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Rise and demise of the New Lakes of Sahara

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ABSTRACT

Multispectral remote sensing data and digital elevation models were used to examine the spatial and temporal evolution of the New Lakes of Sahara in southern Egypt. These lakes appeared in September 1998, when water spilled northwestward toward the Tushka depression due to an unusual water rise in Lake Nasser induced by high precipitation in the Ethiopian Highlands. Five lakes were formed in local depressions underlain by an impermeable Paleocene shale and chalk formation. The lakes developed through three stages. (1) A rise stage occurred from September 1998 to August 2001; the area covered by the lakes reached ~1586 km^2. In this stage the rate of water supply far exceeded the rate of water loss through evaporation. This stage was characterized by an early phase (August 1998–August 1999) when the area covered by the lakes increased by ~75 km^2/month. This was followed by a late phase (August 1999–August 2001), in which area increase averaged ~28 km^2/month. (2) A steady-state stage occurred from August 2001 to August 2003, during which the area covered by the lakes remained relatively unchanged and water lost through evaporation was continuously replaced by water supply from Lake Nasser. (3) A demise stage occurred from August 2003 to April 2007, during which water supply from Lake Nasser stopped completely and water was continuously evaporating. The area covered by the lakes decreased to ~800 km^2 with an average loss of ~17 km^2/month. If this trend continues, the New Lakes of Sahara will disappear completely by March 2011. The spatial distribution of the New Lakes of Sahara is strongly controlled by morphologically defined east-, north-, northeast-, and northwest-trending faults. The water recharge of the Nubian aquifer by the New Lakes of Sahara is insignificant; much of the lakes' area is above an impermeable formation.

Keywords: New Lakes of Sahara, Western Desert, Egypt, Nubian aquifer.

INTRODUCTION

Egypt relies completely on the Nile River for its water supply because it is located in arid and semiarid zones with ~100 mm/yr precipitation (Fig. 1). Almost all of the Egyptian Nile water, which totals ~84 × 10^9 m^3/yr (Abu Zeid and El-Shibini, 1997), comes from the highlands of Ethiopia and Sub-Saharan Africa through the Blue Nile and the White Nile, respectively, where precipitation reaches ~1800 mm/yr (Fig. 1). For decadal management of the Egyptian Nile water, Egypt built the Aswan High Dam, which was completed in 1968. To the south, the dam created Lake Nasser, which is ~500 km long, and ~12 km wide on average (Fig. 2; Said, 1993). This lake covers an area of ~6000 km^2 and stores ~163 × 10^9 m^3 of water. The Aswan High Dam is ~2325 m long,~111 m high, and ~40 m wide at the crest and ~980 m at the bottom. Six tunnel inlets are used for discharge control and water supply to power plants. An escape spillway is provided at the western side to permit excess water discharge if water exceeds the 182 m maximum capacity of the dam.

The water level of Lake Nasser reached ~178 m by 1978, but the lake receded to ~158 m in 1987 due to severe drought in Ethiopia and Sub-Saharan Africa in the mid 1980s (Collins, 2002). In the early 1990s water level began to rise again, and reached ~182 m in 1997 due to above-average precipitation in the Ethiopian Highlands (Kim and Sultan, 2002). By 1998 water level exceeded 182 m and water began to flow northwestward through the Tushka Valley toward the Tushka depression, forming the New Lakes of Sahara (Fig. 3).

Since their formation, only a few presentations have addressed the spatial and temporal evolution of the New Lakes of Sahara and their potential influence on the rechargeability of the Nubian aquifer. Yan et al. (2003) used multitemporal resolution data to estimate water storage in the lakes until 2003 and their possible recharge contribution to the Nubian aquifer. El-Bastawesy et al. (2007) used digital elevation models (DEMs), extracted from airborne photogrammetic data acquired before the lakes were formed, to estimate water loss. Chipman and Lillesand (2007) used Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) images, Shuttle Radar Topography Mission (SRTM) DEMs,

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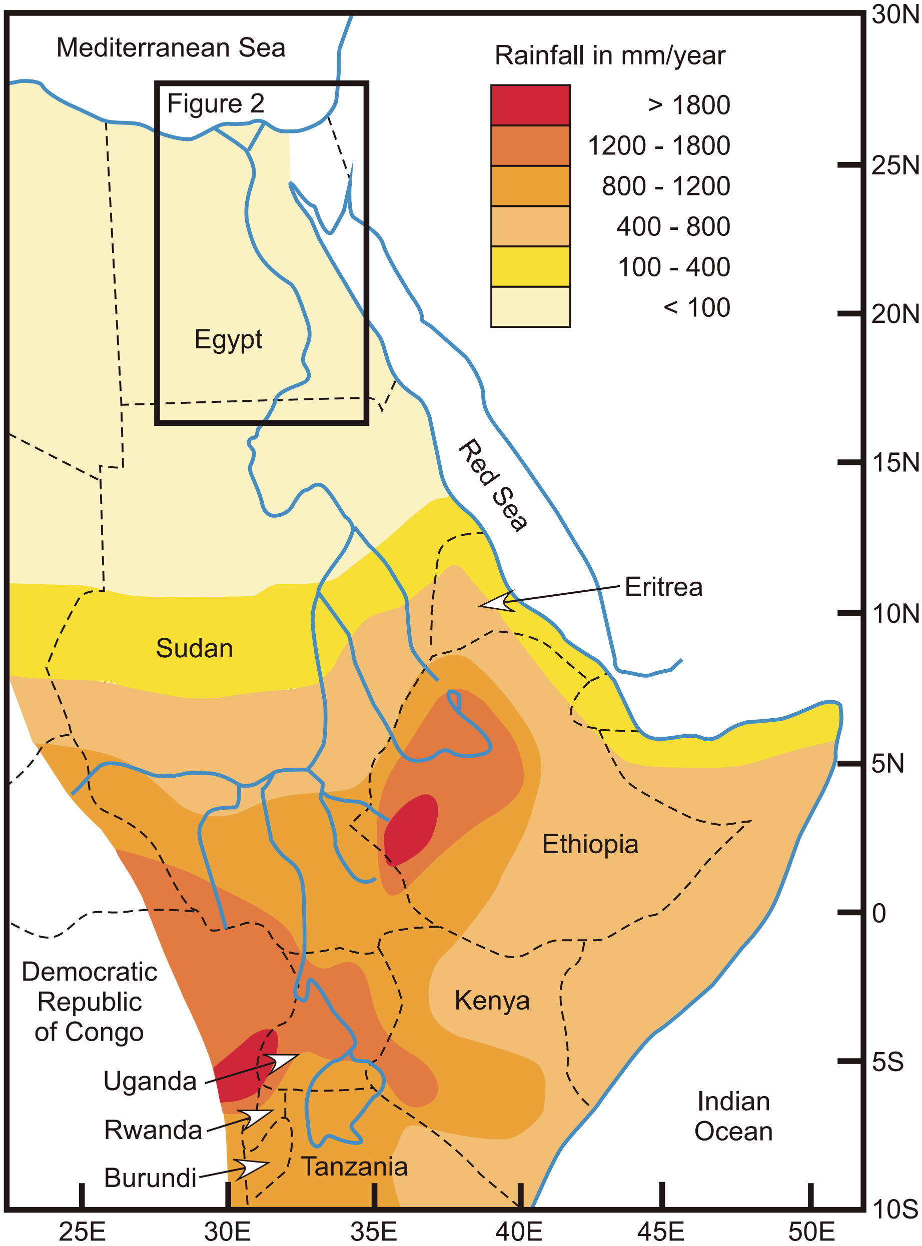

Figure 1. Map of the Nile River system showing annual precipitation. Box shows location of Figure 2.

and laser altimetry data from the ICESat Geoscience Laser Altimeter System (GLAS) to estimate surface area and water volumes of the New Lakes of Sahara until September 2005. In the Chipman and Lillesand (2007) study, the water volume is estimated for only the last lake, because other lakes were already filled prior to the acquisition of SRTM data in February 2000.

