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Review article

Combining bathymetric measurements, RS, and GIS technologies for monitoring the inland water basins: A case study of Toshka Lakes, Egypt

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A B S T R A C T

The current study presents the first bathymetric map of Toshka Lakes in Egypt using the bathymetric method that is based on the combination of in situ measurements, Remote Sensing, and GIS technologies. Such a combination allows an accurate determination of the three-dimensional shapes and volumes of inland water basins, as shown by its implementation in the survey of the Toshka Lakes. The determined total surface area of the Toshka Lakes is 2321.64 km^2, holding a cumulative capacity of 53.28 billion m^3 (almost equal to Egypt's annual water income from the Nile). Being today the Toshka Lakes in a mature stage, the results of the morphometric and hypsometric analyses provide useful information for water conservation. The lakes are also expected to gradually shrink in size, similar to what happened in the past decades. Therefore, besides providing a digital database useful for water management, the proposed study is fundamental for appraising, with more realistic expectations, the future changes in the water basins in the Toshka Depression. This article documents the current status of the Lakes and enables researchers and decision-makers to predict their changes in volume and area with depth in the future.

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Introduction

Freshwater availability is currently a major issue all over the world and it will be one of the most important challenges that humanity will have to face in the next future. In this crucial framework, Egypt has to consider that its water resource system is quite complex and uncertain (Abd Ellah, 2020). Constrained by water availability, which is constantly changing, the country is experiencing several substantial obstacles to its socioeconomic development. According to UNEP (2010), since the 1990s Egypt is at risk of freshwater shortages due to its limited resources, which are subjected to the rising demand from its growing population and increasing competition for water from the upper Nile Basin countries. In addition, the influence of climate change on the Nile discharge has to be considered as another challenge for the water resources of the country. Therefore, constant efforts and further research are required for the monitoring and management of the Egyptian freshwater lakes in the most efficient manner.

Lakes are essential elements in the hydrological and biogeochemical water cycles because of their basic ability to store, retain, clean, and consistently provide freshwater (Crétaux et al., 2016). In addition, lakes are a key component in flood control, hydroelectric power generation, and fish production, and they significantly influence the lifestyle of communities along their shores. Lakes also harmonize temperatures and precipitations, influencing the local climate. However, their ecosystems are most sensitive to environmental changes (i.e., chemical and biological processes), which are affecting their water volume (Hamilton and Schladow, 1997). Therefore, readily available data, being continuous in time and spatially consistent, are greatly needed for lakes as vital freshwater resources.

In general, lakes can be monitored using three different approaches, which are in situ measurements, Remote Sensing (RS) observations, and modeling, accompanied by specific bathymetric retrieval algorithms (Valdiviezo-Navarro et al., 2019; Arreola-Esquivel et al., 2021; Caballero and Stumpf, 2021; Haque et al., 2021; Hossen et al., 2022; Sundt et al., 2022). Nowadays, hydrography is demanding accurate and consistent bathymetric mapping, due to its increasingly important role in various practical applications. Among applications, we can find the bathymetric mapping of the lakes, fundamental to defining their stage-storage relationships and circulation/transport processes (Khazaei et al., 2022). This is especially true for the Toshka Lakes. For the future of this Egyptian freshwater resource, it is necessary to have a continuous record and a good upgrading of the changes in their morphometric features. This relevant survey can be obtained using hypsographic curves of area and volume versus depth (Abd Ellah, 2021).

Actually, few previous studies have been conducted on the Toshka Lakes (Abd Ellah, 2021). These studies have demonstrated that their water total surface, measured from different RS spatial-resolution images, is strongly correlated to Lake Nasser water level. In the 1990 s, Lake Nasser level was so high that the overflow of the Toshka Canal was considered to be used; through it, the Toshka Lakes were formed later on (Conway, 2000). El Bastawesy et al. (2007) investigated the Toshka Lakes water loss by integrating RS and the geographic information systems (GIS) techniques to aerially study the Lakes shrinkage that started in 2006 (Sparavigna, 2011). Moreover, Labib and Nashed (2013) demonstrated that GIS enabled easy and quick evaluation of numerous soil properties, for any further analysis required by the expansion of the National Projects in the Toshka region.

