THE GEOLOGICAL SOCIETY OF AMERICA®

Aquifer recharge, depletion, and connectivity: Inferences from GRACE, land surface models, and geochemical and geophysical data

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ABSTRACT

Data from the Gravity Recovery and Climate Experiment (GRACE) and outputs of the CLM4.5 model were used to estimate recharge and depletion rates for large aquifers, investigate the connectivity of an aquifer's subbasins, and identify barriers and preferred pathways for groundwater flow within an aquifer system. The Nubian Sandstone Aquifer System and its subbasins (Dakhla, Northern Sudan Platform, and Kufra) in northeast Africa were used for demonstration purposes, and findings were tested and verified against geological, geophysical, remote sensing, geochronologic, and geochemical data. There are four major findings. (1) The average annual precipitation data over recharge areas in the southern Kufra section and the Northern Sudan Platform subbasin were estimated at 54.8 km^3, and 32.8 km^3, respectively, and knowing the annual extraction rates over these two areas (~0.40 ± 0.20 km^3), recharge rates were estimated at 0.78 ± 0.49 km^3/yr and 1.44 ± 0.42 km^3/yr, respectively. (2) GRACE-derived groundwater depletion rates over the Dakhla subbasin and the Northern Kufra section were estimated at 4.44 ± 0.42 km^3/yr and 0.48 ± 0.32 km^3/yr, respectively. (3) The observed depletion in the southern parts of the Dakhla subbasin is apparently caused by the presence of the east-west–trending Uweinat-Aswan basement uplift, which impedes the south-to-north groundwater flow and hence reduces replenishment from recharge areas in the south. (4) A major northeast-southwest–trending shear zone (Pelusium shear system) is apparently providing a preferred groundwater flow pathway from the Kufra to the Dakhla subbasin. Our integrated approach provides a replicable and cost-effective model for better understanding of the hydrogeologic setting of large aquifers worldwide and for optimum management of these groundwater resources.

INTRODUCTION

In arid and semiarid areas, assessment of the groundwater resources, the hydrogeologic settings of aquifers, and the recharge and discharge (natural or anthropogenic) of these systems is essential for the development of sound management scenarios for these resources and for the economic development of such areas (Simmers, 1997). Various approaches have been applied to assess the recharge, discharge, and depletion rates of aquifer systems and to investigate the connectivity of their subbasins, using physical and chemical methods as well as modeling techniques (de Vries and Simmers, 2002; Scanlon et al., 2002; Milewski et al., 2009; Rodell et al., 2009; Sultan et al., 2011; Shamsudduha et al., 2012; Ahmed et al., 2014a; Voss et al., 2013; Mulder et al., 2015; Papa et al., 2015; Richey et al., 2015). These methods are difficult to apply on regional scales, and their results are often suspect given the paucity of the data sets required for the implementation of these methods, and the extensive efforts and resources required to collect them.

Fortunately, the launch of the Gravity Recovery and Climate Experiment (GRACE) mission is now providing opportunities to measure mass variations over large hydrologic systems and settings (e.g., Wouters et al., 2014). GRACE is a joint project between the National Aeronautics and Space Administration (NASA) in the United States and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) in Germany launched in March 2002 to map Earth's static and temporal global gravity fields (Tapley et al., 2004). Over the years, GRACE-derived terrestrial water storage (TWS) data have provided groundbreaking discoveries in hydrological investigations, including: (1) water balance applications on the basin scale (e.g., Rodell et al., 2004; Syed et al., 2005), (2) storage variabilities on the basin and subbasin scale. (e.g., Crowley et al., 2006, 2008; Bonsor et al., 2010; Xavier et al., 2010; Ahmed et al., 2011; Ferreira et al., 2012; Papa et al., 2015), (3) quantification of aquifer recharge and depletion (e.g., Leblanc et al., 2009; Rodell et al., 2009; Sultan et al., 2013; Ahmed et al., 2014); and (4) characterization of natural and anthropogenic controls on mass variations and water availability (Ahmed et al., 2011, 2014b). These applications are hampered by the low horizontal resolution of GRACE data and by the absence of vertical resolution for GRACE (e.g., Ahmed et al., 2016). GRACE cannot differentiate between the contributions from the various compartments (e.g., surface water, groundwater, and soil moisture) of TWS. The integration of land surface model outputs with GRACE data is now providing opportunities to extract individual components from GRACE-derived TWS estimates, and to improve the horizontal resolution of the data.

We provide a demonstration of the way in which GRACE data and outputs of land surface models could be used to estimate recharge, natural and anthropogenic discharge, and depletion rates for large aquifer systems and to investigate the hydrologic and geologic settings and the connectivity of subbasins. Throughout this demonstration, the GRACE-derived inferences are supported by geophysical, geochemical, isotopic, and chronological data. The Nubian Sandstone Aquifer System in northeast Africa was used as the study area. Addressing these issues for the Nubian Sandstone Aquifer System is critical for the development of sound management plans for the aquifer system and for the development of replicable models that can be applied to similar aquifers worldwide.

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GSA Bulletin; May/June 2017; v. 129; no. 5/6; p. 534–546; doi: 10.1130/B31460.1; 10 figures; 1 table; published online 22 December 2016.

GEOLOGY AND HYDROGEOLOGY OF THE NUBIAN SANDSTONE AQUIFER SYSTEM

The Nubian Sandstone Aquifer System extends over 2×10^6 km^2 in Egypt, Libya, Chad, and Sudan (Fig. 1). The Nubian Sandstone Aquifer System consists mainly of water-bearing Paleozoic and Mesozoic sandstone (Nubian Sandstone Formation) with intercalations of Tertiary shale and clay of shallow-marine and deltaic origin (Hesse et al., 1987). The aquifer is bounded to the east, south, and west by basement outcrops, and to the north by the saltwater-freshwater interface (Fig. 1).

The Nubian Sandstone Aquifer System is formed of three major subbasins (Fig. 1). The Kufra subbasin (area: 0.89×10^6 km^2) in Libya, northeastern Chad, and northwestern Sudan, the Dakhla subbasin (area: 0.66×10^6 km^2) in Egypt, and the Northern Sudan Platform subbasin (area: 0.36×10^6 km^2) in northern Sudan. Basement uplifts separate these subbasins. The Northern Sudan Platform subbasin is separated from the Dakhla subbasin to the north by the Uweinat-Aswan uplift and from the Kufra subbasin to the west by the Uweinat-Howar uplift (Hesse et al., 1987; Fig. 1). The thickness of the sedimentary successions of the Nubian Sandstone Aquifer System varies spatially; the maximum thickness in the Kufra, Dakhla, and Northern Sudan Platform subbasins is ~4, 3, and 0.5 km, respectively (Thorweihe, 1986; Hesse et al., 1987). In the Dakhla subbasin, the aquifer is unconfined south of latitude 25°N, but it is confined north of it. The confining layers are the thick (several hundred meters) marine shale and clay of the Campanian Mut Formation and the Campanian to Lower Paleocene Dakhla Formation (Hesse et al., 1987).

Previous studies have shown that the Nubian Sandstone Aquifer System has been recharged in previous pluvial periods in the Quaternary by intensification of paleomonsoons (Sarnthein et al., 1981; Prell and Kutzbach, 1987; Yan and Petit-Maire, 1994) or intensification of paleowesterlies (Sultan et al., 1997; Sturchio et al., 2004; Abouelmagd et al., 2014). The westerlies refer to prevailing winds that blow from the west at midlatitudes and are thought to have migrated southward in Saharan Africa in previous wet climatic periods (Sultan et al., 1997). While such inferences are largely accepted, it has been demonstrated that, locally, the Nubian Sandstone Aquifer System is receiving modern recharge over areas of relatively high precipitation (e.g., Sinai) in dry periods such as the one prevailing at present (Sultan et al., 2000, 2011). Published isotopic data indicate that in northern Sudan, oxygen and hydrogen isotopic compositions are enriched compared to those of groundwater from the Kharga, Dakhla, Farafra, and Bahariya Oases in the central and northern parts of the Western Desert, the desert to the west of the River Nile in Egypt (Haynes and Haas, 1980; Hesse et al., 1987; Thorweihe, 1990; Froehlich et al., 2007; Sultan et al., 2013), possibly indicating mixing between fossil groundwater and modern precipitation in recharge areas to the south.