This work presents a comprehensive documentation of temporal and spatial evolution of the New Lakes of Sahara using multidate remote sensing data and DEMs. We present time slices of the evolution of the lakes since their formation in September 1998 until April 2007, and predict their ultimate disappearance. In addition, geomorphological and geological controls on the evolution of the lakes are examined. We then discuss the effect of the appearance and disappearance of the lakes on the Sahara Desert and the contribution of the lakes to the recharge of the Nubian aquifer.

DATA AND METHODS

Multidate (September 1998–April 2007) Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, SRTM DEMs (Table 1), and previously published geological information were used in this study. Bands 2, 4, and 7 of Landsat TM and ETM+ data are used to outline the areal extent of the New Lakes of Sahara and to generate a time series for the evolution of the lakes between August 1998 and April 2007 (Fig. 4). For this, a one-class (water) parallelepiped supervised classification is used to reduce the commission error (error arises from the incorrect inclusion of pixels representing land cover other than water). The accuracy of supervised classification in detecting small water bodies and wetlands in dry regions can sometimes be low due to variation of spectral signatures as a function of ecological conditions (Gond et al., 2004). However, it is expected here that the accuracy of parallelepiped classification will be significantly high because of the sharp difference between the spectral signatures of water within the New Lakes of Sahara (which absorbs bands 2, 4, and 7) compared to the surrounding Sahara sand (which reflects bands 2, 4, and 7). This is evident in the 7–4-2 Landsat TM and ETM+ images in which the New Lakes of Sahara (black) can be clearly distinguished from the surrounding sand of the Sahara Desert (white to light brown). In addition, the accuracy of the supervised classification is evaluated through the computation of the lake's perimeter to lake area ratio. This ratio is between 0.66 and 0.31 for all lakes (Fig. 4), indicating a high accuracy of results of supervised classification. Scan Line Corrector (SLC)–off mode is selected for Landsat ETM+ data acquired after 31 May 2003 to avoid image distortion caused by malfunctioning of the SLC since that date. Results of the supervised classification are subsequently used to calculate the area of each lake as well as the total area of all lakes. The change of area covered by the New Lakes of Sahara is presented as a function of time (Fig. 5). A linear regression modeling is implemented to predict the life expectancy of the lakes (Fig. 6). A 7–3-1 ASTER mosaic is draped onto the STRM DEMs to create three-dimensional (3D) perspective views of the New Lakes of Sahara and the surrounding terrain (Fig. 7). These 3D perspective views are used, together with previously published geological information, to map lithological units and morphologically defined faults (Fig. 8) to outline geomorphological and geological controls on the evolution of the New Lakes of Sahara.

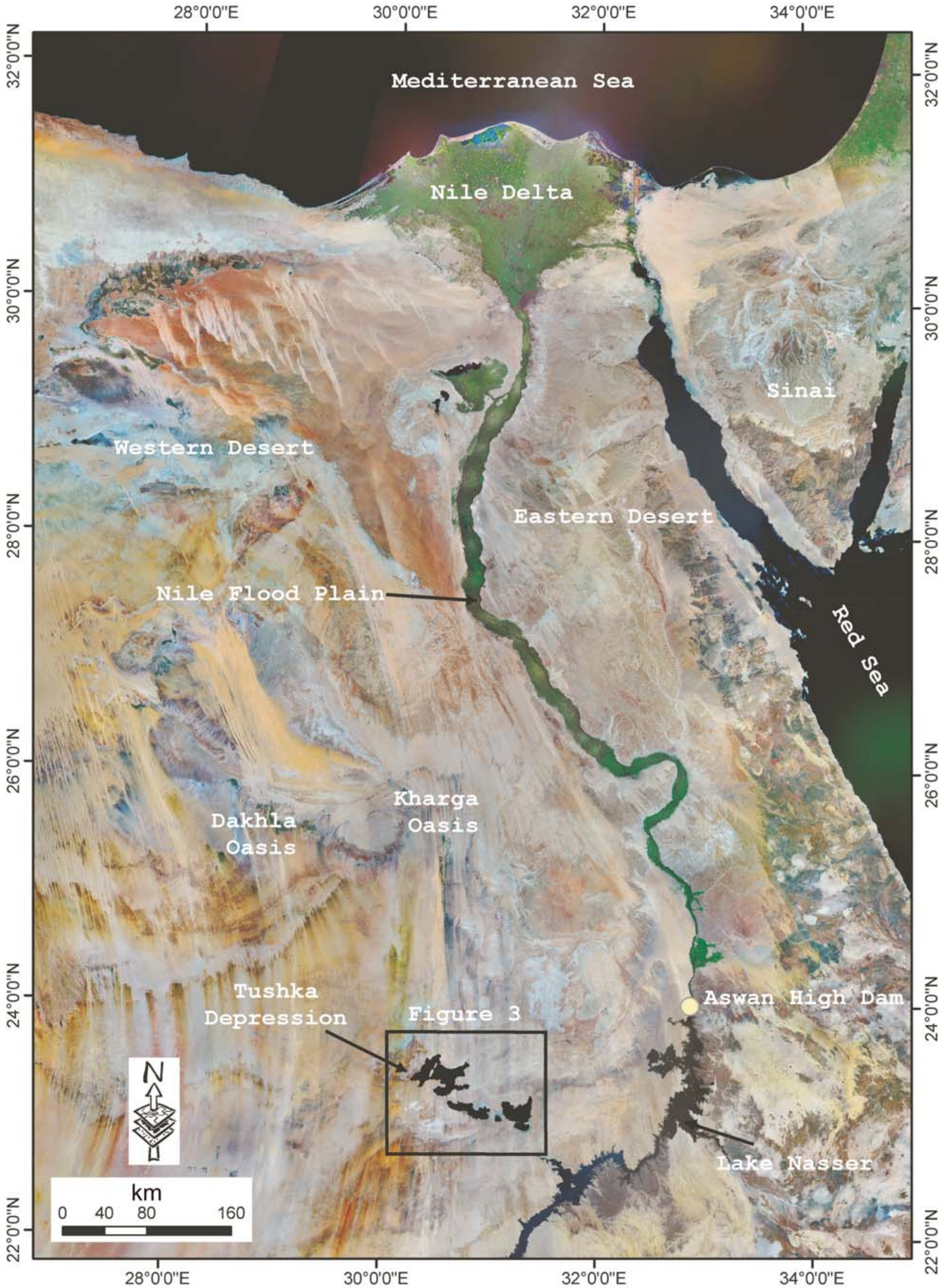

Figure 2. A 7–4-2 Landsat Enhanced Thematic Mapper Plus (ETM+) mosaic produced from images acquired between 2001 and 2002 showing physiographic features of Egypt and the location of the New Lakes of Sahara within the Tushka depression west of Lake Nasser. Box shows location of Figure 3.

