. **e** 3D drawdown for scenario 3 (double 2060 pumping rates after 2060 in currently existing areas plus three hypothetical new areas indicated by *arrows*). Maximum modeled drawdown is 920 m. **f** Scenario 3, maximum 2110 drawdown among all depths in NAS

discharge areas (costs of drilling to groundwater and lift costs during pumping are minimized where the water table is shallow), there will likely be adverse impacts on the sustainability of natural groundwater discharge in these areas, threatening the existence of some oases. Figure 15 shows drawdown at the water table in 2060 and 2110, for scenario 1. Widespread impacts are forecast by modeling; where drawdown reaches the ground surface, oases will be decreased in area or lost. For scenario 1, by 2060, water-table elevations below oases co-located with Bahariya, Farafra, and Dakhla in Egypt are forecast to drop between 0.5 and 5 m, while Jaghbub, Tazerbo, and south Kharga (due to Darb Al Arbain pumping) are forecast to undergo drops of at least 5 m, and the water table at East Oweinat in Egypt and Kufra in Libya are forecast to drop by more than

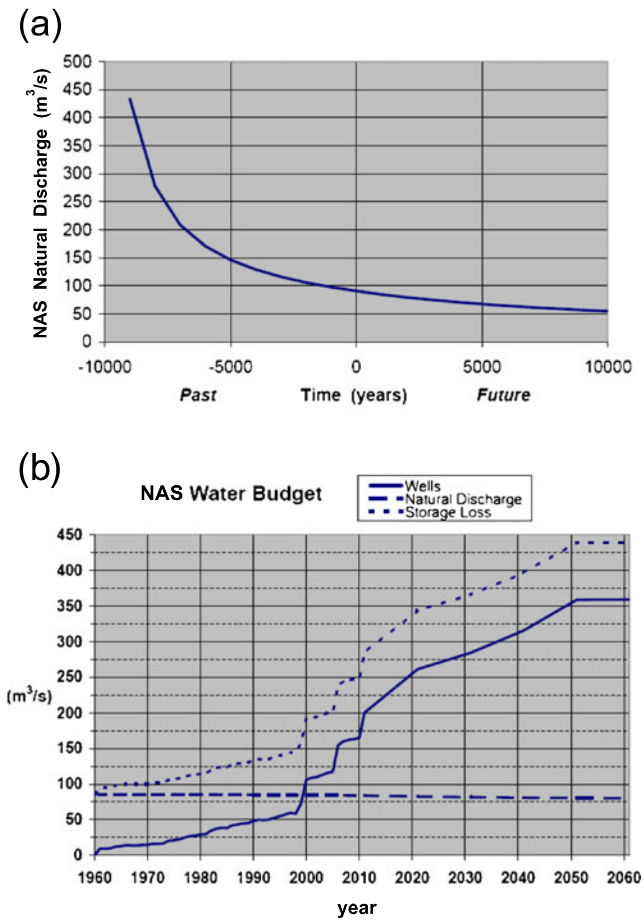


Fig. 14 Modeled NAS groundwater flux and budget. **a** NAS natural discharge evolution during Holocene (past and future 10 ka) as forecast by the two-zone base model. **b** NAS groundwater budget for 1960 to 2060. Natural discharge and loss of water from aquifer storage are forecast by the two-zone base model. Pumping rates are both historic and projected (as reported in Table 2 of the ESM)

