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ORIGINAL ARTICLE

Environmental monitoring and change assessment of Toshka lakes in southern Egypt using remote sensing

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Abstract The High Dam in Aswan was designed so that if the water level behind the dam approaches 178 m above the sea level, surplus water should be diverted naturally toward the Toshka depression in the Western Desert of Egypt. The objective of this study was designed to map the spatial extent of temporal changes that occurred as a result of the formation of Toshka artificial lakes west of the Nile Valley from 2000 to 2013 using the Moderate Resolution Imaging Spectroradiometer (MODIS). A group of spectral transforms have been examined to extract the surface area of water in the lakes as revealed in 14 MODIS images on the basis of one image per year. The Land Surface Water Index, the Normalized Difference Vegetation Index (NDVI), and the new Normalized Difference Lake Index (NDLI) were operated. Results showed that the NDLI was the best to eliminate spectral interferences from surrounding non-water objects. The lakes, which approached their maximum surface area in 2002 have experienced considerable diminishing and are expected to eventually disappear due to evaporation. Salinization and sand encroachment were observed in satellite data at areas, which were previously inundated by water. MODIS images have proved that they could afford an efficient and sustainable source of remotely sensed information for monitoring water bodies in hyper-arid deserts.

Keywords Toshka · OLI · NDVI · MODIS · Desertification

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Introduction

A country of explosive population growth and limited water resources and agricultural land, Egypt has executed an aspiring development project during the last decade of the 20th century to reclaim one of the most inhospitable and hostile places on the Earth to move people out of the crowded Nile Valley and Delta and to shrink the gap between the agricultural production and consumption. The idea of moving people was based on the fact that if the Nile water behind the Aswan High Dam reaches 178 m above the sea level (the upper safe level behind the dam), excess water should be diverted by gravity toward a natural depression extending from the western side of the Lake Nasser (Bastawesey et al. 2008) and protruding into the Western Desert. Such idea was first proposed once after the construction of the Aswan High Dam in 1964, but economic challenges had retarded its inception. After a long period of low flooding seasons, fortunately, a high flood (above 178 m) drove water to enter the depression for the first time in 1998 forming the earliest lake that continued westward until another four lakes were eventually created by 2001 (Fig. 1).

The natural flow of water toward the Western Desert, particularly after high floods in riparian countries, has encouraged reinitiating the idea of erecting a huge agricultural project in southern Egypt. The project aimed in its primary phase to reclaim about 0.5 million acres of desert land in Toshka region and it is an integral part of a comprehensive plan to develop an axis parallel to the Nile Valley. The project is formally known as the Southern Valley Development Project (SVDP) or the Toshka Project. A canal of 590 km long is to be constructed from the Lake Nasser northward to the Kharga depression in the Western Desert to reclaim 3.4 million acres, 18 new urban

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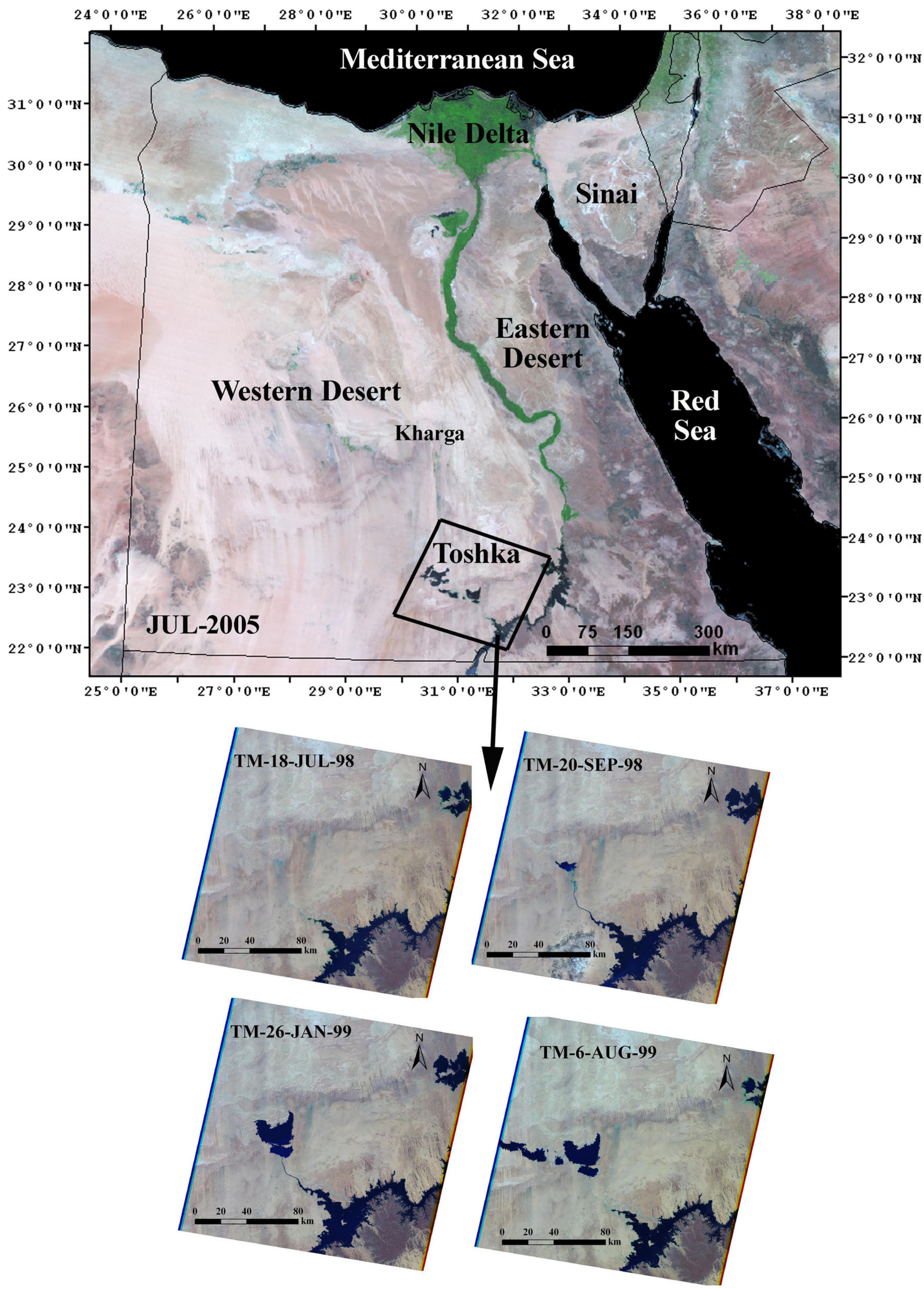