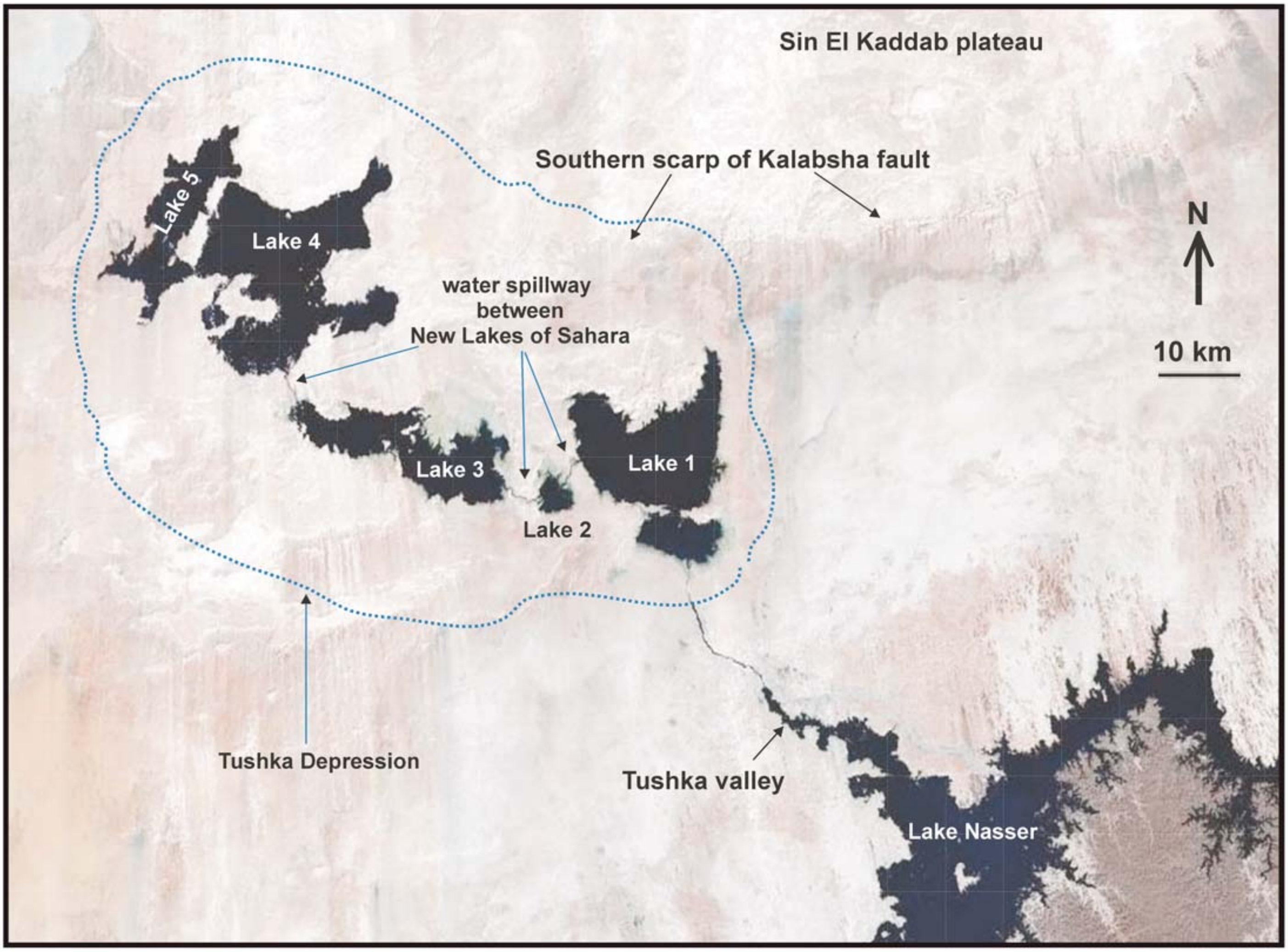

Figure 3. A 7–4-2 Landsat Enhanced Thematic Mapper Plus (ETM+) image acquired in January 2001 showing the New Lakes of Sahara at the peak of their development. Note that lake 1 is connected to Lake Nasser through the Tushka Valley and lakes 1, 2, 3, 4, and 5 are connected with each other through narrow conduits. The lakes were formed within the Tushka depression, which is bound in the north by the Kalabsha fault zone, which represents the southern escarpment of the Sin El Kaddab Plateau. See Figure 2 for location.

RESULTS

Temporal Evolution of the New Lakes of Sahara

The temporal evolution of the New Lakes of Sahara is characterized by a rise stage, a steady-state stage, and a demise stage (Fig. 5).

Rise Stage

This stage is characterized by rapid development of the New Lakes of Sahara as water started spilling northwestward from Lake Nasser toward the Tushka depression through the Toshka Valley, starting September 1998, resulting in the development of five new lakes connected with each other through narrow conduits (Fig. 3). These lakes are named (from east to west and from oldest to youngest) lakes 1, 2, 3, 4, and 5. Lake 1 appeared first in September 1998, covering an area of ~78 km^2 (Fig. 4A). The area of this lake increased rapidly to ~192 km^2 in October 1998 (Fig. 4B), and reached ~359 km^2 by November 1998 (Fig. 4C). Water continued to spill northwestward from Lake Nasser throughout 1999 to completely fill lake 1, which covered an area of ~400 km^2 by August 1999 (Fig. 4D). Subsequently, water started spilling southwestward to form the small circular lake 2 followed by a westward spill of water from lake 2 to form the east-west–elongated lake 3 (Fig. 4D). Lakes 2 and 3 covered an area of ~500 km^2, and the total area of the three lakes reached ~900 km^2 by August 1999 (Fig. 4D). Water level in Lake Nasser remained above the maximum capacity throughout 2000 and water continued to supply the New Lakes of Sahara. As a result, water started to spill northward from lake 3 to form the irregularly shaped lake 4, which covered a total area of ~430 km^2 by September 2000; the total area covered by the lakes reached ~1330 km^2 (Fig. 4E). In August 2001 water spilled westward from lake 4, resulting in the formation of the northeast-elongated lake 5, covering an area of ~256 km^2. The total area of the New Lakes of Sahara reached its peak of ~1586 km^2 by August 2001 (Fig. 4F). This estimation is lower than the maximum lakes extension of 1740 km^2 of Chipman and Lillesand (2007). This difference might be due to a number of factors. First, the estimation in this study is based on data acquired in August 2001, whereas Chipman and Lillesand (2007) based their conclusion on