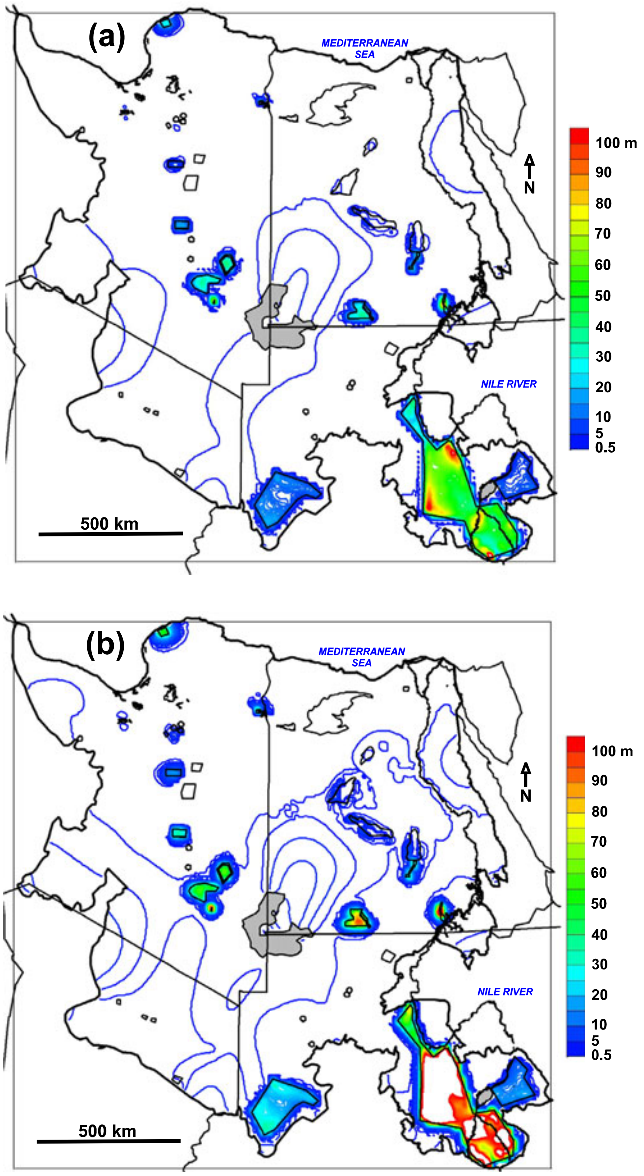


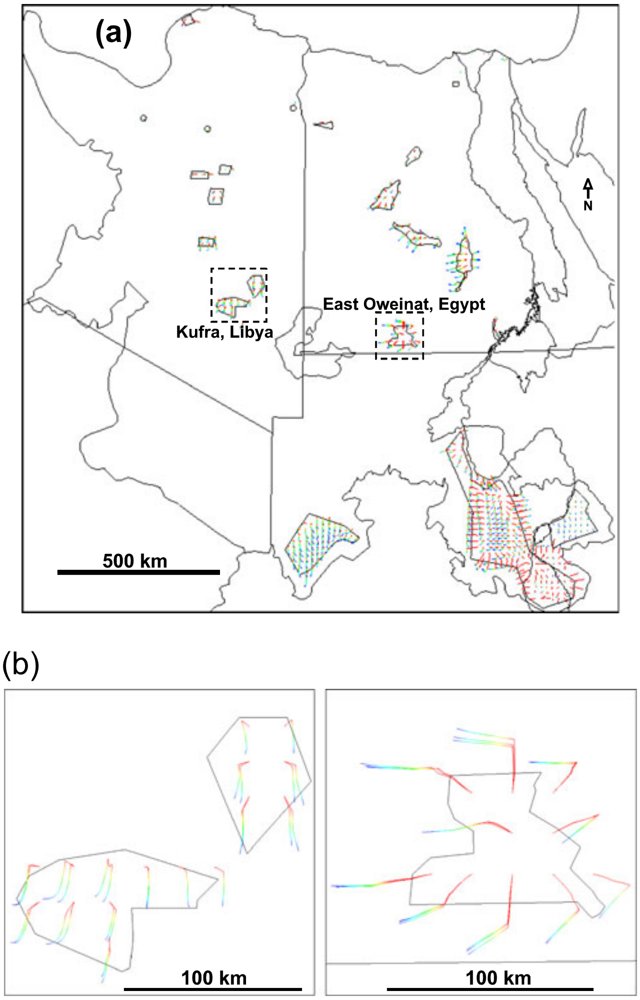
Fig. 15 Drawdown at the water table (top of aquifer) from 1960 predevelopment conditions (forecast with two-zone base model) for scenario 1 (continued 2060 pumping rates after 2060 in currently existing areas). Oases, sabkhas and water development areas are enclosed by *black lines*. Water-table drawdown scale in m, with contours every 0.5 m. **a** Drawdown at water table in 2060. **b** Drawdown at water table in 2110. Simulated drawdown in Sudan exceeds 240 m where *white area* is shown inside *red contours*