Fig. 1 A MODIS image (2005) of Egypt showing the location of Toshka area and the lower images are a sequence of TM images of the Toshka lakes in 1998 and 1999

centers, and 25 industrial zones will be constructed by 2017 (Longergan and Wolf 2001). To sustain the continuity of water discharge to the project a great water pumping station was constructed to convey 5 billion m^3/y of the Nile water (Warner 2013) through an open canal (Sheikh Zayed canal). In addition to the surface water that would be utilized for irrigation, local groundwater wells are another auxiliary source of water mainly for municipal and industrial uses in the project (Elarabawy and Tosswell 1998). Total investments of the SVDP approach $100 billion until 2017, of which 20–25 % should be committed by the Egyptian Government, whereas the remaining 75 % should be supplied by the private sector (Wafeek 2004).

Because the Toshka region is experiencing highly temporal changes of surface water extent, it would be difficult to monitor spatial changes by traditional tedious and costly surveying methods. This gives the opportunity for using satellite remote sensing that have the advantages of frequent imaging, availability, wide ground coverage, and the multi-spectral information of the ground features. Recently, there are new generations of well-corrected and frequently revisiting satellites that offer near daily observation of the earth's land features and their dynamics, such as Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, which was launched in December 2000. The first image acquired by MODIS *Terra* sensor was acquired in February 2000 and it is still working until today. The sensor provides reflectance data in the visible and near infrared bands, as well as vegetation indices and land cover products. Such data have been operated successfully to map flooding along river systems (Thenkabail et al. 2005; Sakamoto et al. 2007) and to monitor wetland area in semi-arid Africa (Landmann et al. 2010) using the Normalized Difference Vegetation Index (NDVI) and the Land Surface Water Index (LSWI). The Landsat program, which started in 1972 provided generations of satellites (from Landsat-1 to Landsat-8) for exploring earth resources until today in finer spatial resolution than the MODIS data. However, the availability and the geographic coverage (185 × 185 km) are the main limitations of the Landsat sensor. The Landsat-5 (TM) was suspended in November 2001, whereas the period since May 2004 has experienced bad quality imaging by the working satellite, Landsat-7 (ETM+) of that era due to a scan-line malfunction. Fortunately, a new sensor (the Landsat-8 or the Operational Land Imager, OLI), was launched in February 2013. The OLI has continued affording data on the earth's resources with additional spectral enhancements over the older Landsat generations. As the main changes occurred in the Toshka depression are rapid and with considering the above-mentioned limitations of the Landsat satellite, MODIS images are the most suitable source of data that cover the entire region spatially and temporally from 2000 to 2013. Although MODIS images have lower spatial resolution (250 m), the images are likely to be appropriate for regional mapping as each image covers 1200 × 1200 km. Nevertheless, Landsat data are inevitable for mapping reclaimed desert area locally. The objectives of this study are to investigate the effectiveness of using MODIS 250 m data to monitor spatial changes of the artificial Toshka lakes between 2000 and 2013; to estimate the total cultivated land as of 2013 using the Landsat-8 OLI data and to evaluate the feasibility of constructing such wide-geographic development project with considering environmental conditions of the region and public expectations.