TABLE 1. CHARACTERISTICS OF THE REMOTE SENSING DATA USED IN THIS STUDY

Parameter	Sensor			
	Landsat TM	Landsat ETM+	ASTER	SRTM
Date launched	March 1984	April 1999	December 1999	February 2000
Orbit platform	satellite	satellite	satellite	Space shuttle
Lifetime	5 years	5 years	5 years	11 days
Organization	NASA	NASA	NASA/MITI	NASA/NIMA/DLR/ASI
Swath width	185 km	185 km	60 km	X–band—50 km C–band—225 km
Altitude	919 km	919 km	750 km	233 km
Class	optical	optical	optical	RADAR
Spectral region	VNIR 1, 2, 3, 4 SWIR 5, 7 TIR 6	VNIR 1, 2, 3, 4 SWIR 5, 7 TIR 6 Pan 8	VNIR 1, 2, 3 SWIR 4, 5, 6, 7, 8, 9 TIR 10, 11, 12, 13, 14	microwave
Bands wavelength (μm)	1 = 0.45–0.52 2 = 0.52–0.60 3 = 0.63–0.69 4 = 0.76–0.90 5 = 1.55–1.75 6 = 10.40–12.50 7 = 2.08–2.35	1 = 0.45–0.52 2 = 0.52–0.60 3 = 0.63–0.69 4 = 0.76–0.90 5 = 1.55–1.75 6 = 10.40–12.50 7 = 2.08–2.35 8 = 0.52–0.90	1 = 0.52–0.60 2 = 0.63–0.69 3 = 0.76–0.86 4 = 1.60–1.70 5 = 2.145–2.185 6 = 2.185–2.225 7 = 2.235–2.285 8 = 2.295–2.365 9 = 2.360–2.430 10 = 8.125–8.475 11 = 8.475–8.825 12 = 8.925–9.275 13 = 10.25–10.95 14 = 10.95–11.65	X–band = 3000 C–band = 5600
Spatial resolution (m)	VNIR = 30 SWIR = 30 TIR = 120	VNIR = 30 SWIR = 30 TIR = 60 Pan = 15	VNIR = 15 SWIR = 30 TIR = 90	30–90
Polarization				X–band = VV C–band = HH, VV
Identification and dates of data used in this study	P/R 175/44 1998/09/20 1998/10/06 1998/11/07 1999/08/06 P/R 176/44 1999/08/13	P/R 176/44 2000/09/01 2001/08/19 2002/07/21 2003/08/09 2004/08/11 2005/08/14 2006/08/01 2007/04/14 P/R 176/44 2000/08/23 2001/08/26 2002/08/29 2003/08/16 2004/08/19 2005/07/04 2006/07/07 2007/04/05	L1A.003;2003200906 2001/05/31 L1A.003;2003200908 2001/05/31 L1A.003;2005269218 2001/12/09 L1A.003;2005269220 2001/12/09 L1A.003;2010985018 2003/01/29 L1A.003;2010985024 2003/01/29	SRTM_42_08 SRTM _43_08

Note: NASA—U.S. National Aeronautics and Space Agency; MITI—Japan Ministry of International Trade and Industry; NIMA—U.S. National Imagery and Mapping Agency; DLR—German Space Agency; ASI—Italian Space Agency; ASTER–Advanced Spaceborne Thermal Emission and Reflection Radiometer; SRTM—Shuttle Radar Topography Mission; ETM+—Enhanced Thematic Mapper Plus; VNIR—very near infrared; SWIR—shortwave infrared; TIR—thermal infrared.

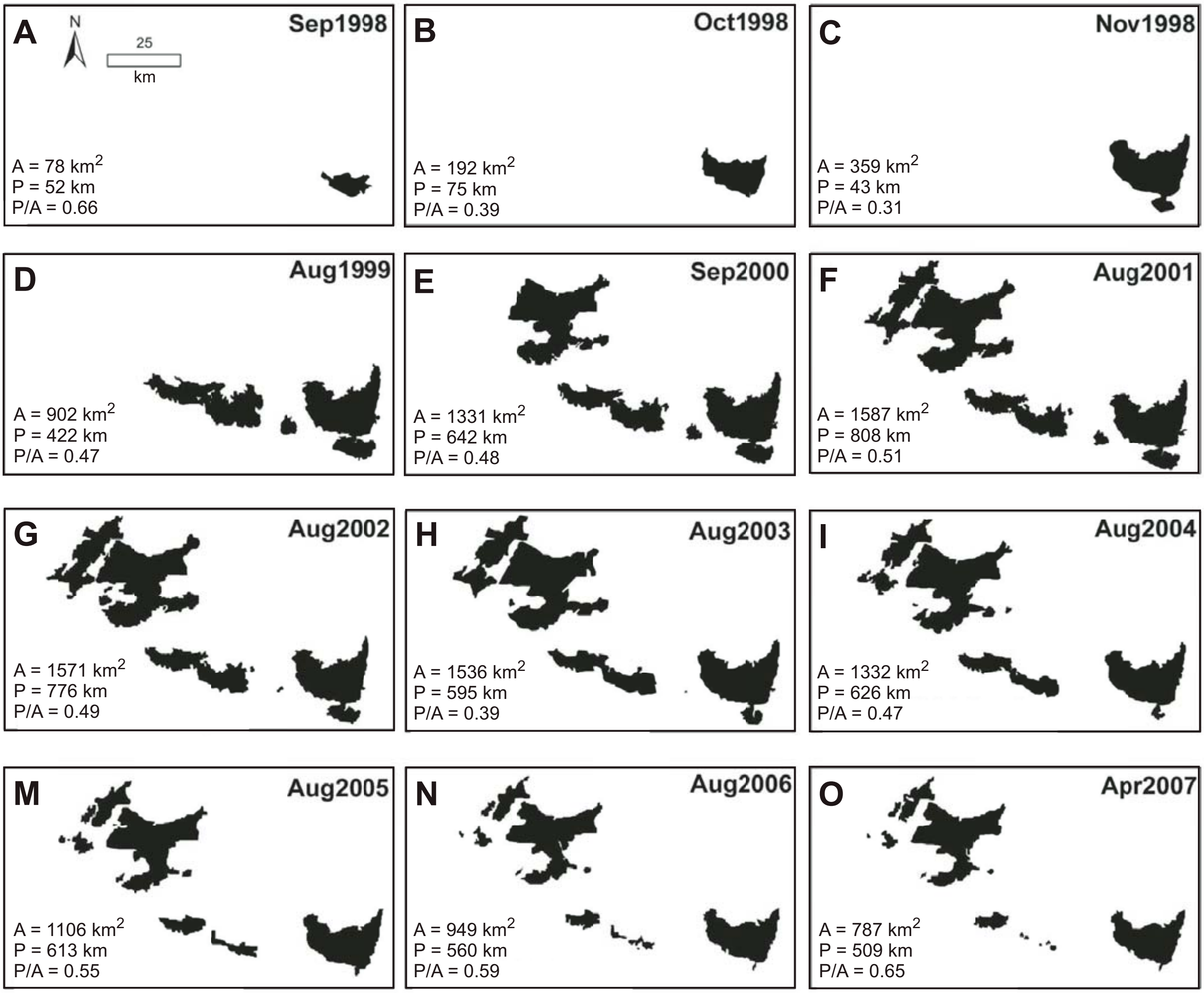

Figure 4. A 10-yr time series of the evolution of the New Lakes of Sahara between September 1998 and April 2007 developed from one class (water) parallelepiped supervised classification using bands 2, 4, and 7 of multitemporal resolution Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). A—area, P—perimeter.

data collected in December 2001. Second, this study implemented Landsat TM and ETM+ data with 30 m spatial resolution, whereas Chipman and Lillesand (2007) used MODIS and AVHRR data with 500 and 1000 m spatial resolution, respectively. Third, supervised parallelepiped classification is used in this study, whereas a subpixel linear unmixing technique was used by Chipman and Lillesand (2007). The total volume of water within the lakes in 2002 is estimated to be ~25.3 × 10^9 m^3 based on calculations from DEMs extracted from airborne photogrammetric data acquired before the lakes were formed (El Bastawesy et al., 2007).