30 m. By 2110, water-table drops of more than 5 m are forecast at all oases co-located with pumping centers, with water-table drop forecast to reach 100 m at Kufra and East Oweinat. In a few oases, pumping is deep enough and vertical hydraulic conductivity is low enough, such that large drawdown is forecast to not reach the ground surface, thereby minimizing drainage. Due to the lack of modeled hydrogeologic detail within oasis-development areas, these forecasts should only be viewed as indicative of the general magnitude of water-table drop. However, a correct forecast of even a few meters of drop below the ground would result in loss of springs and oases. Thus, these results highlight a clear concern regarding viability of oases.

Capture zones

The source of groundwater pumped from each NAS development area can be determined by tracking its path backwards from each pumping center. The capture zone is a stationary subsurface volume, from which a well that pumps continuously takes water. The full capture zone extends from the well screen to the point in the aquifer where the groundwater was recharged. Partial capture zones are sub-portions of the full zone that represent water captured within a specified time after start of pumping. Figure 16 reveals partial capture zones for all NAS development areas by visualization of flow paths to wells. The first part of each path shows groundwater motion prior to pumping for the 10 ka predevelopment (pre-1960) period simulated with the base NAS model. Where paths begin, they are displayed with blue color. Pumping begins in 1960 and evolves through 2060 (according to Table 2 of the ESM); thereafter, pumping is held constant for 950 years. The paths end (red color) at the location of the groundwater in 3010, just before these parcels of groundwater are removed by the wells. Red parts of paths mark travel during the 1,000-year future period. The rest of each path (with colors other than red) shows where the groundwater that will be captured traveled in the 10,000 years before pumping began. The 1,000-year capture zones are the volumes between the point where the flowpaths turn abruptly when pumping begins toward the pumping areas (the red parts of the path lines) and the center of the pumping area. The earlier part of each flowpath (near blue end) shows the natural path of groundwater flow, prior to pumping for a 10 ka pre-pumping travel time. After pumping begins, the groundwater moves more quickly, in some areas, travelling as far in the 1,000-year pumping period as it travelled in the 10 ka predevelopment period.

The limited extent of flowpaths for all NAS development areas (and the need to examine 1,000 years of pumping to observe capture zones that are not trivially small) indicates that water removed by pumps is derived from local groundwater storage; water pumped in 1,000 years comes from a region equal to or at most roughly twice that of the development` area. The capture zone is laterally smaller where the aquifer is thicker, such as Kufra, and is laterally wider where the aquifer is thinner, such as East Oweinat (Fig. 16b).



Kufra, Libya　　East Oweinat, Egypt

Fig. 16 Partial groundwater capture zones for NAS development areas. Shows map view of 3D pathlines tracked backwards from each grid cell that is included in a pumping area. *Colors* illustrate travel time; paths shown begin at the location of the groundwater captured by the wells at a time 10 ka before 1960 (at the end where pathline color is *blue*). Pumping begins in 1960 and evolves through 2060 (according to Table 2 of the ESM). After 2060, pumping is held constant at 2060 levels for 950 years. The paths end (at the end where pathline color is *red*) at the location of the groundwater in 3010 (1,000 years from present). The *red* parts of the paths mark travel during the 1,000-year future period. **a** Paths for all development areas in NAS. *Dashed squares* show locations of areas enlarged in part **b**. **b** Map view of 3D flowpaths for Kufra and Kufra-GMMR, Libya (*left*) and for East Oweinat, Egypt (*right*). *Red* portions of flowpaths, following bend in flowpaths, occur during 1,000 years of pumping. Groundwater between the bend and the *red end* of the flowpath indicate the volume captured by pumping during 1,000 years