For what concerns the biology of the Toshka Lakes, at the beginning of their formation, the Nile fauna and flora filled them, resulting in a rich fish population. However, over time, the Lakes suffered from a rapid increase in their salinity. Fauna and flora were consequently impoverished, and life in the lakes started to decline (El-Shabrawy and Dumont, 2009).

As a conclusion of his recent review, Abd Ellah (2021) has evidenced that despite the added significant features of the Lakes to the Egyptian Western Desert landscape and the provision of a new wetland, Toshka Lakes remain confronted with many challenges that must be addressed. Consequently, additional studies are needed to adequately characterize the ecology of Toshka Lakes, protect them, and optimize their benefits. In this framework, the aim and focus of the present study are to combine the bathymetric data evaluation method, with RS and GIS technologies, to derive the exact morphological parameters and hypsometric curves of Toshka Lakes. To our knowledge, the present work is the first systematic investigation of the Lakes with in situ bathymetry. The proposed combination can serve as a tool for obtaining comprehensive information on bathymetry and morphometry data, strictly required by future research on the management and protection of Toshka Lakes.

Study area and methodology

Study area

Lake Nasser, which is one of the largest man-made lakes in the world, is a national freshwater reservoir of Egypt. The lake level experiences annual dramatic changes because of fluctuations in the amount of floodwater from the Nile River. The Toshka spillway was built to allow control of the floodwater level and to discharge more water during heavy floods to ensure the safety of the Aswan High Dam (Sadek and Aziz, 2005). When the level of Lake Nasser exceeds 178 m above mean sea level (a.m.s.l.), its excess water is directly discharged to Toshka Depression, which prevents the lake water from reaching a dangerously high level (Sutcliffe et al., 2016). Toshka Depression (23° 10′ N; 30° 47′ E) is located 56 km west of Lake Nasser in the Western Desert of Egypt (Fig. 1). This Depression is bordered by hills and high edges and includes several interconnected small depression levels between 112 and 180 m a.m.s.l. Its area, at an altitude of 180 m a.m.s.l., is about 6000 km^2. The Toshka Depression can store up to 120 km^3 of water. The total amount of water is subdivided into five large basins that are known as Toshka Lakes, which are formed by the water discharge through the Toshka Canal from Lake Nasser (Moussa, 2018).

Methodology and data processing

The current study used the combination of two evaluation methods for lake bathymetric measurements, namely, RS and GIS technologies, to accurately determine the morphometry of Toshka Lakes (Fig. 2).

Bathymetric survey

To determine the geometric parameters and prepare the bathymetric maps, a field survey was conducted from November 12 to November 25, 2021. The lake bathymetry was based on global positioning systems (GPS) and portable sonar sounders mounted on small boats. A GPS device, GARMIN 78, was used to determine the positions and record the location coordinates (latitudes and longitudes) in the study area. As the satellite signal was strong, the GPS position was accurate up to 3 m, according to GARMIN's manual. Let us stress that this accuracy is smaller than the size of boats used for the survey, besides being one-tenth of the cell size, 30 m, of Landsat 8 imagery we are using for remote sensing. The depths of Toshka Lakes were measured using a digital Echo Sounder (NAVMAN FISH 4500). The instrument operates in the dual frequencies of 50 and 200 kHz for depth measurement. The