The rise stage of the New Lakes of Sahara is characterized by an early and a late phase. During the early phase the area covered by the lakes increased rapidly between September 1998 and August 1999, averaging ~75 km^2/month (Fig. 5). However, during the late phase (between August 1999 and August 2001), the rate of area increase decreased to an average of ~28 km^2/month (Fig. 5). This is attributed to the fact that during the early phase, water was filling the empty subdepressions within the Tushka depression, allowing for rapid expansion of the lakes. However, during the late phase a significant amount of water was already present within the lakes. This resulted in a "push back" effect, resulting in a decrease of water flow coming from Lake Nasser; regardless, water level remained the same throughout the rise stage.

Steady-State Stage

This stage spans August 2001 and August 2003. The New Lakes of Sahara reached their peak by August 2001, covering an area of ~1586 km^2. After August 2001 the water level of Lake Nasser began to recede and the water flow toward the Tushka depression started to decrease, but water had been steadily flow-

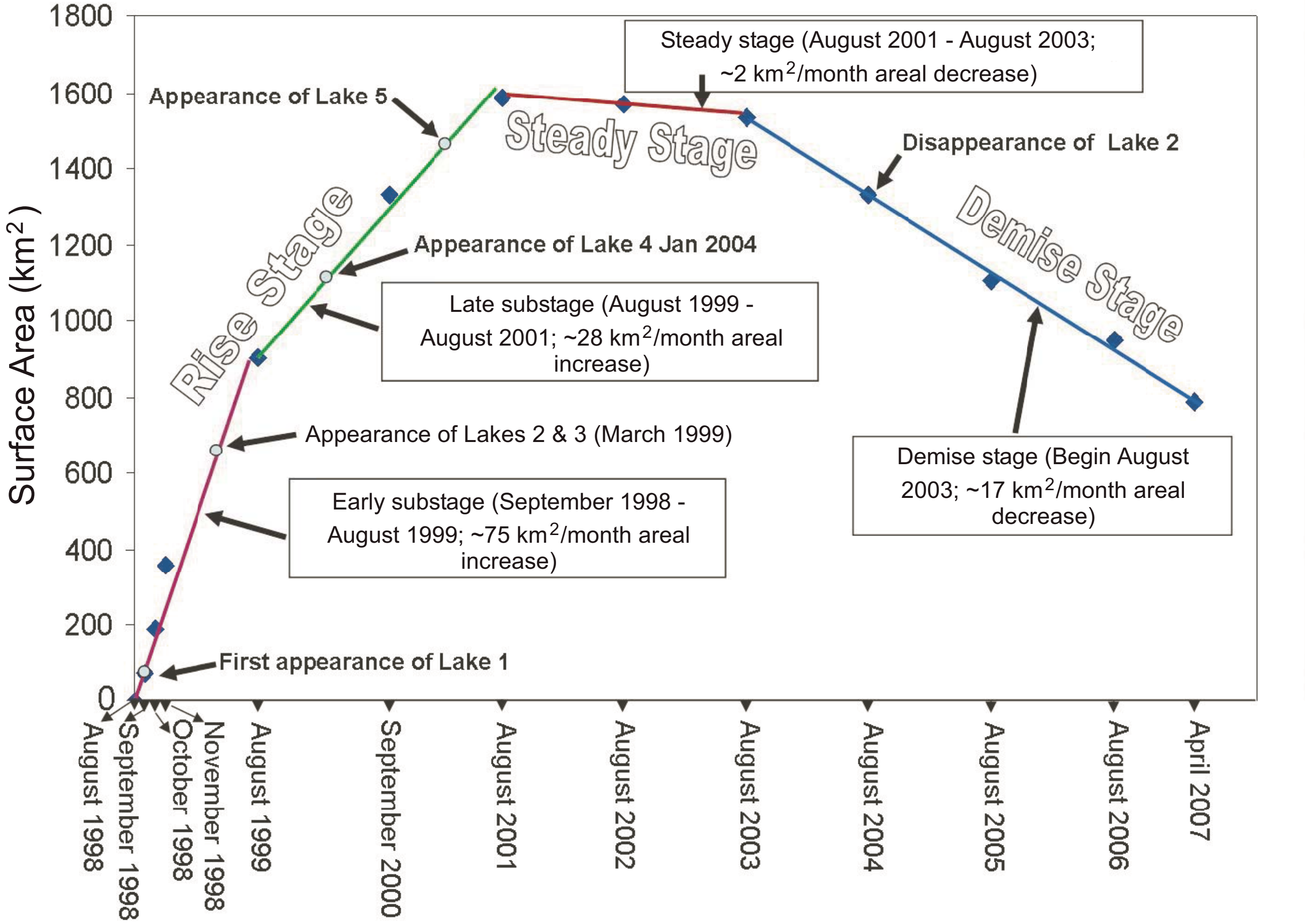

Figure 5. Graph showing area covered by the New Lakes of Sahara versus time between August 1998 and April 2007. The graph clearly shows that the New Lakes of Sahara have evolved through three stages: a rise stage (divided into an early and a late substage), a steady-state stage, and a demise stage. The graph also shows the appearance and disappearance of individual lakes.

ing toward the New Lakes of Sahara. In these two years, the area covered by the lakes decreased slightly, from ~1586 km^2 to ~1535 km^2 (Figs. 4F–4H). Hence, during this stage, the rate of the decrease of the area covered by the lakes was ~2 km^2/month (Fig. 5). It is likely that during this stage the amount of water lost from the lakes through evaporation was slightly higher than that supplied by Lake Nasser. Adopting an evaporation rate of 2.3 m/yr (as measured by the General Authority for the High Dam from September 2003 to August 2004; El Bastawesy et al., 2007) and no significant infiltration, the New Lakes of Sahara must have received an annual recharge of ~3.5 × 10^9 m^3 from Lake Nasser for the period between August 2001 and August 2003. Assuming equilibrium between water evaporation and water supply, the amount of water needed to keep the areal extent of the New Lakes of Sahara constant during this period can be calculated by the multiplication of the evaporation rate (2.3 m/yr) by the areal extent of the lakes (~1535 km^2).

Demise Stage

This stage covers the time span between August 2003 and April 2007. By August 2003 water supply from Lake Nasser had completely stopped and the conduits between the Tushka Valley and lake 1 as well as those connecting the lakes had completely dried out. Water was continuously evaporating from the New Lakes of Sahara. It is argued here that evaporation, rather than infiltration, was the dominant factor in the drying of the New Lakes of Sahara. This is because these lakes are underlain by an impermeable Paleocene shale and chalk formation (Figs. 8A, 8D). A similar conclusion was reached by El Bastawesy et al. (2007). By August 2004 lake 2 had disappeared completely, and lakes 1, 3, 4, and 5 had started to shrink. The total area covered by the lakes decreased to ~1330 km^2 (Figs. 4L). Between August 2005 and April 2007 the lakes continued to shrink, resulting in an almost complete disappearance of lakes 3 and 5 (Figs. 4M–4O). The area covered by the New Lakes of Sahara was ~1100 km^2 in August 2005, ~950 km^2 in August 2006, and ~800 km^2 in April 2007 (Figs. 4M–4O), indicating an average water loss of ~17 km^2/month (Fig. 5).