Discussion

Representativeness of two-zone NAS model

The objective in constructing the current model of the NAS was to create a quantitative representation of how hydraulic heads and groundwater flow in the aquifer respond to natural and human stresses over both long and short time frames and over the full regional spatial scale of the aquifer, while keeping the representation as simple as possible, not adding complexity beyond what is clearly justified by available hydrogeologic data. The practical approach to achieving this objective was to identify the fewest possible number of hydrogeologic parameters that control the long-term and short-term responses of the aquifer to stresses, then, find ranges of controlling parameter values that allow the modeled aquifer response to match the long- and short-term data, and identify parameter values that give the best fit to these data. The resulting simply structured model captures the main behavior (long- and short-term evolution of hydraulic head including response to climate change and pumping) of NAS.

The model requires only two spatial zones of parameter values, the north zone (the area within the Post-Nubian boundary) and the south zone (the area south of the Post-Nubian boundary). Within each zone, the values of all parameters are constant and no more complexity is required for the model to fit all available data. It might be argued that different zonations with two zones might also give similarly good fits to available data. This is possible and is the type of discussion that will help to improve future understanding of the system; such a discussion goes to the center of the question regarding non-uniqueness of groundwater models. The current zonation choice was based on the knowledge that vertical anisotropy in hydraulic conductivity is an important control on NAS behavior. This knowledge and the assumption that vertical anisotropy should be different for zones in which the stratigraphic sequence is significantly different (more-strongly stratified within the Post-Nubian boundary) provided motivation for this particular zonation. Indeed, the fitted values of vertical anisotropy in hydraulic conductivity are found to be greater in the north zone than in the south zone. It can be argued that, at the very least, this finding does not conflict with the motivation for the zoning choice.

Hydrogeological assessment of base model parameter values

The two-zone NAS base model has a relatively high degree of vertical anisotropy in hydraulic conductivity (about 10^4) and a relatively low value of specific yield (0.01) and high value of specific storage (about 10^{-4} m^{-1}). These are regional-scale values of the four controlling parameters, applicable for large-scale response of the aquifer hydraulic heads to natural and human-imposed stresses, because fitting was based on hydraulic heads that were affected by regional-scale stresses on the aquifer system.

The reliability of these parameter values should be considered in light of the assumptions made to derive them. The strongest, most-reliable parameter values are the two compound controlling parameters, with values determined from long-term (10 ka) aquifer water-level drop, vertical anisotropy (Kh/Kv) and hydraulic diffusivity (Kh/Sse). This means that the high value of vertical anisotropy, one of the four controlling parameters in the base model, is a good representation of the regional effect of vertical layering in the NAS aquifer fabric. However, the fitted value of hydraulic diffusivity (with total storativity, *S*, approximately between 0.1 and 0.4, equivalently with effective specific storage, Sse, approximately between 1×10^{-4} and 4×10^{-4}) does not distinguish between the subcomponents of total storativity, water-table storage (specific yield, Sy) and compressive storage (specific storage, Ss). Obtaining separate values of these two parameters required fitting time-dependent measured drawdowns that result from pumping stress near only three development areas. The drawdown most distant from each pumping center (the NAS response to local pumping measured on the largest local spatial-scale) was used for fitting these parameters, but estimates of these two parameters are less reliable. This is because the assumption of regional homogeneity in parameter values may not be applicable, should each area have significantly different hydrogeologic structure from the regional average. This means that the estimated values of specific yield and specific storage are less robust than the other regional parameter value estimates. Despite this, it is interesting that the estimated values of Sy and Ss are similar to values determined from local field tests.