Materials and methods

The study area

The Toshka depression is a part of a huge valley in the Western Desert of Egypt runs parallel to the Nile Valley and extends to more than 600 km (Fig. 2). The head of the depression starts at Khor Toshak along the Lake Nasser at an elevation of 179 m above the mean sea level and flows in a northwest direction with a gradient of about 0.5 %, then it wraps around a wide plateau, about 85 km wide and 515 m high, separating the depression from the Nile Valley. Then the depression extends in a north direction until Kharga Oasis in the Western Desert. The Toshka depression is carved in Cretaceous Nubian sandstone rocks in its southern part then it passes through Eocene limestone strata in the north. The surface of the depression is extensively covered by sand dune clusters. Hereher (2010) reported that the area of the Toshka region is under a high energy winds environment blowing from the north and is severely impacted by active dune movements. The region is the driest on the earth's surface, where the incident solar radiation is capable of evaporating over 200 times the amount of precipitation (Henning and Flohn 1977). Ayyad and Ghabbour (1986) classified the region as a hyper-arid land. Temperatures range from 42 °C in summer to 25 °C in winter and absolute maximum temperature rises to 50 °C in July and August. Annual precipitation does not exceed 2 mm and the number of rainy days is 0.8/year (Aboukhaled 1975), whereas potential evaporation is as high as 14–15 mm/day (Vogg and Wehmeier 1985). Previous studies on the Toshka area are little because the region is remote, under hostile environmental conditions and barely accessible from the Nile Valley. Vogg and Wehmeier (1985) carried out a pedological study on Toshka region and observed that soils belong mainly to *Aridisols* with an *aridic* moisture regime and with sub-surface horizons of *calcic*, *gypsic*, and *salic* accumulations. They also concluded that the area have lower potential for

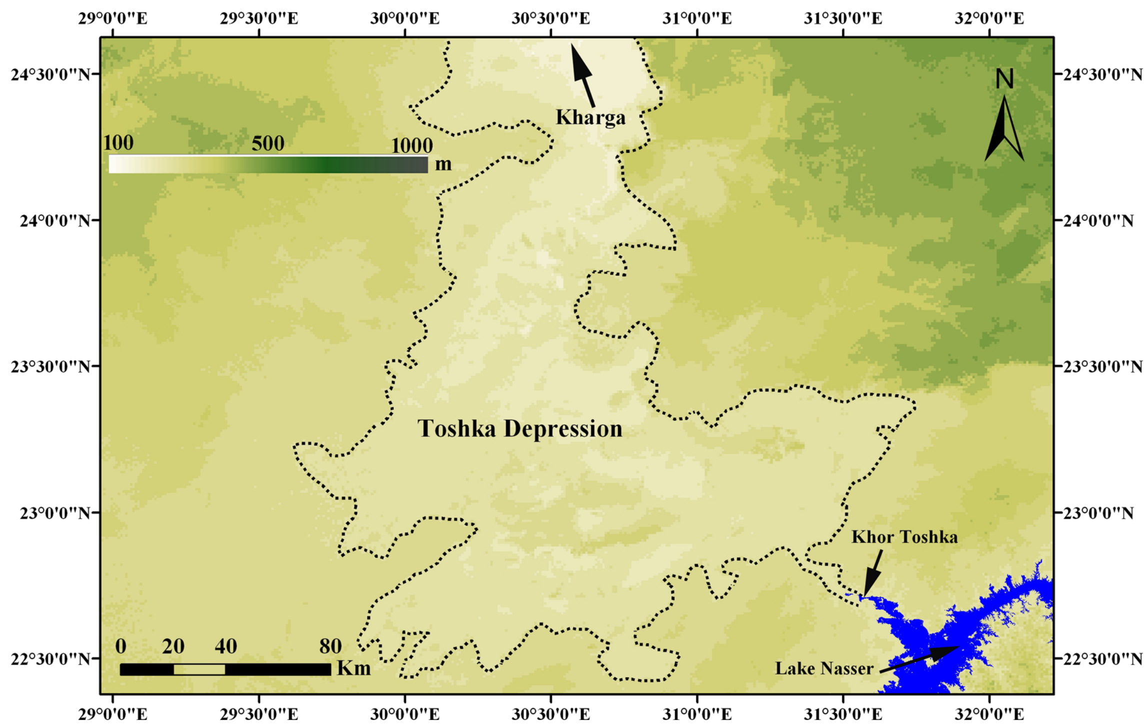

Fig. 2 A Digital Elevation Model (DEM) of the Toshka depression showing the extension within the Western Desert of Egypt. The *dashed line* represents the contour line of 200 m above sea level

agricultural development. Chipman and Lillesand (2007) operated MODIS data in conjunction with digital elevation models (DEM) and laser altimeter to analyze the extent and storage of the Toshka lakes between February 2000 and June 2006. They reported that maximum area occurred in 2002. Bastawesy et al. (2008) estimated the loss of water from the Toshka lakes between 2002 and 2006 using SPOT and DEM data. They reported that about 12.6 billion m^3 of water had been lost from the lakes mainly by evaporation.

Satellite images

Moderate Resolution Imaging Spectroradiometer images have been chosen to undergo the present investigation, because: (1) they are freely available at a spatial resolution of 250 m, at high temporal resolution (16-day composites), and allow monitoring the earth over almost a decade (Petus et al. 2013). (2) Landsat images are not available except for the most recent generation, OLI, which was launched in 2013. (3) Although MODIS images have widely been utilized for monitoring vegetation dynamics and conditions (Ahl et al. 2006; Wardlow and Egbert 2008; Sheng et al. 2011), yet they are used for mapping large lakes in the world (Huang et al. 2012). A series of 14 images from the MODIS VI product (MOD13Q1) was acquired (Tile h20v6) as one image per year to assess the surface area of lakes. The date of image acquisition is the 81st Julian day each year and every image (MOD13Q1) include blue, red, near infrared, and middle infrared bands in a sinusoidal projection. MODIS images were acquired from the NASA Land Processing Distributed Active Archive Center (LP DAAC—https://lpdaac.usgs.gov). Since MODIS images have coarse spatial resolution not suitable to accurately distinguish bare soils from young vegetation and due to the wide geographic extent of the Toshka region, two images from the OLI sensor onboard the Landsat-8 satellite were acquired to assess the area of the reclaimed desert in the project. The OLI sensor provides an up-to-date high spatial resolution (30 m) and wide spectral range of visible/IR bands. Images from the Landsat-8 satellite were acquired on August 19th 2013 (path 176 row 44) and August 28th 2013 (path 175 row 44) in the UTM-WGS84 projection. Images were acquired from the United States Geologic Survey (USGS) free open resources (http://earthexplorer.usgs.gov/).