Future of the New Lakes of Sahara

Monitoring land cover changes with remote sensing data and predicting future trends is sometimes limited by weak correlation between remote sensing data and biophysical variables, lack of consistency in frequency of observations, and inadequate temporal resolution compared to

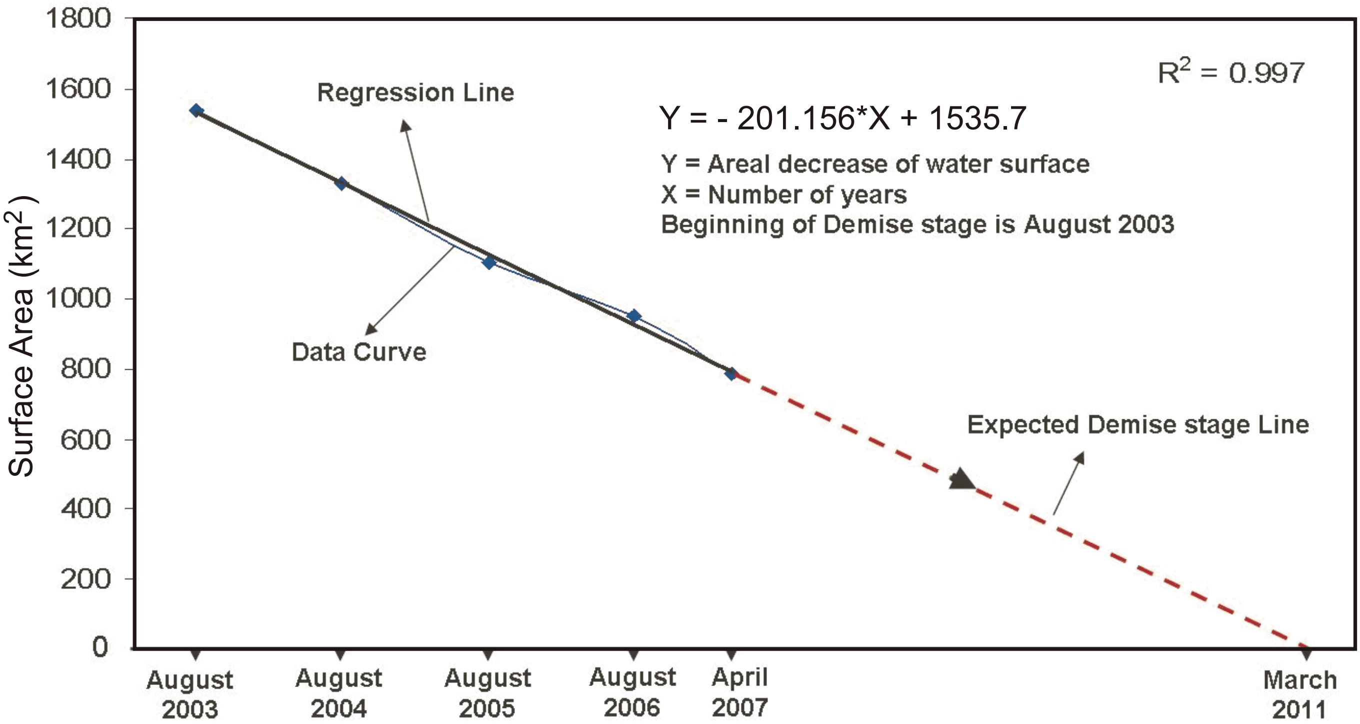

Figure 6. Regression line model developed to predict life expectancy of the New Lakes of Sahara and their ultimate disappearance in March 2011. The model was developed through first-order polynomial fit of data extracted from the demise stage (August 2003 and April 2007) of the New Lakes of Sahara. R—correlation coefficient.

the dynamicity of some phenomena (Lambin, 2001). Our attempt to predict the future evolution of the New Lakes of Sahara is based on the facts that (1) the New Lakes of Sahara are drying out, primarily due to evaporation, which is expected to maintain a constant rate of 2.3 m/yr, and (2) no more water will be received from Lake Nasser. This allows for modeling the demise of the lakes as a linear function. The consistency of the frequency of observation and adequacy of temporal resolution are ensured by using Landsat ETM+ images acquired in the same month (August) between 2003 and 2006 (Table 1). Linear regression is used to determine the life expectancy of the New Lakes of Sahara and when they will disappear: the regression line suggests that the lakes will disappear completely by March 2011 (Fig. 6). The regression line has a strong correlation (correlation coefficient R = 0.997) benefiting from the fact that the rate of water loss during the demise stage remained steady and can be modeled as a first-order polynomial fit (Fig. 6). This prediction contradicts a previous model that suggested that the New Lakes of Sahara will expand in the future to cover a wider region beyond the Tushka depression (Yan et al., 2003). We recommend that future remote sensing studies be carried out to test the prediction of this work.

The linear regression modeling indicates that the duration between the beginning of the demise stage (August 2003) of the New Lakes of Sahara and their ultimate disappearance (March 2011) is 7.6 yr. This time span, together with the evaporation rate of 2.3 m/yr, is used to conclude that the New Lakes of Sahara must have stored a minimum of ~26.8×10^9 m^3 of water at their peak. This is calculated through the multiplication of the evaporation rate (2.3 m/yr) by the time span needed for the complete disappearance of the lakes from the beginning of the demise stage in August 2003 to their ultimate disappearance in March 2011 (7.6 yr), by the area covered by the lakes in August 2003 (~1535 km^2). This estimation is in good agreement with the ~25.3×10^9 m^3 calculated by El Bastawesy et al. (2007) through DEMs covering the Tushka depression prior to the beginning of the appearance of the New Lakes of Sahara.

Geomorphological and Geological Controls of the New Lakes of Sahara

A mosaic generated from 7-3-1 ASTER images and SRTM DEMs and previously published geological maps of Egypt [Egyptian Geological Survey and Mining Authority (EGSMA), 1981; Egyptian General Petroleum Corporation and Conoco Coral, 1987] were used to examine possible geomorphological and geological controls on the New Lakes of Sahara. The lakes were formed within the Tushka depression, which constitutes a number of local depressions that are bound in the north by the ~300-m-high southern escarpment of the Sin El Kaddab Plateau (Fig. 3). The escarpment is associated with the seismically active east-trending dextral strike-slip Kalabsha fault zone and separates a plateau dominated by Eocene carbonate rocks in the north from the low-lying Nubia Plain to the south. Farther south and southwest, the Nubia Plain slopes gently toward the lowlands of Sudan. The Nubia Plain exposes Neoproterozoic granitoids, Cretaceous sandstone, Upper Cretaceous sandstone and limestone, and Paleocene shale and chalk formations, which crop out within and beyond the Tushka depression (Fig. 8A).