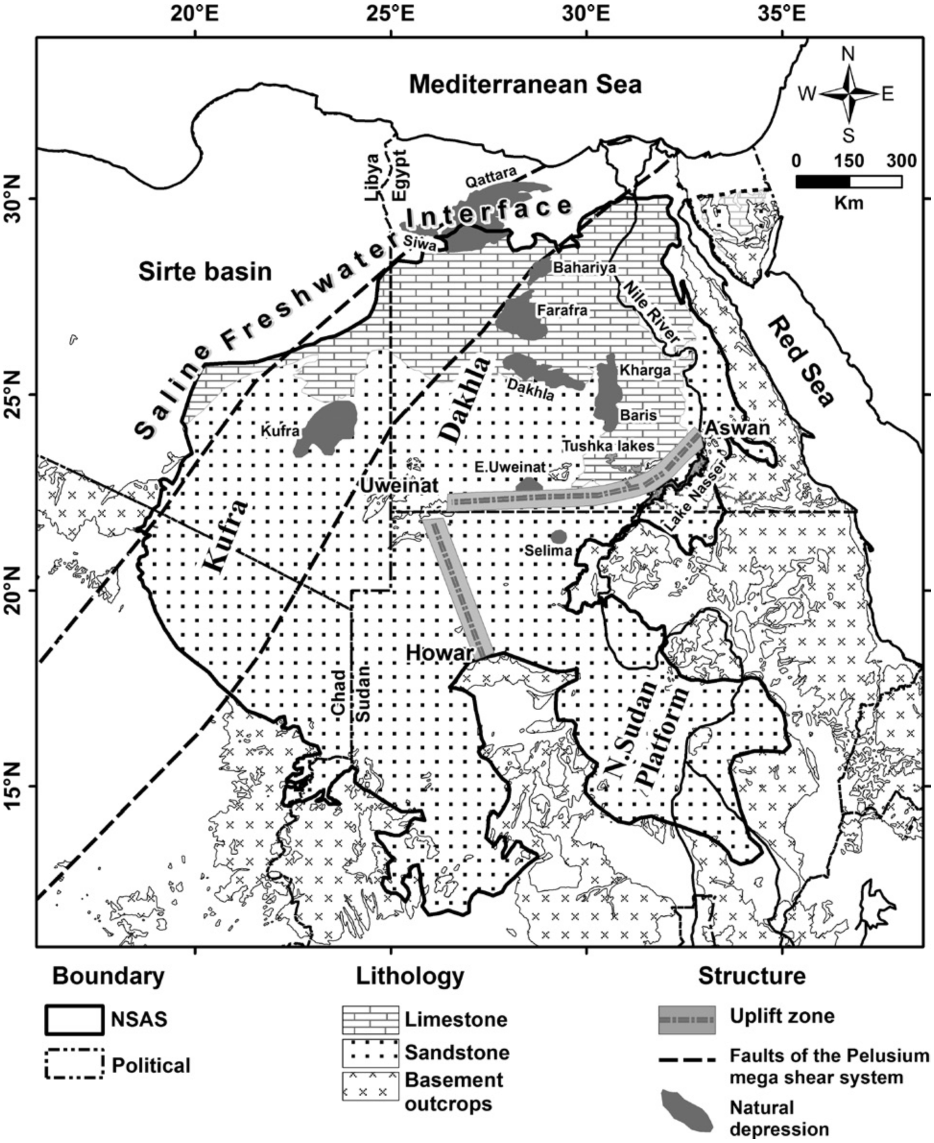

Figure 1. Location map showing the distribution of the Nubian Sandstone Aquifer System (NSAS) and its subbasins (Dakhla, Kufra, and Northern Sudan Platform), the basement uplifts (Uweinat-Aswan, Uweinat-Howar), and the recharge areas within the aquifer.

The concept of regional flow in the Nubian Sandstone Aquifer System was first described by Ball (1927) and Sandford (1935). Using head data from some 56 wells in Egypt, Libya, Chad, and Sudan, they identified a regional southwest-to-northeast gradient in the groundwater surface and concluded that the groundwater follows a gradient from some unknown "intake beds" in the southwest up to the Egyptian oases in the northeast (Fig. 2). The overwhelming majority, if not all, of the existing regional groundwater flow models (e.g., Heinl and Thorweihe, 1993; Ebraheem et al., 2002; Gossel et al., 2004) treat the Nubian Sandstone Aquifer System as a continuous basin, despite the fact that an east-west–trending basement uplift (Uweinat-Aswan uplift) separates the Northern Sudan Platform subbasin from the Dakhla subbasin, and another southeast-northwest–trending uplift (Uweinat-Howar uplift) separates the Northern Sudan

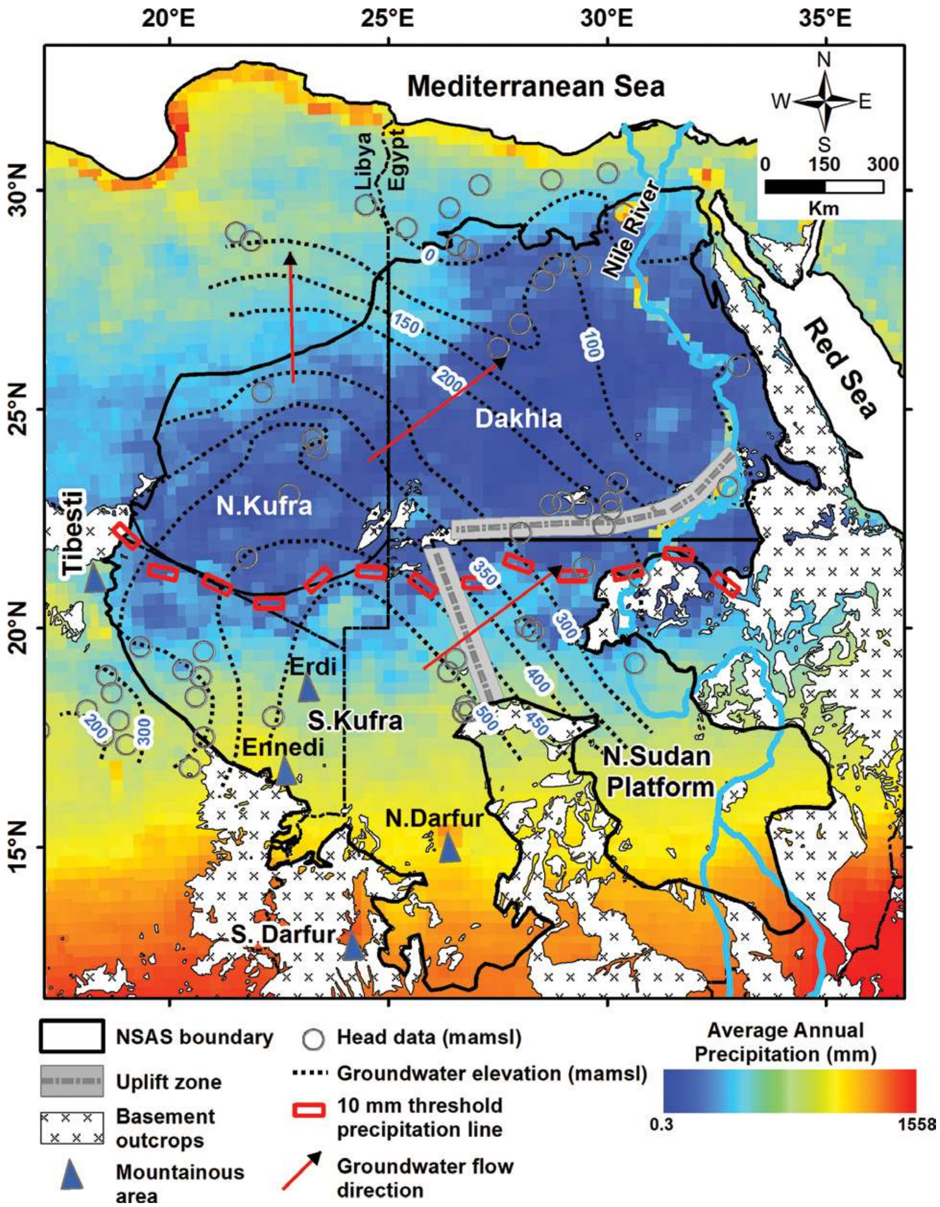

Figure 2. Average annual precipitation (mm) extracted from Tropical Rainfall Measuring Mission (TRMM) data acquired from 2003 through 2012 for the Nubian Sandstone Aquifer System (NSAS) in Egypt, Libya, Sudan, Chad, and surroundings. Also shown are the groundwater water levels (mamsl—m above mean sea level), flow directions, locations of wells in Egypt and Libya from which the head data were extracted, and the 10 mm threshold precipitation line that separates areas of relatively high precipitation and considerable recharge in the south (southern Kufra section and Northern Sudan Platform subbasin) from those of negligible precipitation and recharge to the north (northern Kufra section and Dakhla subbasin).

Platform subbasin from the Kufra subbasin. The degree to which the subbasins of the Nubian Sandstone Aquifer System are connected is not fully understood, and neither is the impact of major structures within the Nubian Sandstone Aquifer System on groundwater flow. The northeastern extent of the Pelusium megashear system, which extends in a northeast-southwest direction from the Kufra subbasin in Chad and Libya and into the Western Desert of Egypt, is one of those structures (Fig. 1). The megashear is a system of en echelon strike-slip megashears that witnessed tectonic activity as early as Precambrian times (Neev et al., 1982). It extends from Turkey to the South Atlantic, runs subparallel to the eastern margin of the Mediterranean Sea, and curves northeast-southwest across central Africa from the Nile Delta to the delta of the Niger River in the Gulf of Guinea (Neev et al., 1982).

DATA, METHODOLOGY, AND FINDINGS

Our methodology is a sixfold exercise. First, we delineated the recharge areas across the Nubian Sandstone Aquifer System using satellite-based precipitation data and the distribution of Nubian Sandstone Aquifer System outcrops (step I). We then extracted the temporal variations in GRACE-derived TWS data over the delineated recharge and depletion areas (step II) and estimated the temporal variations in groundwater storage over those areas (step III). This was accomplished by extracting variations in river channel and soil moisture storage data from land surface model outputs and removing these storage variations from GRACE-derived TWS data. Recharge and depletion rates were then calculated for the Nubian Sandstone Aquifer System subbasins knowing the temporal variations in groundwater storage and discharge (natural and anthropogenic; step IV), and a conceptual hydrologic and geologic model was developed to account for findings from the analysis of GRACE data (step V). Finally, the developed model was tested against geophysical, field, isotopic, and chronologic data (step VI).