Image processing

The MODIS (MOD13Q1) images have the advantage of being corrected at the origin for removing atmospheric aerosols and amending radiometric issues raised from solar angle variations and sensor problems and they were also preconverted to surface reflectance data. Using ERDAS Imagine Software, Gridded MODIS HDF data were imported and reprojected to the UTM-WGS84, zone 36 using the nearest neighborhood resampling technique. Subset images including three bands in each MODIS image (red, near infrared, and middle infrared) were created. The two Landsat images were in raw digital numbers, thus they were converted to surface reflectance data using the COST model in ERDAS Imagine. As the satellite sensor collects earth's reflected electromagnetic radiation while traveling back into the space, aerosols and other atmospheric gases modify such reflected energy by scattering and absorption; thus, it is crucial to apply an atmospheric correction to these images that was carried out using the dark object subtraction method of Chavez (1996). Since the two images were acquired in August 2013 with 9 days apart, there was no need for further radiometric calibration as the solar illumination angle is nearly the same in the two images. The two images were then mosaicked to form one integrated and continuous image to the region and a small subset for the area was created.

Spectral transforms

The MODIS images have spectral bands within the visible, near infrared, and shortwave infrared portions of the spectrum, which can be used to calculate a number of spectral transforms to examine the most suitable for addressing lake water surface area. Since the infrared band is sensitive to water, most transforms utilized for delineating water bodies usually depend on this portion of the spectrum. These transforms are: the LSWI (Yan et al. 2010) and the NDVI (Tucker 1979). The LSWI is calculated as $\mathrm{LSWI} = (\rho\mathrm{NIR} - \rho\mathrm{SWIR})/(\rho\mathrm{NIR} + \rho\mathrm{SWIR})$, where ρNIR and ρSWIR refer to the reflectance in the near infrared and the shortwave infrared bands, respectively. The LSWI is effective in capturing free water, soil moisture, and vegetation water content (Chandrasekar et al. 2010). The NDVI, on the other hand, is calculated as $\mathrm{NDVI} = (\rho\mathrm{NIR} - \rho\mathrm{R})/(\rho\mathrm{NIR} + \rho\mathrm{R})$, where ρNIR and ρR refer to the reflection in the near infrared and red bands, respectively. This transform is highly correlated with chlorophyll content (Tucker 1979); therefore, it is used mainly to map green vegetation. As water absorbs most incident energy, NDVI values of water usually are negative; thus, water bodies can be distinguished from non-water objects in NDVI images. However, if wet soil occurs beside water bodies (such as the case of Toshka lakes), the NDVI value for both water and the wet soil usually has negative values, consequently, free water cannot be sharply separated from wet soils in NDVI images. A modified transform of the Normalized Difference Water Index (NDWI) of McFeeters (1996) is then suggested. The NDWI, which is applied mainly to Landsat (TM) images, is estimated as: $\mathrm{NDWI} = (\mathrm{Green} - \mathrm{NIR})/(\mathrm{Green} + \mathrm{NIR})$, where the Green and the NIR refer to the reflectance in the green and NIR portions of the spectrum. As MODIS vegetation index products lack a green band, it is suggested to compensate for the green band by the red band to compile the modified transform; the MODIS Normalized Difference Lake Index (NDLI), as follows: $\mathrm{MODIS\ NDLI} = (\rho\mathrm{R} - \rho\mathrm{NIR})/(\rho\mathrm{R} + \rho\mathrm{NIR})$, where ρR and ρNIR are the reflectance in the red and near infrared portion, respectively. This transform takes the advantage of the high reflectance of non-water features in the NIR portion; thus in the NDLI, all these features have negative values whereas only free water is positive. Actually, the NDLI is a reverse version of the NDVI. The surface area of Toshka lakes has been, thus, estimated using the NDLI. Once this transform was applied to each MODIS image, only positive value pixels that represent free water within the lakes have been recoded and summed up together to get the surface area of the lakes in each MODIS image.

Moderate Resolution Imaging Spectroradiometer data have not been used to estimate cultivated lands in the Toshka Project due to the spectral mixing effect at the pixel level and consequently the poor accuracy for mapping vegetation in small scale areas. Also, spectral interference with other non-vegetation feature may make NDVI not efficient to discriminate vegetation solely in this region. The Landsat-8 OLI images of August 2013 were used to make an inventory of the reclaimed land in the project. The Soil Adjusted Vegetation Index, SAVI (Heute 1988) is preferred to the NDVI in assessing green vegetation because SAVI is designed to reduce soil brightness in the vegetation signature and proved to be effective to eliminate soil background (Heute 1988), particularly in areas severely impacted by soil salinization, such as Toshka area. Masoud and Koike (2006) operated SAVI to map vegetation in a similar area in the Western Desert of Egypt that is affected by saline soil background. This index is calculated as: $\mathrm{SAVI} = [(\mathrm{NIR} - R)/(\mathrm{NIR} + R + L)] \times (1 + L)$, where NIR and R are the reflectance in the near infrared, red spectra, respectively. Heute (1988) considered L as an empirical constant that compensates for soil background effect and equals 0.5.