Speculation regarding the meaning of the estimated parameter values may be of value. As mentioned in the preceding, the vertical anisotropy is a good representation of the regional effect of geologic layering. Considering storage, the values of specific yield and specific storage mean that for every meter of head drop, the water table produces as much groundwater to a well as does about 100 m thickness of deeper aquifer material. Especially where NAS is thick, compressive storage provides as much or more water to wells than does the water table, contrary to what intuition might suggest for a water-table aquifer. Indeed, the low value of specific yield found, 0.01, may be surprising, considering that NAS is a water-table aquifer and considering that the effective porosity determined from fitting groundwater ages is much higher, 0.35. The higher value is believable because it represents the typical porosity of well-sorted sand, so one might ask why the water table does not drain in the same way, with specific yield value of about 0.35. One reason may be that, in the places where drawdown data were available, pumping takes place relatively deep in the aquifer, below units of low hydraulic conductivity. The low vertical conductivity causes drawdown from well screens to preferentially extend laterally, rather than vertically, and not much drawdown had reached upwards to the water table during the period of measurement. Without significant measured drawdown at the water table, it is difficult to reliably estimate specific yield; furthermore, drawdowns in these areas were measured at depth, not at the water table. Although the estimated specific-yield may be lower than it really is, the error does not strongly impact the fit of simulated and measured drawdown in the three development areas with drawdown data.

In a sense, if pumping is relatively deep in a water-table aquifer that has high vertical anisotropy, as does NAS, hydraulic heads in the aquifer initially respond as though the aquifer were confined. Eventually, drawdown in pumping centers will reach the water table, but even in this case, should specific yield be ten times higher than estimated here, thicker parts of NAS will produce as much or more groundwater to wells from compressive storage, as from water-table storage. In thinner parts of NAS (e.g. Khartoum area), water-table storage would be more dominant than compressive storage, and aquifer dewatering would likely become an issue.

Environmental impacts of development

Water budget

During an early future development period (tens of years to possibly a few hundred years), modeling shows that hydraulic heads in much of NAS experience small impact from withdrawals concentrated in the few development areas. Most groundwater pumped from NAS comes from the immediate pumping area via substantial drawdown of hydraulic head and release of water to the wells from water table decline and from compressive storage at depth. Because only local NAS groundwater is pumped locally and because wide-area head drop is small, forecast overall NAS discharge during early development is, not greatly impacted by pumping, decreasing by only several percent per 100 years. Despite this apparently encouraging fact, local-area groundwater budgets might be severely impacted by local pumping.

Oases and sabkhas

Oases and sabkhas exist as a result of local discharge of groundwater that occurs because heads are locally at or above the ground surface. Should heads fall below the ground surface, discharge will cease and oases and sabkhas will shrink and disappear. Indeed, loss of NAS surface discharge areas is part of a long-term natural process that began when the last pluvial period ended; however, pumping may severely accelerate the losses because most pumping occurs where groundwater levels are closest to the ground surface—below oases. The model forecasts large decreases in hydraulic head in some of these areas, with local heads steadily decreasing, irrespective of whether pumping is increased. In these areas, a direct impact on the groundwater discharge that sustains oases is expected.

The greatest drawdown occurs near well screens. Should the hydrogeologic structure of a development area in an oasis have low vertical hydraulic conductivity between the ground surface and the well screen, it is possible that the shallow portions of the aquifer could be protected from extreme drawdown of water levels. Where vertical hydraulic conductivity is high and/or where well screens are shallow, significant drawdown will reach the ground surface. The latter-type well fields will capture groundwater that would have discharged at the surface. By adding local hydrogeologic details to the present NAS model, local drawdown and sustainability of each oasis can be more-carefully evaluated.