Delineation of Recharge Areas Using Satellite-Based Precipitation and Outcrop Distribution

Given the paucity of rain gauge stations over the Nubian Sandstone Aquifer System, the discontinuous nature of some of these stations, and their general absence over the areas of high precipitation (mountains), we resorted to the use of satellite-based rainfall measurements, namely, the Tropical Rainfall Measuring Mission (TRMM; http://disc.sci.gsfc.nasa.gov/). TRMM was launched in 1997 as a joint mission between the National Space Development Agency (NASDA) of Japan and NASA, as part of the Earth Observing System (EOS; Kummerow, 1998; Huffman et al., 2007). TRMM data were acquired (1998–2015) with near-global coverage (50°N to 50°S) at a spatial resolution of 0.25° × 0.25° and with a temporal resolution of 3 h (i.e., precipitation estimates made every 3 h). Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; http://www.esrl.noaa.gov/) data provide merged rainfall estimates from a variety of satellite and ground-based sources from January 1979 to December 2014 (spatial resolution: 2.5°; temporal resolution: monthly; spatial domain: 88.75°N–88.75°S; Xie and Arkin, 1997).

The rainfall data were processed to generate the total monthly rainfall images from the TRMM data taken every 3 h. For each of the investigated subbasins, an average annual precipitation (AAP) image over the entire Nubian Sandstone Aquifer System (Fig. 2) was generated. The rainfall time series were then generated by averaging the rainfall rates for all grid points lying within the individual subbasins. Inspection of Figure 2 shows a progressive north-to-south increase in precipitation over the Nubian Sandstone Aquifer System (AAP north: 5 mm/yr; AAP south: 96 mm/yr), with the highest rainfall over the Tibesti, Ennedi, Erdi, and Darfur mountains in Libya, Chad, and Sudan, hereafter referred to as the southern highlands.

Precipitation data and the distribution of Nubian Sandstone Aquifer System outcrops were used to identify areas of recharge within the aquifer system. Two conditions had to be met in the definition of areas of recharge: the presence of Nubian Sandstone Aquifer System outcrops, and AAP exceeding an arbitrary threshold of 10 mm/yr. In the selection of the threshold value, we were guided by the findings of Milewski et al. (2009), who determined that individual precipitation events of <5 mm across the Egyptian Sahara produced negligible recharge and/or runoff. Given that more than a single precipitation event probably occurs per year in the majority of the investigated areas, it is unlikely that areas receiving <10 mm/yr of precipitation will witness significant recharge.

Figure 2 shows the spatial distribution of recharge areas in the Nubian Sandstone Aquifer System. One coincides largely with the spatial distribution of the Northern Sudan Platform subbasin; the other encompasses areas within the southern sectors of the Kufra subbasin, which receives substantial precipitation. The identified recharge areas within the southern sectors of the Kufra subbasin are hereafter referred to as the southern Kufra section, and the remaining northern areas within the Kufra subbasin are hereafter referred to as the northern Kufra section. Our findings indicate that the southern areas (Northern Sudan Platform subbasin and southern Kufra section) represent recharge areas within the Nubian Sandstone Aquifer System. The AAP values over the Northern Sudan Platform subbasin and the southern Kufra section are 91 mm/yr (32.8 km^3/yr) and 96 mm/yr (54.8 km^3/yr), respectively, and the maximum amount of precipitation (AAP > 1000 mm/yr) is observed over the southern highlands that border, and drain into, the Northern Sudan Platform subbasin and into the southern Kufra section (Fig. 2).

Extraction of Temporal Variations in GRACE-Derived TWS Data Over the Nubian Sandstone Aquifer System

GRACE data were used to estimate the temporal variations in TWS over the Nubian Sandstone Aquifer System subbasins throughout the investigated period (2003–2012). GRACE monthly gravity field solutions (Release 05) from the GRACE database provided by the University of Texas Center for Space Research (ftp://podaac.jpl.nasa.gov/) were used in this study. These solutions are represented in terms of fully normalized spherical harmonic decompositions up to degree and order of 60. The time-variable component of the gravity field was obtained by removing the long-term mean of the Stokes coefficients from each of the monthly values. The systematic correlated errors in the GRACE gravity field coefficients were reduced by applying destriping filters (Swenson and Wahr, 2006). The random errors in the GRACE solutions were then minimized by applying a Gaussian filter with a half-width corresponding to 200 km (Wahr et al., 1998). The spherical harmonic coefficients were then converted to mass grids of equivalent water thickness following the procedures described

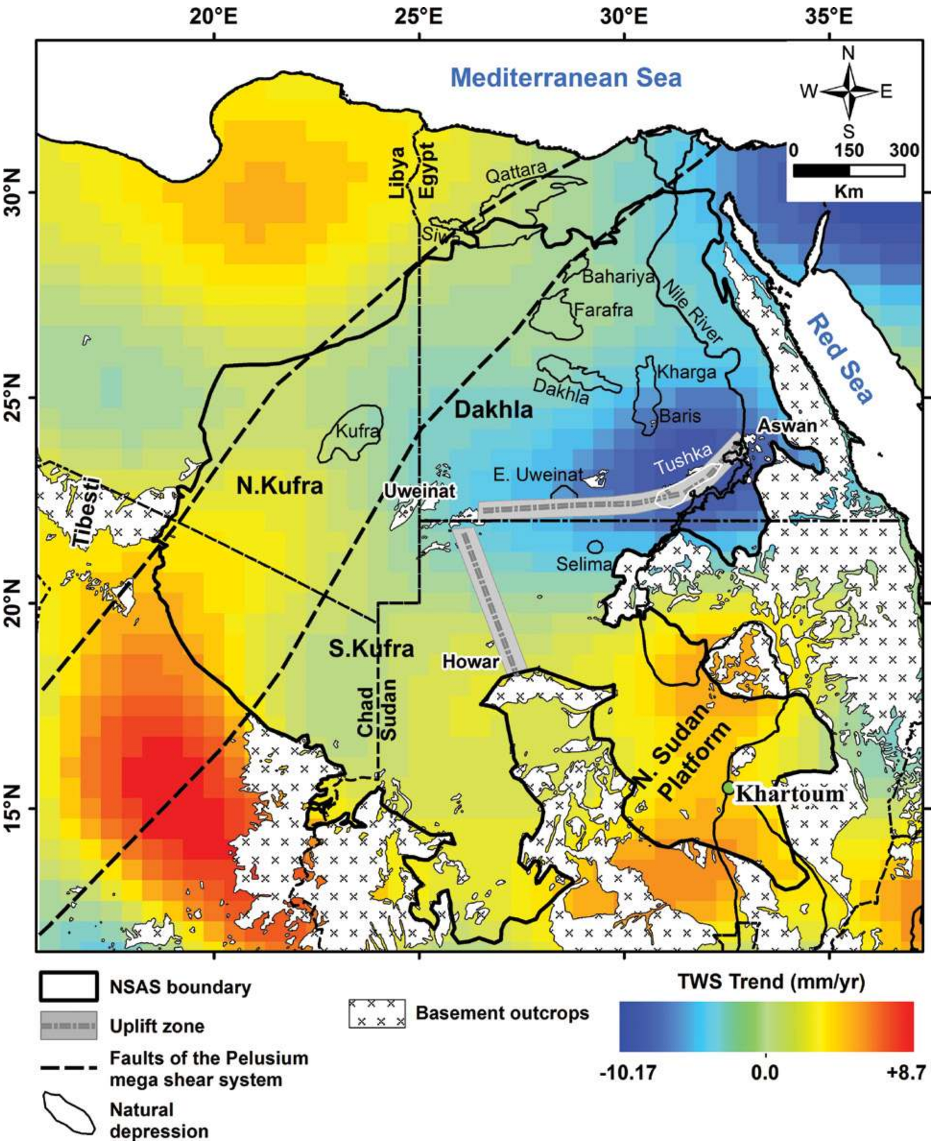

Figure 3. Color-coded secular Gravity Recovery and Climate Experiment (GRACE)–derived terrestrial water storage (TWS) trend (mm/yr) map over the Nubian Sandstone Aquifer System (NSAS).

by Wahr et al. (1998). The secular trend in GRACE-derived TWS data (Fig. 3) was then extracted by simultaneously fitting a trend and seasonal terms to the TWS time series. Errors associated with calculated trend values were then estimated following the approach advanced by Tiwari et al. (2009). Similar procedures were used to extract secular trends for all other time series.

Figure 3 shows the spatial distribution of the secular trends in GRACE-derived TWS data over the Nubian Sandstone Aquifer System and its subbasins. Positive trends indicate an increase in TWS with time, and negative trends indicate the opposite. Inspection of Figure 3 shows that the southern areas (Northern Sudan Platform subbasin and southern Kufra section) are experiencing significant positive TWS trends (shades of yellow, orange, and red); the northern Kufra section is in a near-steady state, whereas the Dakhla subbasin is experiencing a significant negative TWS trend (Fig. 3, shades of blue). It is worth mentioning that the depletion in the Dakhla subbasin is centered over the southern parts of the Dakhla subbasin, whereas in the northern sections, the areas occupied by the Pelusium megashear system and its surroundings, seem to be in near-steady conditions. A positive TWS trend is centered over the Khartoum area and surroundings in the Northern Sudan Platform subbasin and the southwestern boundary of the southern Kufra section.

Smoothed (using the Gaussian 200 km filter) and filtered (destriping applied) GRACE-derived TWS data were used to generate a time series for each of the examined subbasins. The extracted GRACE-derived TWS time series was then rescaled to minimize the effects of smoothing and truncation. Scaling factors and errors associated with the scaling technique were calculated following the procedures described in Sultan et al. (2013). Scaling factors of 2.18 ± 0.31, 1.81 ± 0.38, 1.93 ± 0.83, and 1.96 ± 0.85 were used over the Northern Sudan Platform subbasin, the southern Kufra section, the northern Kufra section, and the Dakhla subbasin, respectively. The Northern Sudan Platform subbasin and southern Kufra section have TWS trend values of +3.09 ± 1.05 mm/yr and +1.06 ± 0.87 mm/yr, respectively (Fig. 4). The northern Kufra section is experiencing a slight overall decline in TWS (–1.56 ± 1.04 mm/yr), whereas a significantly negative (–7.77 ± 0.64 mm/yr) TWS trend is observed over the Dakhla subbasin, centered over east Uweinat, the New Valley or Tushka Project, and the Kharga, Baris, and Dakhla Oases (Figs. 3 and 5).