Results and discussion

The spectral reflectance curves for the main land cover units in the Toshka area (Fig. 3) reveal that water and vegetation have pronounced spectral behavior; water absorbs most of the incident radiation, particularly in the whole infrared spectrum and vegetation has a reflection peak in the NIR portion. On the other hand, the lake margins, which were previously parts of the lakes and were dried up by evaporation of water leaving bare soil

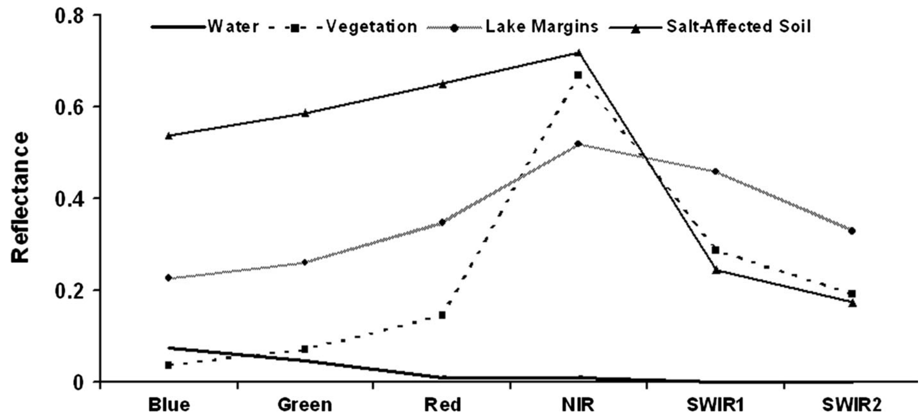

Fig. 3 Spectral reflectance curves for the four land cover units within the six bands of the OLI sensor. *Blue* (0.45–0.51 μm), *green* (0.52–0.66 μm), *red* (0.63–0.68 μm), NIR (0.84–0.88 μm), SWIR1 (1.56–1.66 μm), and SWIR2 (2.10–2.30 μm)