The Neoproterozoic granitoids crop out in the southern part of the Tushka depression, whereas the Cretaceous sandstone and Upper Cretaceous sandstone and limestone formations dominate the margins of the depression in the northwest, southwest, and southeast (Fig. 8A). The Paleocene shale and chalk formation dominates the Tushka depression, where it forms low-lying flat terrain ranging in elevation between ~100

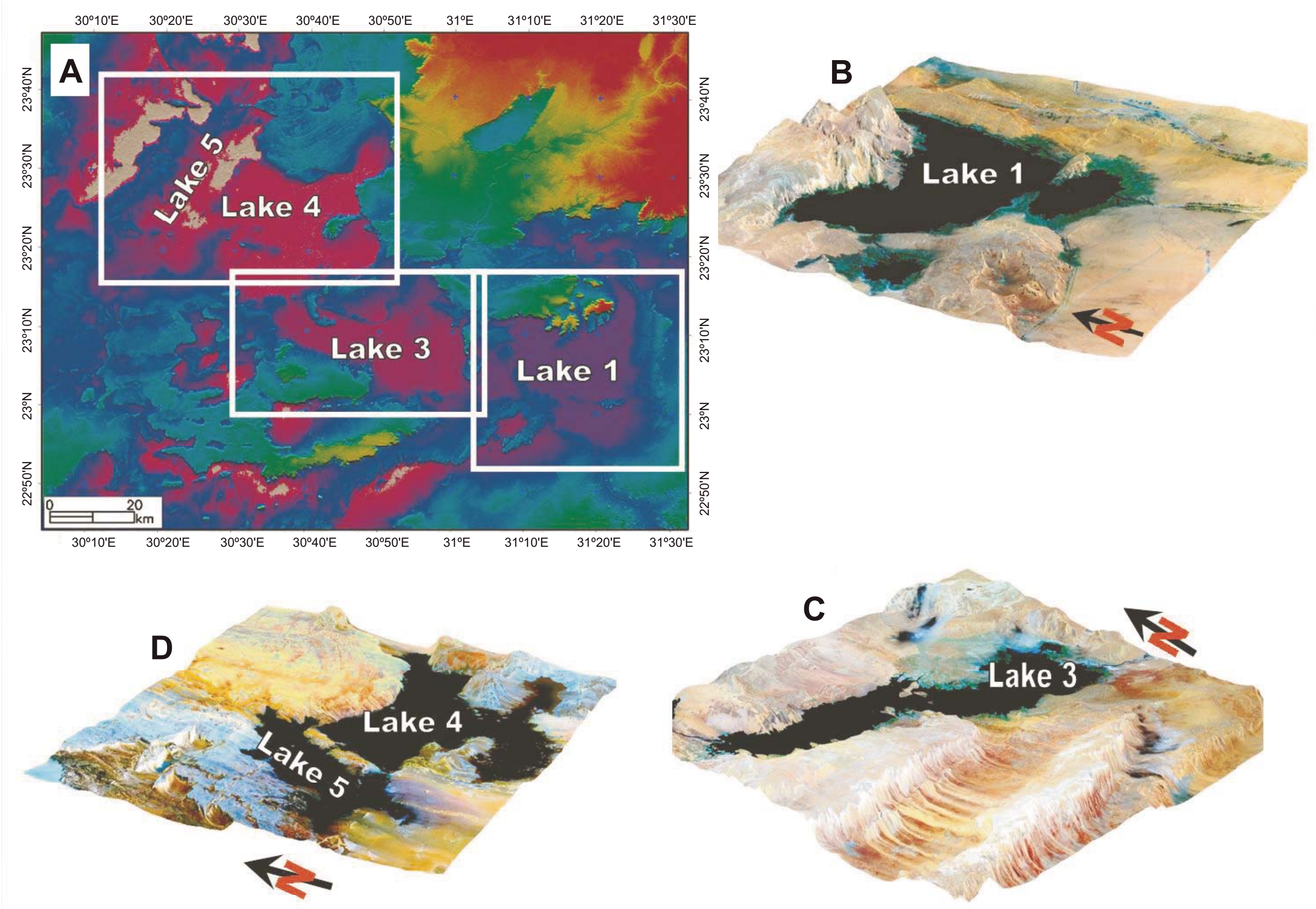

Figure 7. (A) Hill-shade digital elevation model (DEM) covering the New Lakes of Sahara within the Tushka depression extracted from the Shuttle Radar Topography Mission (SRTM) data, which were acquired in April 2000. The hill-shade DEM was developed through 135° sun azimuth and 20° sun angle with RAINBOW color table (red = 300 m and white = 100). (B–D) Three-dimensional perspective views with 20× vertical exaggeration of lakes 1 and 2 (B), 3 (C), and 4 and 5 (D), developed from draping 7–3-1 Advanced Spaceborne Thermal Emission and Reflection Radiometer images onto SRTM DEM.

and ~200 m. This topography contrasts that of the Eocene limestone formation, which forms plateaus, mesas, and buttes with as much as ~300 m elevations (Fig. 8D). Hence, it is likely that the geomorphological characteristics of the Paleocene shale and chalk formation have controlled spatial distribution of the New Lakes of Sahara.

In addition to lithology, the geomorphology of the Tushka depression is strongly influenced by geomorphologically defined faults, especially the most prominent east-trending faults (Figs. 8A, 8B). However, north-, northeast-, and northwest-trending faults are also common (Figs. 8A, 8B). In addition, fractures in the region seen in the Egyptian General Petroleum Corporation and Conoco Coral (1987) geological map show a strong northeast trend (Figs. 8A, 8C). Many faults in the area, whether normal, oblique, or strike-slip faults, are associated with low-lying escarpments that are few tens of meters high (Fig. 7). These escarpments have significantly controlled the spatial distribution of the New Lakes of Sahara. The overall distribution of the New Lakes of Sahara is in an east-west direction, parallel to the east-trending faults. Moreover, the shorelines of the lakes in many cases are parallel to fault escarpments of different orientations. This is evident from lake 1, where its eastern, southern, and to some extent northern shorelines coincide with north- and east-trending faults (Figs. 7A, 7B, and 8A). Similarly, the shorelines of lake 3 are almost entirely coinciding with east- and northwest-trending faults (Figs. 7A, 7C, and 8A). Moreover, east- and northeast-trending faults have controlled the shorelines of lakes 4 and 5 (Figs. 7A, 7D, and 8A).

DISCUSSION

Changing Landscape of Sahara—Humans and Nature

It has been ~6000 yr since any standing body of water was formed in the Sahara Desert. That was during the Holocene, a time that was characterized by intermittent wet and dry periods, leading to the emergence of the Sahara Desert to dominate northern Africa (Sultan et al. 1997; Issawi et al., 1999). After the building of the Aswan High Dam, the Tushka depression became Egypt's first defense to accommodate any sharp unexpected increase in water level in Lake Nasser. This is meant to save Egypt from any massive flooding and to reduce any negative impact on the Aswan High Dam. The unusual increase in the water level of Lake Nasser