Estimating Temporal Variations in Groundwater Storage Over the Recharge and Depletion Areas

GRACE-derived TWS data have no vertical resolution, and GRACE cannot distinguish between anomalies resulting from different components of TWS (i.e., surface water, groundwater, soil moisture, snow, and biomass). For this reason, the simulated TWS components of land surface models were used to remove the non-groundwater components from GRACE-derived TWS data. The following equations were used to estimate groundwater recharge/depletion rates over the investigated Nubian Sandstone Aquifer System subbasins:

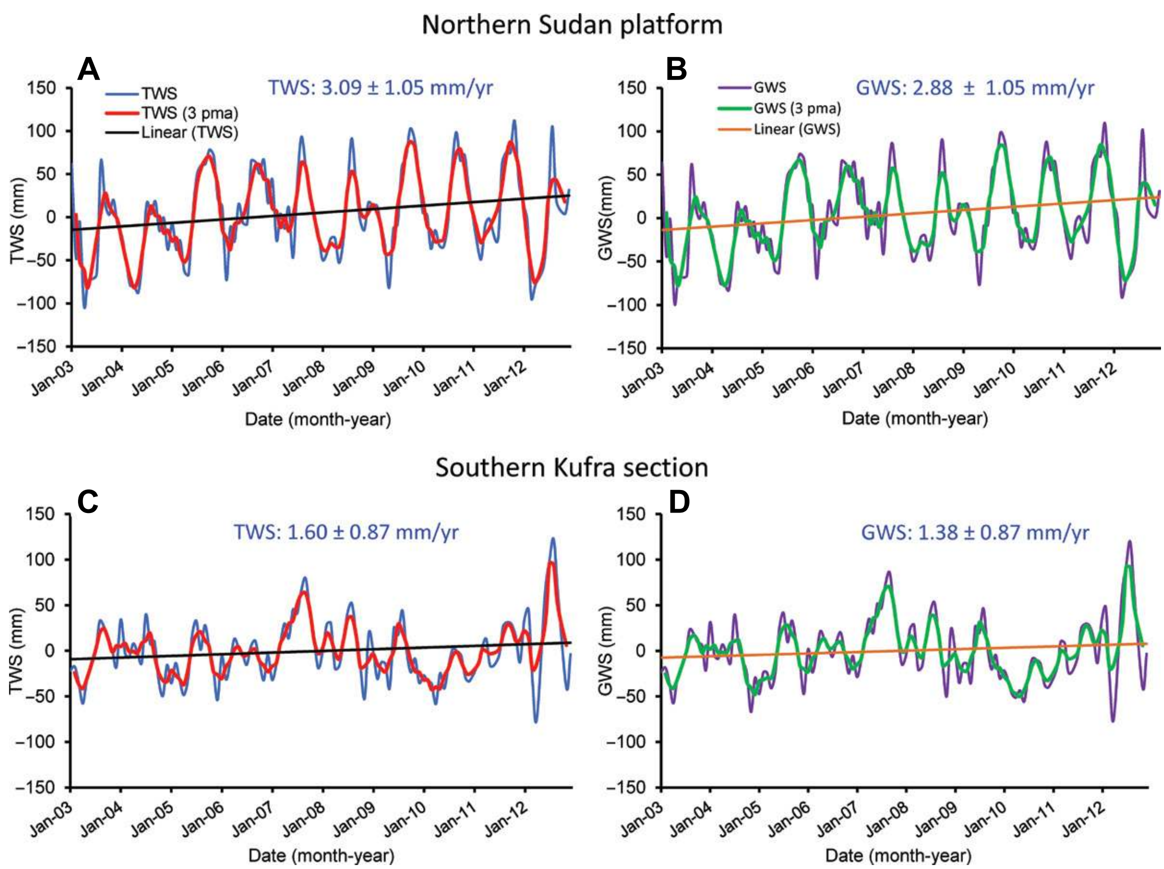

Figure 4. Time series and secular trends for terrestrial water storage (TWS) and groundwater storage (GWS) over the Northern Sudan Platform (A and B) and the southern Kufra section (C and D). 3 pma refers to three-point moving average.

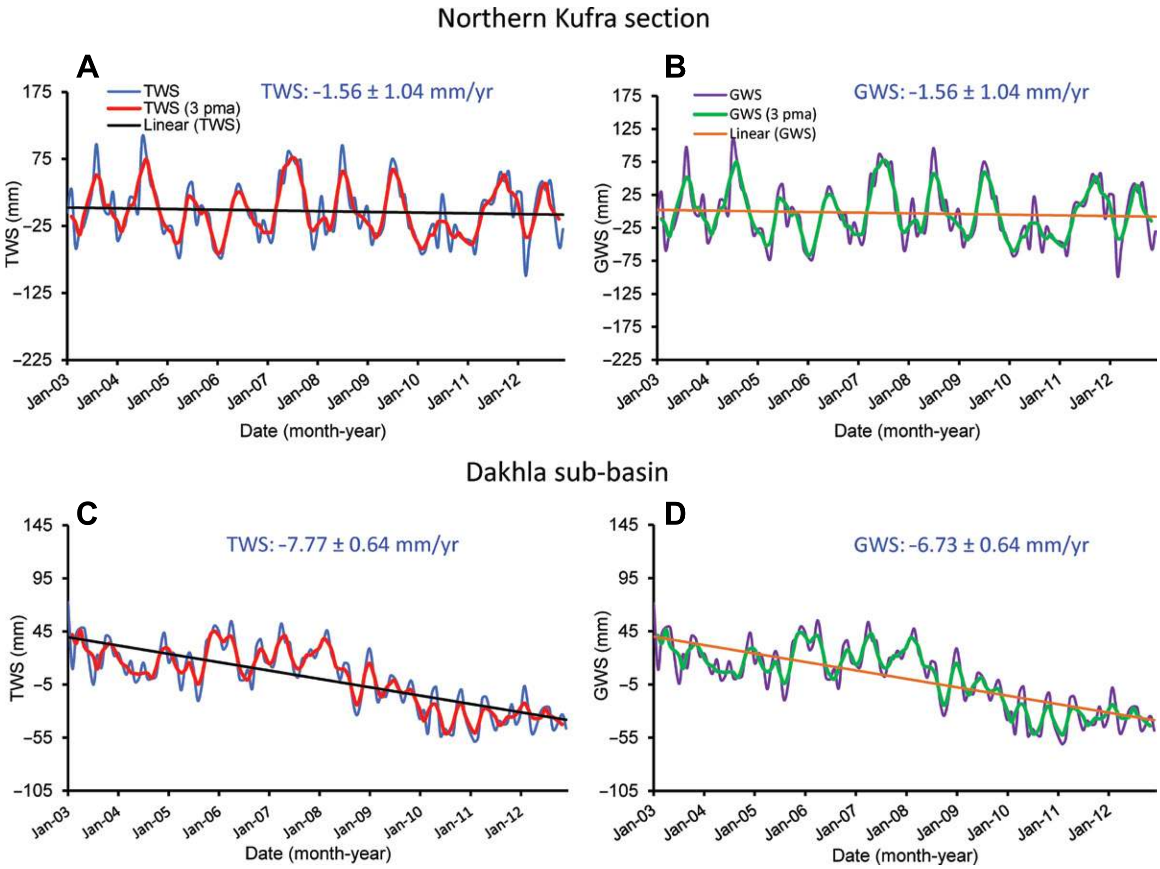

Figure 5. Time series and secular trends for terrestrial water storage (TWS) and groundwater storage (GWS) over the northern Kufra section (A and B) and the Dakhla subbasin (C and D). 3 pma refers to three-point moving average.

$$\Delta GWS = \Delta TWS - \Delta SWS - \Delta SMS, \quad (1)$$

$$\Delta GWS = (R_n + R_a) - (Q_n + Q_a), \quad (2)$$

where, ΔGWS, ΔSWS, and ΔSMS represent the change in groundwater, surface water, and soil moisture storage, respectively; Q_n and Q_a are the natural and anthropogenic discharge, respectively; and R_n and R_a are the natural and artificial recharge, respectively. Because there are no major ongoing artificial recharge projects in the Nubian Sandstone Aquifer System, Equation 2 is reduced to:

$$R_n = \Delta GWS + (Q_n + Q_a). \quad (3)$$

Using SMS and SWS outputs of the Community Land Model, version 4.5 (CLM4.5; Oleson et al., 2013), and applying Equation 1, groundwater storage variations were derived over the four subbasins. The temporal variations in surface-water reservoirs (e.g., Lake Nasser and Tushka Lakes) of the Dakhla subbasin were obtained from Sultan et al. (2013). The detailed calculations, results, and findings are discussed in the following sections.

Recharge and Depletion Rates for the Nubian Sandstone Aquifer System Subbasins

Figure 4 shows the GRACE-derived TWS time series and secular trends over the Northern Sudan Platform subbasin (+3.09 ± 1.05 mm/yr; 1.11 ± 0.37 km^3/yr; Fig. 4A) and the southern Kufra section (+1.60 ± 0.87 mm/yr; 0.91 ± 0.49 km^3/yr; Fig. 4C). The CLM4.5-derived SMS trend is +0.05 mm/yr and +0.22 mm/yr for the Northern Sudan Platform subbasin and the southern Kufra section, respectively, and the SWS trend for the Northern Sudan Platform subbasin is +0.16 mm/yr. The estimated GWS time series and trend for the Northern Sudan Platform subbasin (+2.88 ± 1.05 mm/yr; 1.03 ± 0.37 km^3/yr) and for the southern Kufra section (1.38 ± 0.87 mm/yr; 0.78 ± 0.49 km^3/yr) are displayed in Figures 4B and 4D, respectively.