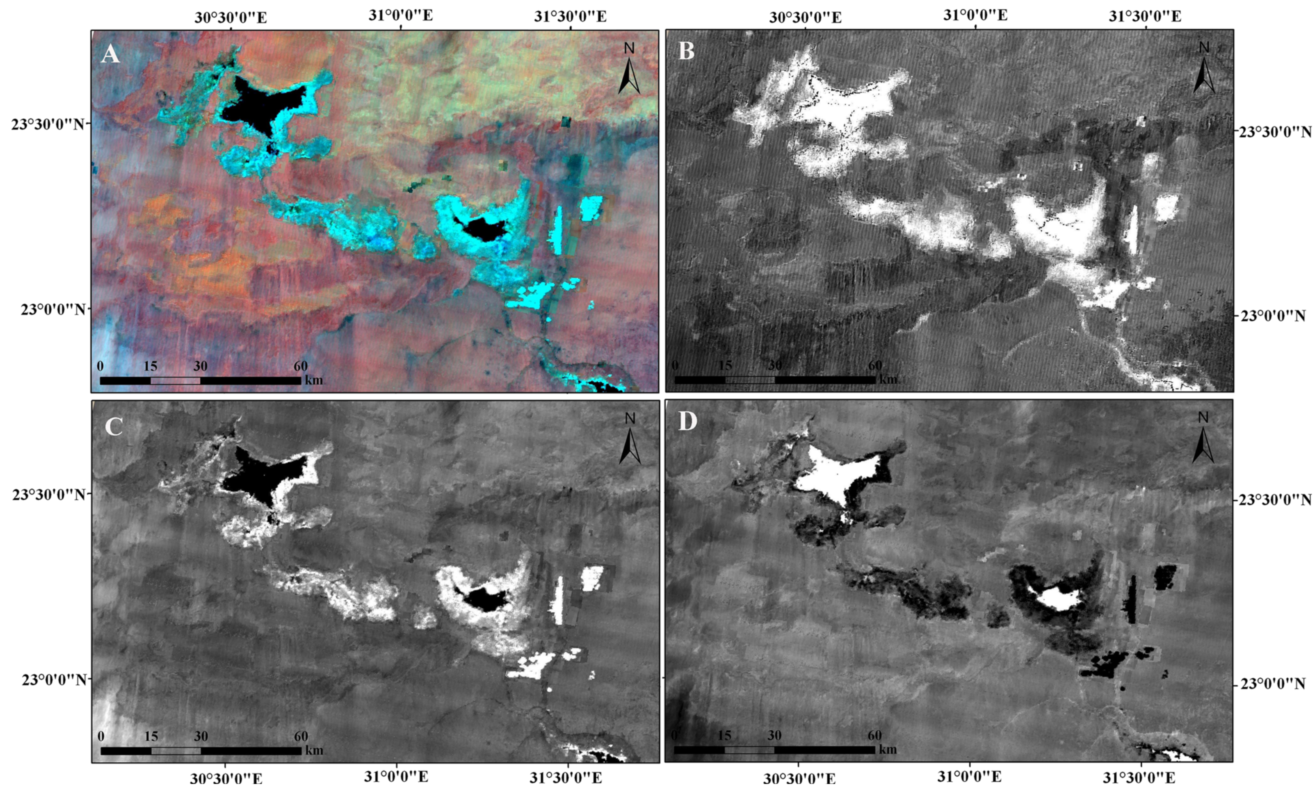

Fig. 4 A MODIS image of Toshka in 2013; **a** is a *false color* composite showing the lakes, the dried up margins and the new reclaimed area; **b** is the LSWI image revealing the interference of these units (*white color*); **c** is the NDVI image showing the interference between lake margins and cultivated lands (*white color*) and the interference between free water and wet soil (*black color*); **d** is NDLI showing the lake water only (*white color*) after removing the interference from other non-water features

encompassing lakes, reflect maximum in the NIR portion. There are some areas of salt-affected soils known by their pronounced spectral behavior that resembles the wet salt crust reported by (Schmid et al. 2009). These areas reflect maximum in the visible/NIR portions and absorb highly in the SWIR region. When applying the LSWI to the MODIS image (Fig. 4b), it is obvious that water, lake margins, and the vegetation altogether have high LSWI value and are grouped together (white color). The higher LSWI for these three units is due to the higher absorption of the SWIR than the NIR bands, which yield a positive value in the LSWI. It is, therefore, difficult to discriminate lake water solely from wet lake shores, which are not counted as free water. Yan et al. (2010) reported that the LSWI could highlight the flood plain (free water–wet soils) in northern Shanghai City, China, and thus this transform was used for monitoring flood inundation. This supports the findings of the present study that the LSWI is not suitable to mask free water only. The NDVI image (Fig. 4c) highlights positive index values in white color, whereas water and wet soil,

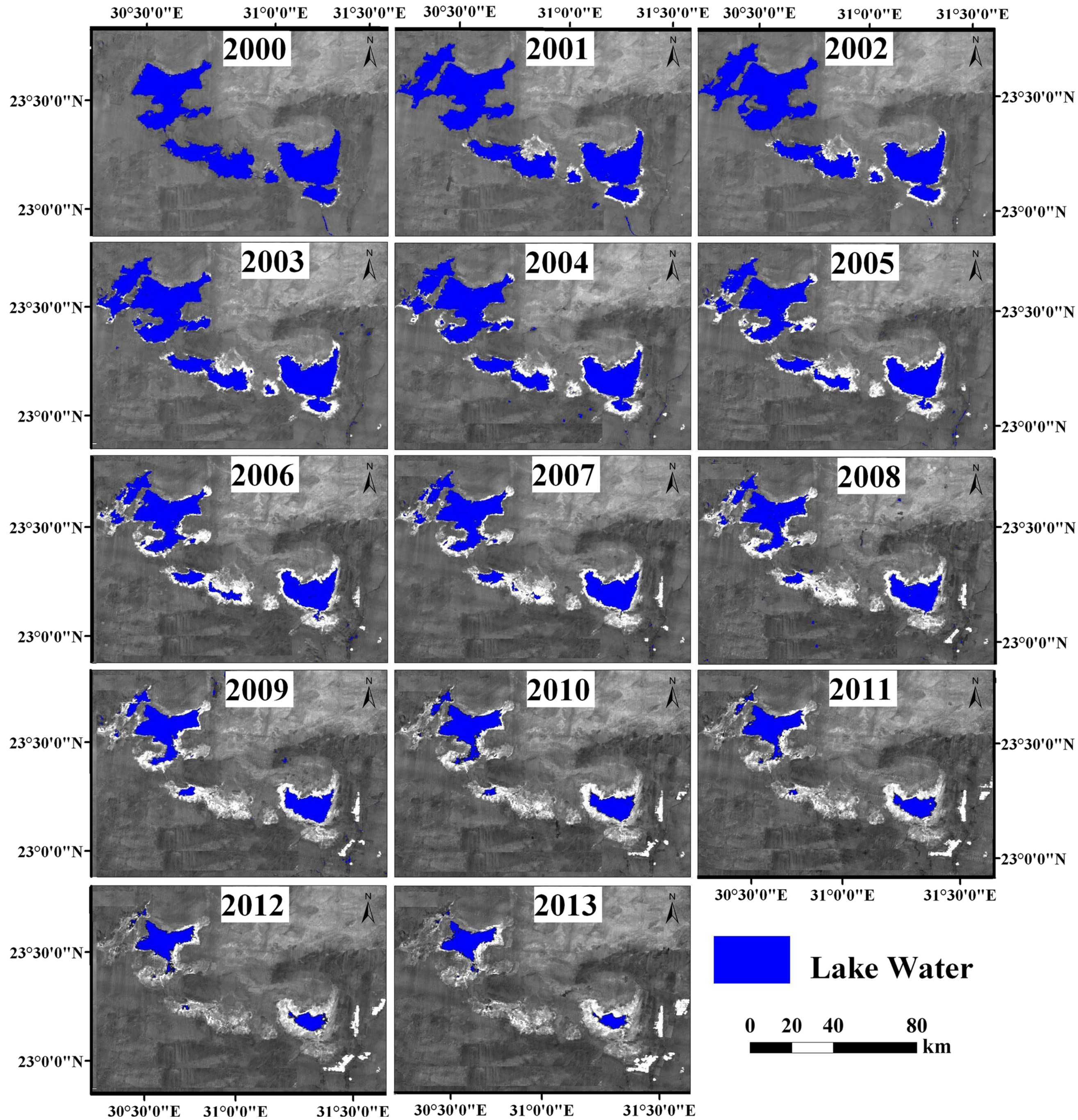

Fig. 5 The changes in the extent of Toshka lakes (*blue color*) between 2000 and 2013 as appear in MODIS images