Transboundary impacts of development

Pumping from NAS initially impacts only groundwater in the local area of each well field. Later, small amounts of drawdown are forecast to extend to greater distances from pumping centers, after a long time coalescing into an NAS-wide drawdown. The long-term fate of NAS water resources is surely of importance, but current water-supply needs and management are of most practical interest, so an initial planning horizon is the immediate 50–100-year future. During this period, transboundary groundwater flows are not significantly impacted by development. Transboundary drawdown is forecast to reach several meters at the top of the aquifer by 2110, but the lateral extent of such cross-border drawdown is forecast to be limited to the immediate near-border region and only as a result of near-border development areas. The current near-border development areas are: East Oweinat in Egypt, near the Egypt-Sudan border; Jaghbub in Libya and Siwa in Egypt, near the Egypt-Libya border. The latter two are on opposite sides of the Libya-Egypt border and drawdown crosses in opposing directions. Considering the most extreme case evaluated in this study, drawdown of up to 10 m from East Oweinat could cross into Sudan by 2060, should assumed base model controlling parameter values all be wrong in an unlikely combination. This combination of parameter values does not allow fitting of the model to the available data, and should therefore be viewed as providing a maximum possible error in the drawdown forecast, not the most-likely forecast.

Local impacts of development

Regarding transboundary water management, in a 100-year planning horizon, cross-boundary water flow and drawdown are not a significant issue, according to model forecasts. This fortunate circumstance for resource sharing has negative connotations for local water management in each development area, because should drawdown extend far laterally, it would not reach such high values in the center of the development area. High local drawdown, from tens to hundreds of meters, is forecast in many of the development areas and drawdowns increase further with time and with additional pumping. Simulations with unlikely combinations of controlling parameter values, selected to give extreme forecasts, indicate even higher local drawdowns could occur at earlier times. One solution to the problem of excessive local drawdown is to decrease local pumping, but the most viable solution is to spread pumping over the maximum area that infrastructure cost and budget will allow. After addition of local hydrogeologic details, model forecasts of drawdown extent and capture zones should allow spacing of wellfields to be optimally designed from the groundwater hydraulics viewpoint. The forecast situation in the Khartoum/Nile valley of Sudan is dire, when projecting future groundwater availability with the pumping rates provided by Sudan. Much of the aquifer will be depleted of water within the planning horizon, but this forecast is based on the assumption of no recharge and no groundwater recharge from the Nile River, possibly too conservative a set of assumptions for the local area. Drawdown would be decreased if aquifer recharge can be induced from the river.

Conclusion

Insight into the functioning of the NAS has been developed in an analysis based on constructing and exercising a parsimonious groundwater model. The primary model basis is proxy hydraulic-head data using oasis locations as a regional map of current water-table location resulting from a groundwater depletion process occurring over thousands of years. The model is also consistent with measured groundwater ages on the order of 1 Ma in Egypt and with local drawdowns at three pumping centers. The model is a strong robust and reliable representation of regional aquifer dynamics, when the model is exercised over ranges of its controlling parameter values that are considered sufficient to cover the ranges of uncertainty in these parameter values. This range of model-based forecasts should be considered as the plausible range of future responses, when discussing optimal management of the resource, whether local-domestic, or regional-international. Selection of appropriate parameter ranges for informing management questions is a key discussion concerning the hydrogeologic functioning of this aquifer system, requiring expert input and perhaps focused new field investigations. Regarding local questions for each development area concerning drawdown, local details of hydrogeologic importance may be added to the present regional NAS description for better resolution of local forecasts.

Forecasts of NAS response to pumping, based on simulation using the base two-zone model described here and on simulations using a variety of parameter values within their plausible range for NAS, show that the greatest concerns regarding management of NAS are at the local scale, particularly large local drawdown increasing pump-lift costs and possibly causing land subsidence and oasis disappearance in some pumping centers with potentially adverse environmental and social impacts. Only for simulation based on a combination of extreme parameter values does significant drawdown cross international borders, and this combination of parameter values is judged to be unlikely. Model analysis thus shows that although the main transboundary concern is drawdown crossing national boundaries, given the large scale of the NAS and its plausible ranges of aquifer parameter values, the magnitude of transboundary drawdown from the present locations of pumping centers is likely small and not an issue of practical concern.

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