We used the CMAP data to investigate whether the observed increase in TWS with time over the Northern Sudan Platform subbasin and the southern Kufra section is related to the increase in the AAP over these two subbasins. The AAP over the Northern Sudan Platform subbasin throughout the investigated period is high (2002–2012, CMAP: 102 mm) compared to the preceding period (1979–2001, CMAP: 92 mm), and so is the case with the southern Kufra section (2002–2012, CMAP: 80.1 mm; 1979–2001, CMAP: 76 mm). We calculated (using Eq. 3) the average annual recharge values by adding the reported average annual groundwater extraction values (Q_a) for the Northern Sudan Platform subbasin (0.406 km^3/yr; –1.13 ± 0.56 mm/yr) and for the southern Kufra section (0.001 km^3/yr; –0.002 ± 0.001mm/yr; Ahmed, 2013) to their respective GWS trends. The natural discharge in both areas was considered to be negligible. The average annual recharge was estimated at 4.01 ± 1.19 mm/yr (1.44 ± 0.42 km^3/yr) for the Northern Sudan Platform subbasin and at 1.38 ± 0.87 mm/yr (0.78 ± 0.49 km^3/yr) for the southern Kufra section. The estimated recharge rate for the Northern Sudan Platform subbasin is similar to that obtained from groundwater flow modeling in the central Sudan rift basins (4–8 mm/yr; Abdalla, 2008) and from application of the chloride tracer method over 14 sites in central Sudan (up to 5.8 mm/yr; Edmunds et al., 1988). The estimated recharge rate should be considered as an upper limit, given that no corrections were applied to account for impoundment of water by the recently erected dams, such as the Merowe Dam, which was constructed in 2009 in northern Sudan.

Figure 5A shows the temporal variations in GRACE-derived TWS and the secular trend (–1.56 ± 1.04 mm/yr; –0.48 ± 0.32 km^3/yr) over the Northern Kufra section. The GRACE-derived TWS trend shows a minimal decline to near-steady conditions, and the CLM4.5-derived SMS trend shows no variabilities (~0.0 mm/yr) over the investigated period. The GWS time series as well as the GWS trend (–1.56 ± 1.04 mm/yr; –0.48 ± 0.32 km^3/yr) are shown in Figure 5B. These apparent near-steady conditions in TWS and GWS are difficult to reconcile given the substantial extraction (0.851 km^3/yr; –2.66 ± 1.32 mm/yr; Ahmed, 2013), which is comparable to that in the Dakhla subbasin. One explanation for these observations is that a south-to-north groundwater flow from recharge areas compensates for extraction.

Figure 5C shows the GRACE-derived TWS time series over the Dakhla subbasin along with the secular trend value. Inspection of Figure 5C shows a significant decline (–7.77 ± 0.64 mm/yr; –5.12 ± 0.42 km^3/yr) in TWS over the Dakhla subbasin. The observed decline is not caused by a decrease in precipitation, given the negligible precipitation over the investigated period (AAP 2002–2012, CMAP: 5 mm) and in the previous periods as well (1979–2001, CMAP: 9.4 mm). The estimated GWS time series is displayed in Figure 5D. To calculate the depletion rate (6.73 ± 0.64 mm/yr; 4.44 ± 0.42 km^3/yr) in the Dakhla subbasin, we subtracted the CLM4.5-derived SMS (–0.01 mm/yr) and SWS (0.1 mm/yr) trend values as well as the Lake Nasser (–0.45 mm/yr; Sultan et al., 2013) and Tushka Lake (–0.68 mm/yr; Sultan et al., 2013) trends from the GRACE-derived TWS trend. The estimated aquifer depletion rate (6.73 ± 0.064 mm/yr; 4.44 ± 0.42 km^3/yr) is similar to the rate (–4.32 mm/yr; –2.85 km^3/yr) obtained by summation of reported (Ebraheem et al., 2003; CEDARE, 2001) average annual groundwater extraction (2003: –1.1 km^3/yr; 2009: –2.2 km^3/yr; average: –2.50 mm/yr; –1.65 km^3/yr) and annual natural discharge (–1.2 km^3/yr; –1.82 mm/yr; Sultan et al., 2007).

Conceptual Model to Account for GRACE-Derived Mass Variations Over the Nubian Sandstone Aquifer System

We advocate the following conceptual model to explain observations extracted from the analysis of GRACE-derived and CLM4.5-derived TWS data. (1) The Nubian Sandstone Aquifer System is receiving modern recharge in the southern parts (Northern Sudan Platform subbasin and southern Kufra section) where precipitation is high and the aquifer is unconfined, whereas the northern parts (Dakhla subbasin and northern Kufra section) are receiving negligible recharge, given the paucity of precipitation over these areas (Figs. 1 and 2). (2) The natural and anthropogenic discharges are largely concentrated in the northern parts of the Nubian Sandstone Aquifer System (e.g., Dakhla subbasin and northern Kufra section; Table 1; Fig. 1). (3) The depletion in the Dakhla subbasin is centered over east Uweinat, the Tushka project, and the Kharga, Baris, and Dakhla Oases, the areas where most of the extraction in the Western Desert occurs. (4) The depletion in the Dakhla subbasin is less pronounced in its northern parts, the areas occupied by the northeast-southwest–trending Pelusium megashear system, which could be providing a preferred groundwater flow pathway from the Kufra to the Dakhla subbasin (Fig. 3). (5) Unlike the northern Kufra section, the extraction in the Dakhla subbasin does not appear to be compensated for by groundwater flow from recharge areas in the south (Northern Sudan Platform subbasin), despite the fact that the recharge in the Northern Sudan Platform subbasin is approximately three to four times that in the southern Kufra section (Table 1). (6) The observed depletion in the Western Desert is caused by excessive extraction that is not replenished by groundwater flow from the south due to the presence of a barrier (Uweinat-Aswan uplift) to groundwater flow from recharge areas in the south. (7) The absence of significant variations in GRACE TWS trends across the north-south–trending Uweinat-Howar uplift could indicate that the uplift is not impeding groundwater flow toward the Northern Sudan Platform subbasin (Fig. 3).

Testing the Conceptual Model Against Geophysical, Field, Isotopic, and Chronologic Data

Mapping Depth to Basement Using Gravity and Field Data

Gravity data were used to map the spatial variations in the thickness of the sedimentary cover of the Nubian Sandstone Aquifer System and to investigate the connectivity of its subbasins. Given the large spatial extent of the Nubian Sandstone Aquifer System, a global Earth Gravity Model (EGM2008; http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/) was used in this study. The EGM2008 is a spherical harmonic model of Earth's gravitational potential that was developed by the National Geospatial Intelligence Agency. Earth's gravitational field was extracted from satellite, airborne, and land data (Pavlis et al., 2012) and was represented in terms of fully normalized spherical harmonic decompositions (degree/order: 2159; ~10 km). The EGM2008 Bouguer anomalies were extracted over the Nubian Sandstone Aquifer System using conventional processing routines, and deep mantle contributions were removed using high-pass filters (filter width: 1000 km; Obenson, 1974; Block et al., 2009; Fig. 6). The depth to the basement rocks was then extracted using two-dimensional (2-D) models (grid size: 1° × 1°), where each of the 2-D models was represented by three layers: a top sedimentary cover (average density: 2.60 g/cm^3; Senosy et al., 2013), a middle basement layer (average density: 2.8 g/cm^3; Gaulier et al., 1988; Marsouk, 1988; Saleh et al., 2006), and a lower upper-mantle layer (average density: 3.25 g/cm^3; Gaulier et al., 1988; Marsouk, 1988; Saleh et al., 2006). Available well data (~2000 wells; Fig. 6; CEDARE, 2001) were used to constrain the extracted depth to basement solutions and to interpolate these solutions across the entire Nubian Sandstone Aquifer Sys-

TABLE 1. PARTITIONING OF TERRESTRIAL WATER STORAGE (TWS) OVER NUBIAN SANDSTONE AQUIFER SYSTEM SUBBASINS AND SECTIONS

Subbasin/section	Q_a (mm/yr)	Q_n (mm/yr)	R_n (mm/yr)	ΔSMS (mm/yr)	ΔSWS (mm/yr)	ΔTWS (mm/yr)	ΔGWS (mm/yr)
Northern Sudan Platform	–1.13 ± 0.56	0.00 ± 0.00	+4.01 ± 1.19	+0.05	+0.16	+3.09 ± 1.05	+2.88 ± 1.05
Southern Kufra section	–0.002 ± 0.001	0.00 ± 0.00	+1.38 ± 0.87	+0.22	0.00	+1.60 ± 0.87	+1.38 ± 0.87
Northern Kufra section	–2.66 ± 1.32	0.00 ± 0.00	+1.10 ± 1.68	0.00	0.00	–1.56 ± 1.04	–1.56 ± 1.04
Dakhla subbasin	–2.50	–1.82	0.00	–0.01	0.1	–7.77 ± 0.64	–6.73 ± 0.64

Note: Abbreviations: Q_a—anthropogenic discharge, Q_n—natural discharge, R_n—natural recharge, ΔSMS—change in soil moisture storage, ΔSWS—change in surface water storage, ΔTWS—change in terrestrial water storage, ΔGWS—change in groundwater storage. Gravity Recovery and Climate Experiment (GRACE) observations, LSMS (Land Surface Models) outputs, and field data were used to estimate the partitioning of TWS in SWS, SMS, and GWS over areas occupied by the Nubian Sandstone Aquifer System and its subbasins.