which have negative values, appear in black. This may lead to overestimation of free water if NDVI is applied. It is also obvious that the NDVI clusters dry lake margins with reclaimed vegetated area together; thus, it is difficult to separate these two units individually. When applying the modified transform, NDLI, to the MODIS images, a clear and sharp limit of water in the lakes is obvious (Fig. 4d). The point of strength in this transform is that all the non-water features (vegetation, the lake margins, the damp and salt-affecting soils) have negative values because they have higher NIR than the *R* reflection (Fig. 3), whereas the free water only has positive values as the red is little exceeding the NIR reflection. Thus, the NDLI is the most suitable and efficient to estimate the change in the lake water area. The most conspicuous point in using MODIS for the present analysis is the regional coverage of each image, which

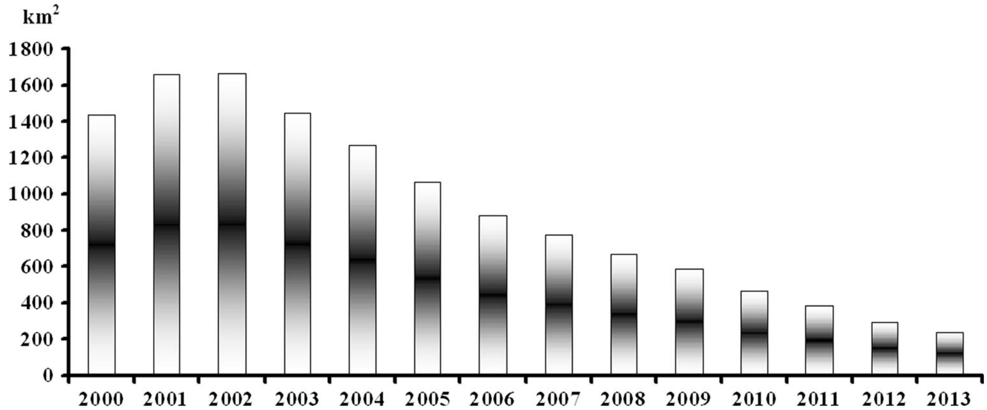

Fig. 6 The area change of the Toshka lakes between 2000 and 2013 as obtained from MODIS images