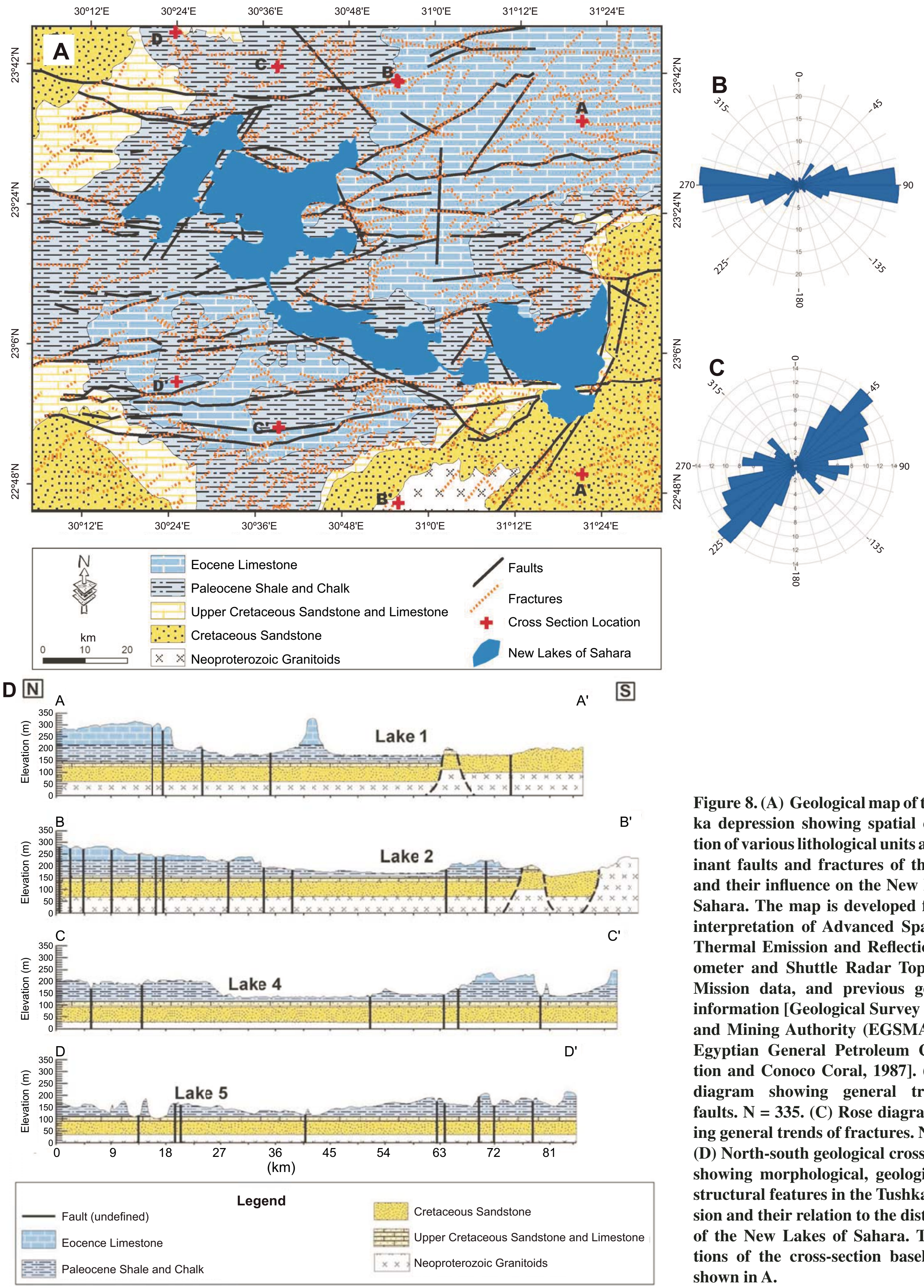

Figure 8. (A) Geological map of the Tushka depression showing spatial distribution of various lithological units and dominant faults and fractures of the region and their influence on the New Lakes of Sahara. The map is developed from the interpretation of Advanced Spaceborne Thermal Emission and Reflection Radiometer and Shuttle Radar Topography Mission data, and previous geological information [Geological Survey of Egypt and Mining Authority (EGSMA), 1981; Egyptian General Petroleum Corporation and Conoco Coral, 1987]. (B) Rose diagram showing general trends of faults. N = 335. (C) Rose diagram showing general trends of fractures. N = 1028. (D) North-south geological cross sections showing morphological, geological, and structural features in the Tushka depression and their relation to the distribution of the New Lakes of Sahara. The locations of the cross-section baselines are shown in A.

between 1998 and 2001 and the formation of the New Lakes of Sahara is a testimony to the effectiveness of this strategy. The rise and demise of the New Lakes of Sahara and potentially similar events in the future will change the landscape of eastern Sahara forever. The question becomes whether this change will have a positive or a negative environmental impact on the region. For example, the rise and demise of the New Lakes of Sahara will leave behind an area of ~1600 km^2 underlain by lake playas, where near-surface interaction between water and the Paleocene shale and chalk formation results in concentration of massive amount of saline sediments (Fig. 9). It is not clear whether this change will hinder future agricultural development plans of Egypt. Currently, Egypt is involved in a major undertaking in which an irrigational-agricultural developmental project—The New Valley Project—is underway to inhibit the Tushka depression. This project is independent of the natural northwestward spilling of Lake Nasser, which formed the New Lakes of Sahara. The New Valley Project plans to take 5 × 10^9 m^3 of water/yr from Lake Nasser for the irrigation of 0.5 × 10^6 acres of land dominantly within the Toshka depression. It is feared here that some areas planned to be cultivated through the New Valley Project might have been damaged by salt accumulation resulting from the drying out of the New Lakes of Sahara.

Surface Water—Groundwater Interaction

The New Lakes of Sahara were formed in a region that is underlain by the Nubian aquifer, one of the world's largest, extending into Egypt, Libya, and Sudan, with a reservoir capacity of 75,000 × 10^9 m^3 (Hess et al., 1987). Water contained within this aquifer is mostly fossil nonrenewable groundwater accumulated during Quaternary time (Sultan et al., 1997). Nevertheless, the Nubian aquifer close to the Nile might have received recent recharge from Lake Nasser (Abdel Karim, 1992). Kim and Sultan (2002) concluded from a two-dimensional groundwater flow model that the recharge of the Nubian aquifer by Lake Nasser between 1970 and 2000 is ~53 × 10^9 m^3, and this is likely to decrease by 86% in the next 50 yr. The Nubian aquifer is undersaturated and it could have accommodated much of the New Lakes of Sahara water through infiltration. These lakes, however, are underlain by the Paleocene shale and chalk formation, and it is accepted that infiltration is limited (e.g., El Bastawesy et al., 2007). Yan et al. (2003) estimated that only 13% of the New Lakes of Sahara water has infiltrated to recharge the Nubian aquifer. This translates to ~0.45 × 10^9 m^3/yr at the peak of the lakes where the amount of water is estimated to be ~26.8 × 10^9 m^3. Yan et al. (2003) concluded that the only condition for a meaningful recharge of the Nubian aquifer by the New Lakes of Sahara is for the latter to spill in the future beyond the Paleocene shale and chalk formation to cover the Cretaceous sandstone formation. This work has demonstrated that this is an unlikely scenario. Unfortunately, the infiltration rate remained insignificant despite the efforts of the Egyptian authority to drill injection wells within the New Lakes of Sahara to recharge the Nubian aquifer.

Figure 9. Photograph acquired January 2001 showing the southern margin of lake 1 of the New Lakes of Sahara with extensive salt deposits (white, foreground) resulting from near-surface interaction between water and the Paleocene shale and chalk formation. Height of shrubs ~7 m.

CONCLUSION

The New Lakes of Sahara were formed in the Tushka depression in the Sahara Desert in southern Egypt and they have gone through three stages of progression. (1) During the rise stage (September 1998–August 2001), water supply from Lake Nasser far exceeded the evaporation rate. The area covered by the lakes reached a peak of ~1586 km^3 with an average expansion of ~40 km^2 a month. (2) During the steady-state stage (August 2001 and August 2003), the rate of water supply was close to that of water lost through evaporation. (3) During the demise stage (August 2003–April 2007), water supply from Lake Nasser completely stopped and water was constantly evaporating. The areal extent of the lakes shrunk to ~800 km^2 during this stage. It is predicted that the New Lakes of Sahara will disappear completely by March 2011 if the water supply and evaporation rate conditions remain the same.

The New Lakes of Sahara were spread over an impermeable Paleocene shale and chalk formation that has prevented water from infiltrating to recharge the Nubian aquifer. This unit, which provided low-lying terrain, together with east-, north-, northeast-, and northwest-trending morphologically defined faults, influenced the spatial distribution of the New Lakes of Sahara.

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