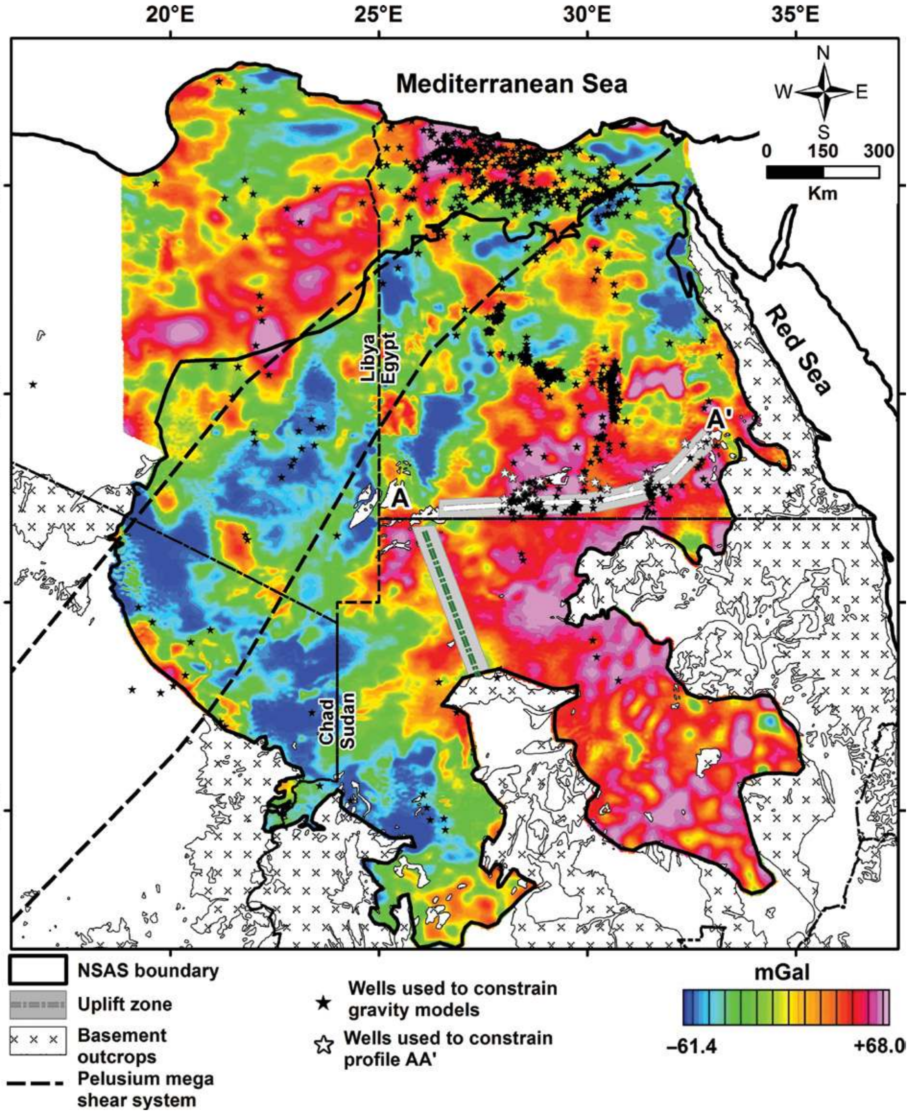

Figure 6. High-pass filtered Bouguer gravity anomaly map generated over Nubian Sandstone Aquifer System (NSAS). Also shown are the locations of cross-section A-A′ (Fig. 9) and the wells that were used to constrain the gravity model and the cross section.

tem. The EGM2008-derived three-dimensional basement relief map is shown in Figure 7.

Examination of Figure 7 shows that the Nubian Sandstone Aquifer System sediments thicken (up to 7000 m) toward the Mediterranean Sea coastal areas and thin (<500 m) in the southern parts of the Dakhla subbasin in areas proximal to the Uweinat-Aswan uplift. The uplift separates the deep intracratonic Dakhla subbasin from the shallow Northern Sudan Platform subbasin. Along the uplift, basement rocks crop out and/or extend at shallow depths under the sedimentary cover. In the next section, we demonstrate, using the extracted basement relief map, that the groundwater flow from the south is obstructed along large sectors of the Uweinat-Aswan uplift in areas where the elevation of the basement exceeds that of the groundwater. We also show that the increased depth to basement (average depth: 700 m) and the shallow depth to water table (average depth: 200 m) along the Uweinat-Howar uplift compared to the Uweinat-Aswan (average depth to water table: 10–50 m; average depth to basement: 200 m) can explain why the Uweinat-Aswan uplift, but not the Uweinat-Howar, impedes groundwater flow.

The basement relief map was also used to map the distribution of the northeast-southwest–trending Pelusium megashear system in the Western Desert and eastern Libya, where these areas show pronounced negative Bouguer gravity anomalies and thickened sedimentary sequences (Figs. 6 and 7). Within the megashear system, the thickness varies from 3 km to more than 4 km (Fig. 7), mostly filled by Paleozoic–Lower Cretaceous sandstones in the Kufra subbasin and by Paleozoic–Upper Cretaceous sandstone in the Dakhla subbasin (Thorweihe and Heinl, 2002). Structures like the Pelusium megashear system, which are subparallel to groundwater flow direction, act as preferred pathways for groundwater flow, whereas others that intersect the flow at high angles impound groundwater up gradient (Gudmundsson, 2000; Babiker and Gudmundsson, 2004; Mohamed et al., 2015).

Spatial Variation in Head Data

As described earlier, the regional groundwater flow in the Nubian Sandstone Aquifer System is from southwest to northeast (Fig. 2). Digital interpolation (using spline interpolation techniques) of the same 56 well data points that were used by Ball (1927) and Sandford (1935) revealed a similar regional gradient. However, significant deviations on the local scale were observed that we attribute to the presence of preferred groundwater flow pathways (Pelusium megashear system) and basement uplifts (Uweinat-Aswan; Fig. 8).

Inspection of Figure 8 shows that groundwater flows away from the Tibesti Mountains in the Kufra subbasin in a northeasterly direction along the Pelusium trend toward the Dakhla subbasin and in a northerly direction toward the Mediterranean Sea. The variations in groundwater levels measured in the Kufra and Sirte basins support this suggestion (Wright et al., 1982). Given that the Pelusium megashear system represents an area of concentrated and extensive brittle deformation (Neev et al., 1982), one would expect enhanced porosity, permeability, and groundwater flow within, and proximal to, the megashear compared to its surroundings. Inspection of reported hydraulic conductivity values across the Western Desert and eastern Libya shows that this is indeed the case; hydraulic conductivities extracted from pumping tests conducted within, and proximal (<50 km) to, the megashear are high (Siwa: 3.43×10^{-4} m/s; Abu Munqar: 2.18×10^{-4} m/s; Kufra: 0.7×10^{-4} m/s), compared to those reported from the remaining areas within the Western Desert (Kharga: 0.29×10^{-4} m/s; Dakhla: 0.61×10^{-4} m/s; Farafra: 0.54×10^{-4} m/s; and Bahariya: 0.43×10^{-4} m/s; Thorweihe, 1982; El Ramly, 1983; CEDARE, 2001; Fig. 8). The suggestion that the megashear is a preferred pathway for groundwater flow is supported by the high groundwater levels within the megashear when compared to the levels outside it (Fig. 8).

We have shown that the general flow from the southern highlands to the Kufra subbasin is to the