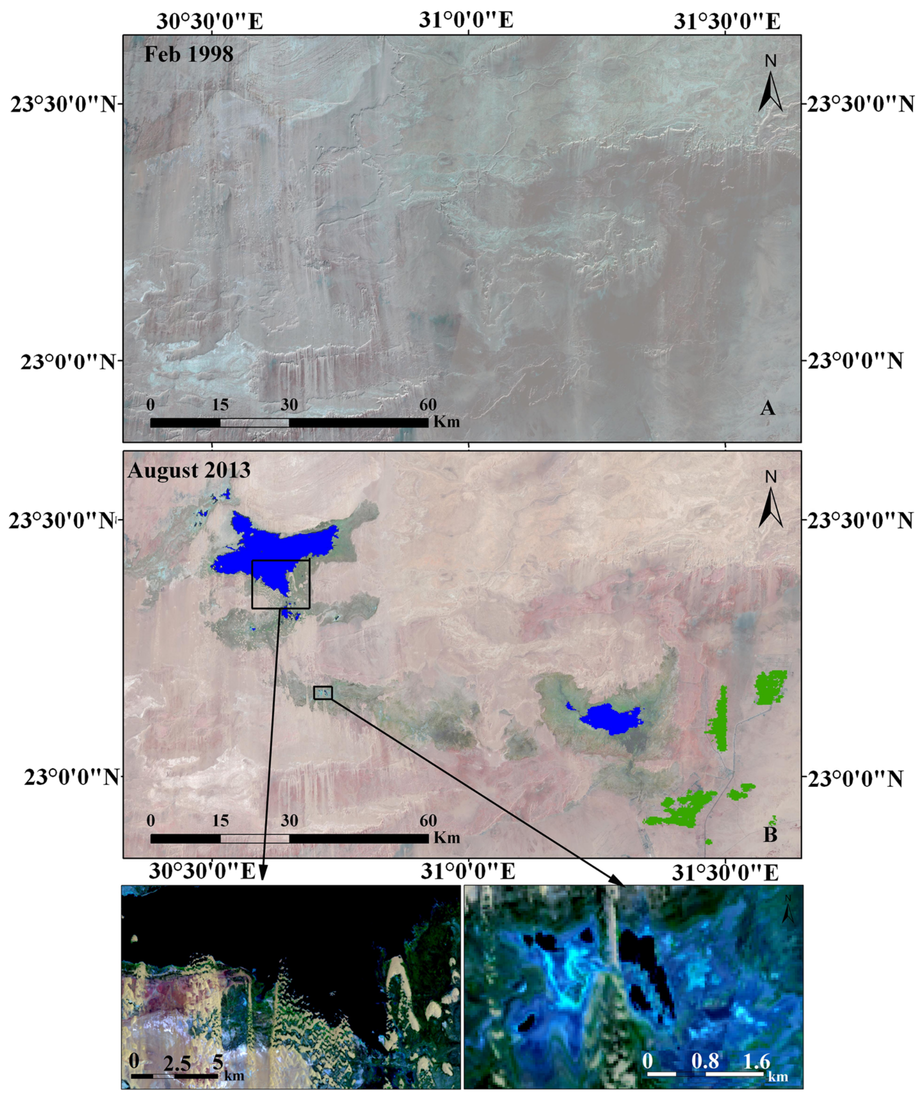

Fig. 7 Land cover change in Toshka region between 1998 (upper TM) and 2013 (middle OLI). The remaining lake water is shown in *blue*, the total reclaimed area is shown in *green*, and the *two boxes* highlight the salt crust (*lower right*) and the sand dune clusters (*lower left*)

confirms with previous studies that demonstrate satisfactory results for mapping rice paddy fields and flooding areas at a regional scale (Xiao et al. 2005 and Landmann 2010).

Figures 5 and 6 provide a sequence of the surface area change in Toshka lakes as revealed by applying the NDLI to each MODIS image. Figure 5 highlights the spatial change of water surface in the lakes between 2000 and

2013 and Fig. 6 quantitatively estimates the change in the surface area of water in these lakes for the same period. In March 2000, there were four lakes in Toshka totaling 1437 km^2 in surface area. With the continuous discharge of water into the depression, the lakes expanded in 2001 to 1658 km^2 and by time, a fifth lake was formed in the western side. By 2002, the lakes approached their maximum extent ever in the 14 images (1664 km^2). Maximum surface area of Toshka lakes is comparable to previous estimates. It was estimated at 1740 km^2 in 2002 by Chipman and Lillesand (2007) and 1591 km^2 in 2002 by Bastawesy et al. (2008). Since then, the lakes have experienced gradual diminishing in their areas until 240 km^2 in 2013. It is expected that the lakes will disappear in the near future due to the high evaporation rates, which approach 14–15 mm/d (Vogg and Wehmeier 1985). Bastawesy et al. (2008) in their study on evaporation rates at Toshka lakes reported that water loss was attributed mainly to evaporation (90 %) and recharge to groundwater (10 %). The total reclaimed land was estimated by SAVI after applying the suitable threshold (0.2), with pixels greater than this threshold were counted as cultivated lands (Fig. 7). The reclaimed land area as revealed by SAVI (Fig. 7) is only 31,000 acres irrigated by the center pivot and dripping irrigation systems. SAVI is, then, proved to capture green vegetation in areas affected by bright soils background. Alhammadi and Glenn (2008) reported that SAVI is suitable to quantify date palm greenness change in areas suffering from severe salinity in the eastern part of the UAE. Cultivated lands in Toshka occur at the eastern side (up stream) of the depression. This little cultivated area does not reflect the public expectations and the official promises of the project. Although it was planned to reclaim 0.5 million acres in the first phase of the project, only 31,000 acres were cultivated. In addition, there is a significant concern about investments spent for the infrastructure as well as about wasting of the most important natural resource of the country, i.e., Nile Water (10 % of Egypt's annual share). This may reduce per/capita water allowance at the time where there is a blurred sight of the Nile water supplies.

There was a debate about the development of an agriculture project in the hyper-arid Toshka region. The tough environmental setting, such as high temperatures, scant rainfall, high evaporation rates, and the remoteness in the deep desert, are the most potential hostile conditions. Wasting of water in a hyper-arid desert could lead to an accelerated salinization and formation of salt-affected soils, which have been distinguished in satellite data by their bright tone (turquoise color) (Fig. 7). Salinization is one of the main processes of soil degradation and desertification in arid lands (UNEP 1991). Primary (climatic) salinization is encountered in the Toshka region due to severe evaporation rates. The region, which has a high energy wind environment, is also under the encroachment of active sand dunes. These dunes form clusters of barchan (crescentic) type funneling from the north (Fig. 7). Abou El-Magd et al. (2013) reported that dune advance rate in this region approaches up to 19 m/y, which could threat any development activity. Although Draz and Zaghloul (2007) proposed a green belt to protect the main canal in the Toshka Project from sand drift, the length and the alignment of the canal (W–E), which is transverse to the moving dunes (N–S), the aridity and the severity of wind energy are significant obstacles for any efficient system to suppress dune movement.

Conclusions

A modified and effective spectral transform of MODIS spectral bands suggested by this study is utilized to estimate changes in the surface water area in Toshka lakes of Egypt. The modified transform overcomes the spectral interferences of land cover features and is efficiently capable of addressing surface water area. The surplus of the Nile water flood was discharged into the desert in a country suffering from limited water resources. Salinization and sand drift instead of greening and cultivation are observed at the locations of the dried water masses. The region is under the process of desertification by sand encroachment and soil salinization. Harsh environmental conditions and aridity are considerable obstacles for development of such remote hyper-arid desert. The Toshka Project must be reviewed again and its environmental impacts as well as its economic outcomes must be reviewed and considered.

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