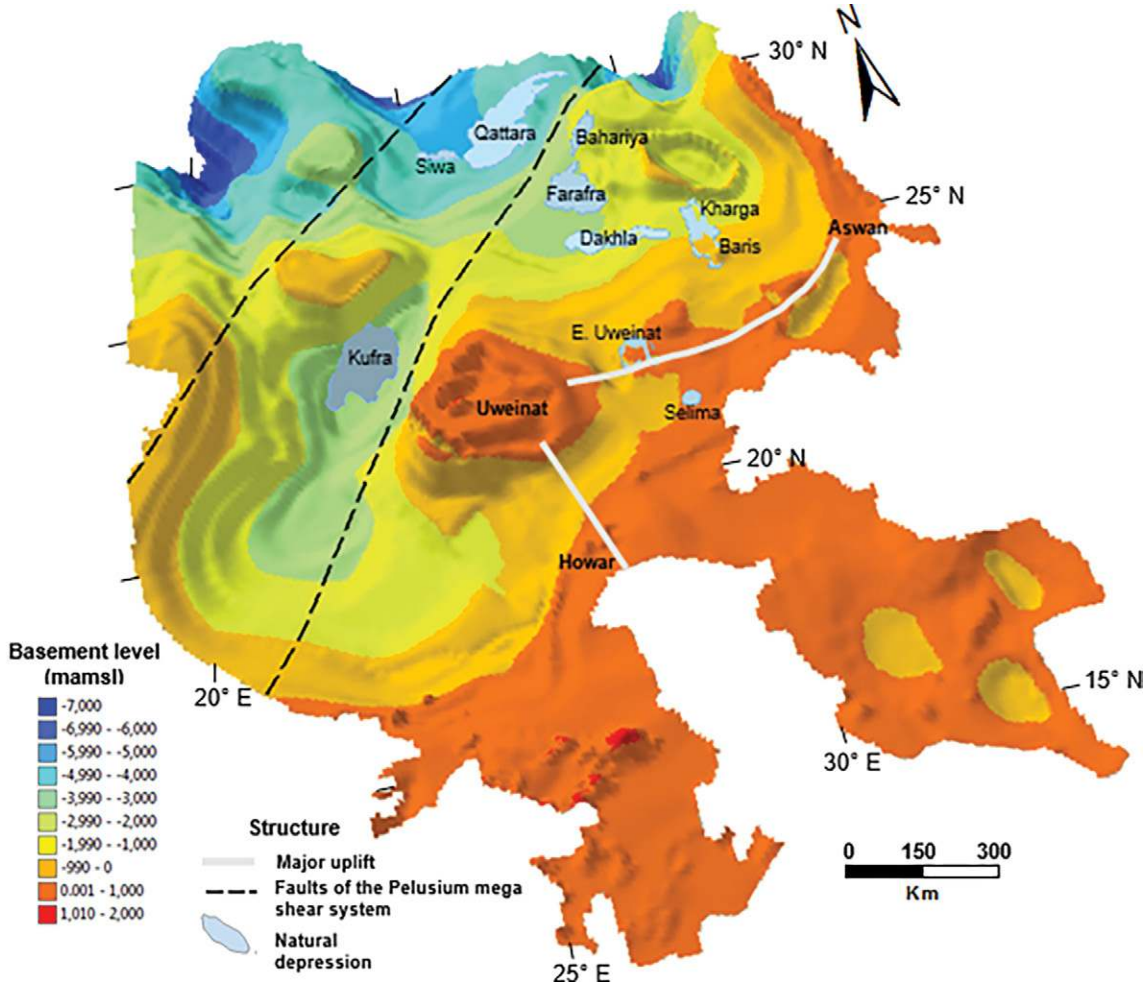

Figure 7. Basement relief three-dimensional image extracted over Nubian Sandstone Aquifer System showing thickening of the sedimentary sequences (mamsl—m above mean sea level) to the north and along the northeast-trending Pelusium megashear.

northeast and that toward the North Sudan Platform subbasin is to the east-northeast (Fig. 8). We suggest that this difference in groundwater flow direction could be in part related to the presence of the east-west–trending Uweinat-Aswan uplift, which redirects the general southwest-to-northeast groundwater flow direction to align with its elongation (east-northeast) as the flow approaches the uplift, thus impeding the south-to-north groundwater flow toward the Dakhla subbasin. The uplift does not obstruct the south-to-north groundwater flow along its entire length, but allows such flow through the various uplift segments where the depth to basement exceeds that to the water table. These suggestions are supported by the distribution of depth to basement measurements along the postulated extension of the uplift (Figs. 7 and 9). Figure 9 is a cross section that was generated using: (1) surface elevation extracted from a digital elevation model, (2) depth to basement data extracted from 12 wells located along, or proximal to, the postulated extension of the Uweinat-Aswan uplift, (3) the depth to basement map extracted from the basement relief map (Fig. 7), and (4) groundwater elevation data from Ball (1927). Inspection of Figure 9 shows that the groundwater flow from the south is obstructed along large sectors of the uplift, in areas where the elevation of the basement exceeds that of the groundwater. This occurs along ~50% of the length of the uplift. The groundwater flow is enabled across the uplift through windows where the groundwater elevation exceeds that of the basement. Several such areas are observed on the cross section, the largest of which is sandwiched between Gebel Kamil and Bir Tarfawi (Fig. 9).

Isotopic and Geochronologic Data

At present, there is minimal precipitation over recharge areas in the Dakhla subbasin (Fig. 2), and thus extraction from the Dakhla subbasin could only be possible through south-to-north groundwater flow from the Northern Sudan Aquifer and west-to-east groundwater flow from the Kufra subbasin. If the groundwater flow from the south is not obstructed or impeded, one would expect that the isotopic compositions of groundwater to the north and south of the uplift would be similar. That is not the case.

Stable isotopes are used routinely to "fingerprint" the origin of water bodies, to map their geographic distributions, and to identify and quantify processes (e.g., evaporation, mixing) that could have affected them. High-temperature hydrothermal systems are exceptions, none of which were reported from the study area. Samples to the north of the uplift are depleted (average ± 1 standard deviation of 37 samples: δ^{18}O: –10.7‰ ± 0.9‰; δD: –80.8‰ ± 3.9‰) compared to those to the south of the uplift (average of seven samples: δ^{18}O: –8.6‰ ± 1.4‰;

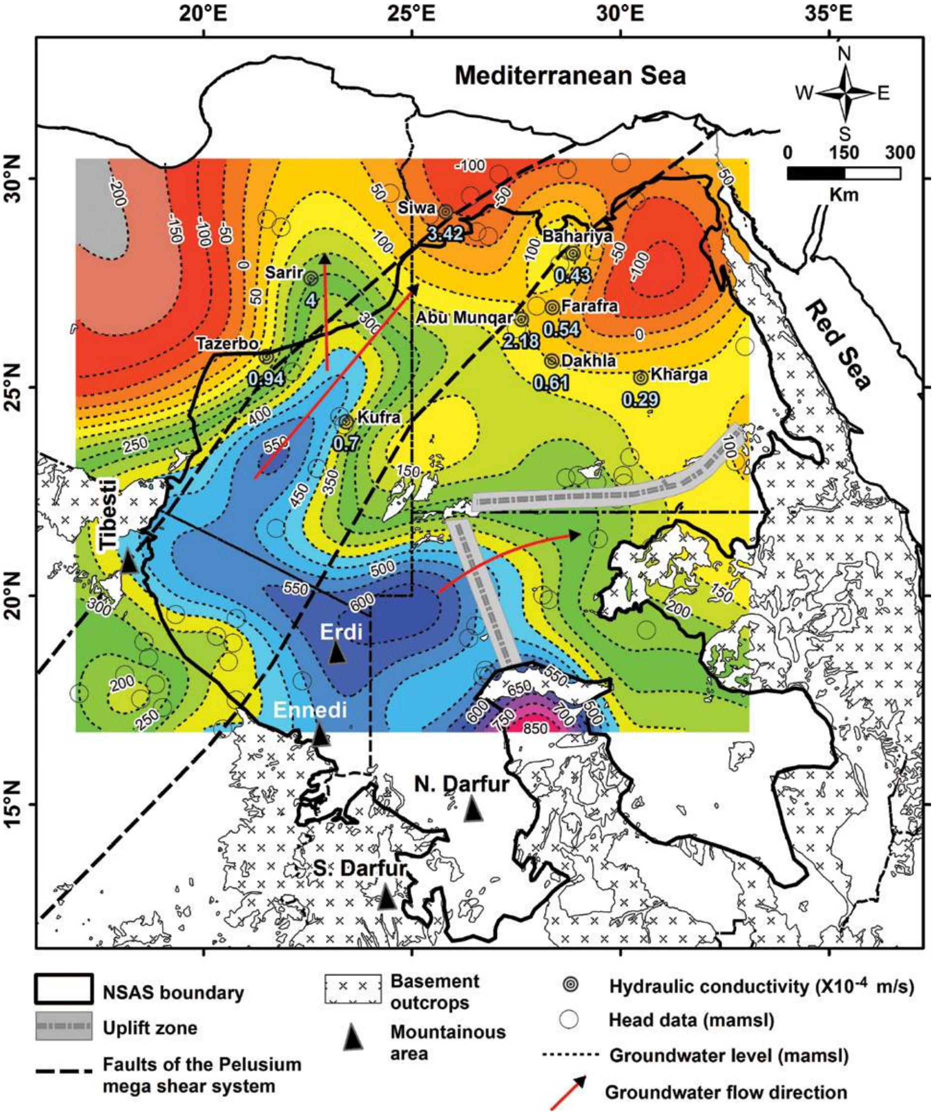

Figure 8. Groundwater elevation contours generated by interpolation (spline interpolation) of head data provided by Ball (1927) and Sandford (1935). Also shown are the locations of wells from which the head data (mamsl—m above mean sea level) and hydraulic conductivity values were extracted. NSAS—Nubian Sandstone Aquifer System.

δD: –40.8‰ ± 5.6‰; Fig. 10; Sultan et al., 2013). The isotopic depletions of the groundwater north of the uplift are best explained by progressive condensation of water vapor from paleo-westerly wet oceanic air masses that traveled across North Africa and operated at least as far back as 450,000 yr ago, whereas the enrichment of the samples in the south could indicate mixing of Nubian fossil groundwater with modern precipitation (Sultan et al., 1997, 2013).

The observed variations in isotopic compositions across the uplift could indicate that the uplift is hampering the replenishment of the Dakhla subbasin by groundwater flow from the south. This suggestion is supported by the large differences in ages between groundwater samples on either side of the uplift. The ages of the samples north of the uplift increase progressively along the groundwater flow direction. Krypton-81 and chlorine-36 (Sturchio et al., 2004; Patterson et al., 2005) show a progression of groundwater ages away from the uplift, reaching ages of 680 ka in Kharga and up to 1000 ka in the Bahariya, Bauti-1. These older ages contrast with those reported from areas south of the uplift. In those areas, young Cl-36 ages were reported from East Uweinat (<30 ka),

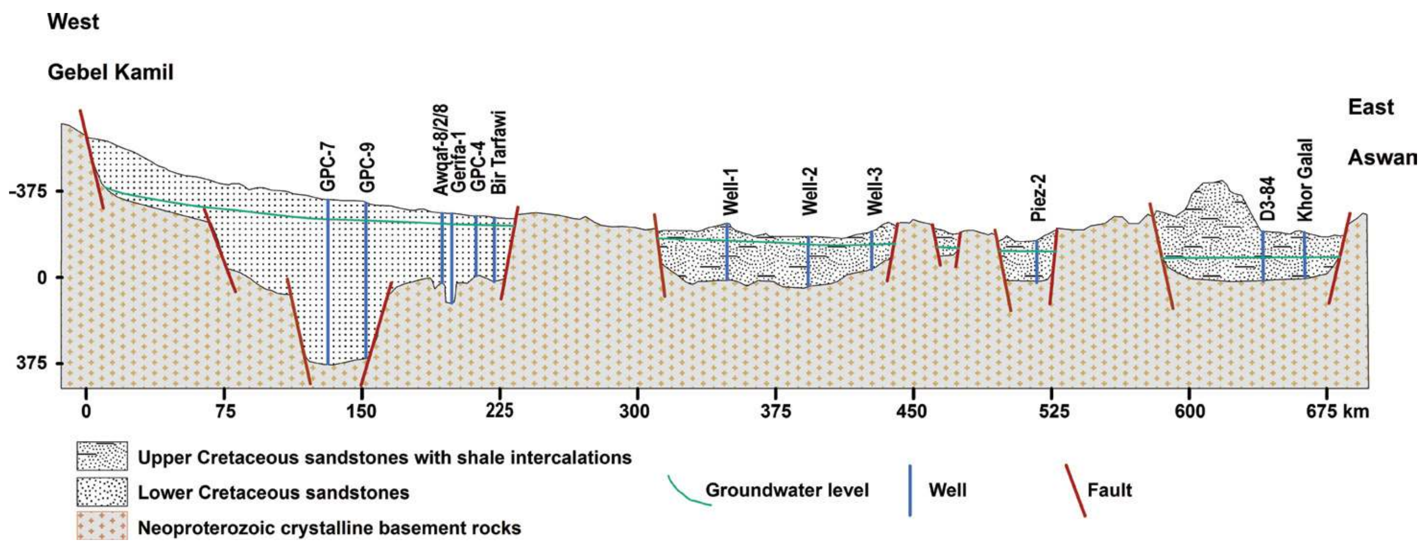

Figure 9. Schematic geological west-east cross section along the Uweinat-Aswan uplift (profile A-A′; Fig. 6) generated from well data and basement relief map (Fig. 7).

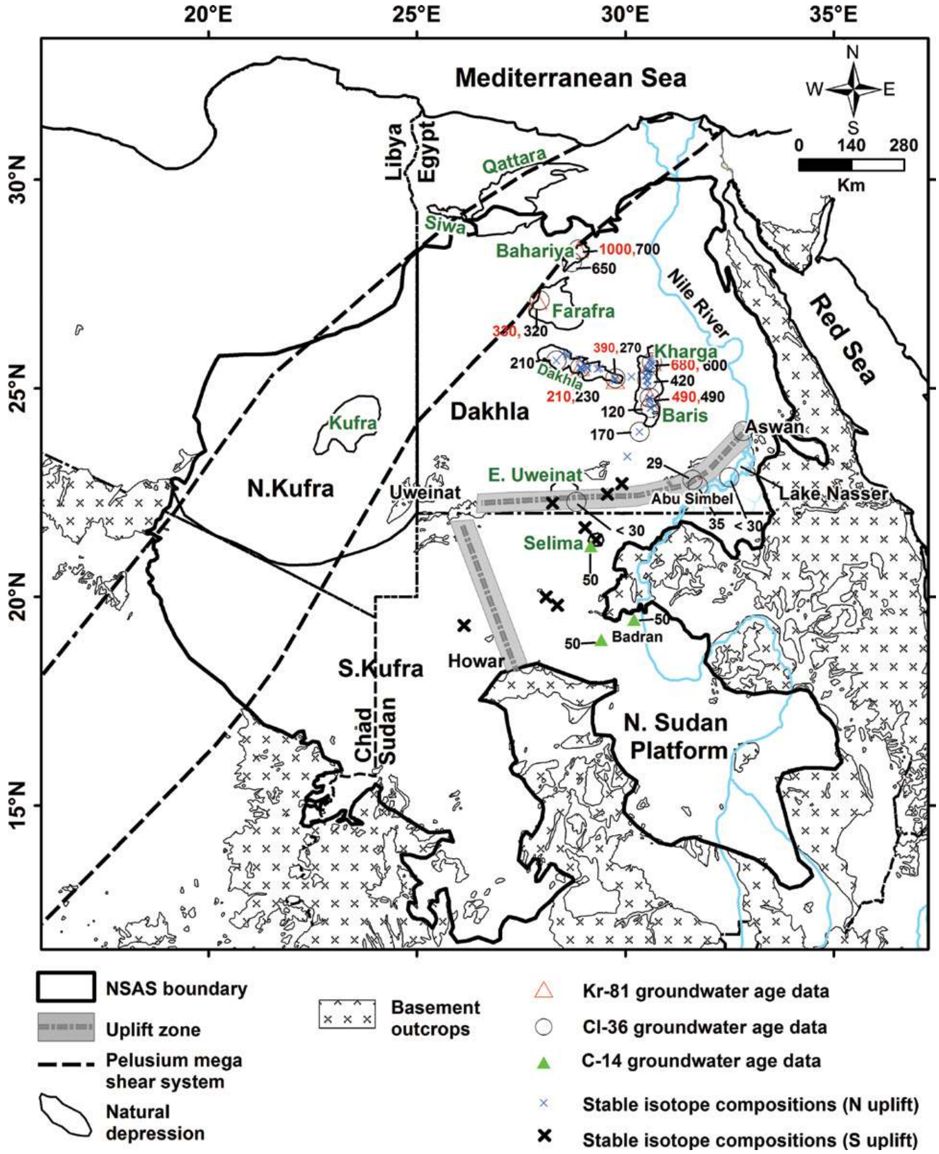

Figure 10. Locations of dated (Kr-81: Sturchio et al., 2004; Cl-36: Patterson et al., 2005; C-14: Froehlich et al., 2007) and isotopically (O, H) analyzed groundwater samples north and south of the Uweinat-Aswan uplift. NSAS—Nubian Sandstone Aquifer System.

Abu Simbel (29–35 ka), and south Aswan (<30 ka; Patterson et al., 2005), and young C-14 ages (ca. 50 ka) were reported from the Selima and Badran areas in northern Sudan (Froehlich et al., 2007; Fig. 10).

CONCLUSION

Our results indicate that the southern subbasins are receiving appreciable precipitation (AAP: Northern Sudan Platform subbasin: 91 mm/yr; southern Kufra section: 96 mm/yr). The average annual recharge is estimated at 4.01 ± 1.19 mm/yr (1.44 ± 0.42 km^3/yr) for the Northern Sudan Platform subbasin, ~4.5% of the average annual precipitation over the subbasin. For the southern Kufra section, the average annual recharge rate is estimated at 0.78 ± 0.49 km^3/yr (1.38 ± 0.87 mm/yr). The average annual recharge for the two southern basins is estimated at 2.22 ± 0.64 km^3/yr. In the northern subbasins, a different pattern is observed. Precipitation is negligible, and extraction is heavy. The depletion rates over the Dakhla subbasin and northern Kufra section are estimated at 4.44 ± 0.42 km^3/yr and 0.48 ± 0.32 km^3/yr, respectively. These two estimates are consistent with reported natural and anthropogenic discharge.

Extraction in the northern Kufra section is apparently compensated for by natural flow from the south. That is not the case with the Dakhla subbasin, especially in the southern parts, where groundwater flow from the south is impeded by the Uweinat-Aswan uplift. The northern parts of the Dakhla subbasin are apparently replenished by groundwater flow along a preferred northeast-trending groundwater flow pathway provided by the extension of the Pelusium megashear system in the Western Desert. Along this shear zone, the thickened aquifer, extensive brittle deformation, high hydraulic conductivity, and replenishment by flow from the southwest make this shear zone a promising area for agricultural expansion and development. In contrast, areas proximal to, and north of, the Uweinat uplift are the least-promising areas, given the shallow basement, limited aquifer thickness (~300–800 m), and presence of barriers to groundwater flow from the south.

Using the Nubian Sandstone Aquifer System as our test site, we demonstrated that GRACE data can provide accurate measures for mass variations over large hydrologic systems that are difficult to accomplish otherwise. We also showed that GRACE data, together with other relevant data sets, could be used to address questions pertaining to the locations where, and the rates at which recharge or discharge occur, as well as to determine whether aquifers and their subbasins are in steady-state conditions or are being depleted—and if they are being depleted, to investigate whether depletion is caused by natural or anthropogenic factors. GRACE data were also used to identify barriers and preferred pathways for groundwater flow. All of these demonstrations were accomplished by verifying GRACE measurements and observations against geochemical, geochronologic, geophysical, and field data. The advocated conceptual model can be used to construct sound groundwater flow model(s) for the Nubian Sandstone Aquifer System, and the latter, upon calibration, could be used to further validate the advocated conceptual model. Answering the questions listed herein for the Nubian Sandstone Aquifer System is critical for optimum management of the Nubian Sandstone Aquifer System, and, more importantly, for the development of replicable models that can be readily applied to similar aquifers worldwide.

ACKNOWLEDGMENTS

Funding was provided by National Aeronautics and Space Administration Earth Science Division grant NNX12AJ94G and the National Academies of Sciences grant 2000007141 awarded to Western Michigan University; the Egyptian Ministry of Higher Education and Scientific Research; and the Earth Sciences Remote Sensing Facility at Western Michigan University. We thank the editor (Aaron J. Cavosie), associate editor (Jeff Clark), and reviewers of the *GSA Bulletin* for their instructive comments and suggestions.

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Science Editor: Aaron J. Cavosie
Associate Editor: Jeffrey Clark

Manuscript Received 20 November 2015
Revised Manuscript Received 22 August 2016
Manuscript Accepted 14 November 2016

Printed in the USA