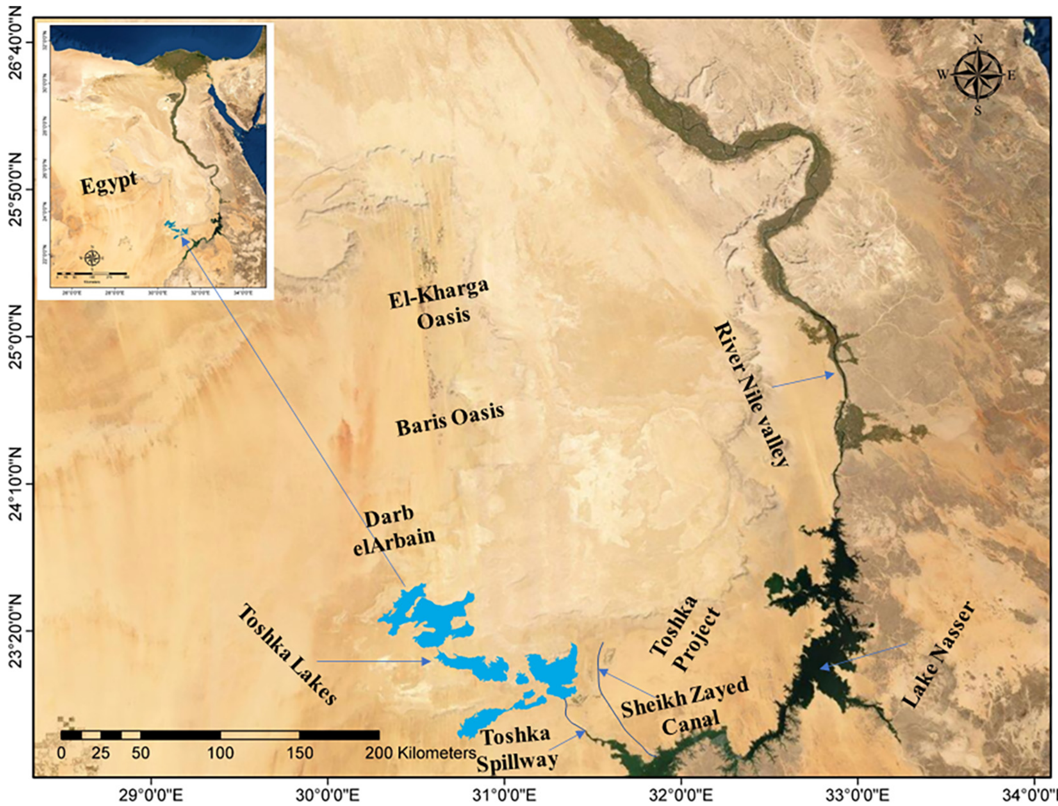

Fig. 1. Egypt, Western Egyptian Desert, Toshka Lakes, and other features.

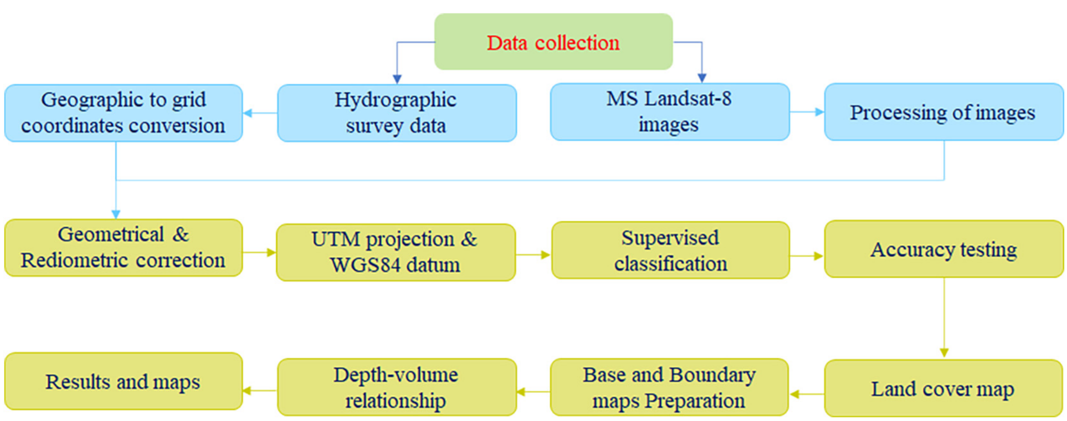

Fig. 2. Flowchart showing the processing steps used to estimate water depth, area, and volume in the Toshka Lakes.

low frequency is more accurate at a larger depth, whereas the higher frequency is reliable at a smaller depth. For the calibration of the instrument, the specific procedure indicated by the manual was performed. The survey of the Toshka Lakes was made in very tranquil conditions, with no wind and negligible surface ripples less than 0.1 m high. The vertical oscillation of the boat was consequently within the sensitivity of the used sonar instrumentation. As the boat changed from lake to lake, the uncertainty of the position sounder was maintained within half a meter. Cautiously, the uncertainty of the depth measurement of the lakes was given in 1 m.

RS and GIS techniques

Landsat 8 data (cell size, 30 m) were downloaded from the website Earthexplorer.usgs.gov and were used to evaluate the surface areas of Toshka Lakes. The satellite images correspond to the days of the in situ survey. After a geometrical correction, the satellite images became a subset in the domain of the collected in situ bathymetry maps, prepared during the recent in situ hydrometric survey. A classification technique was used to determine the surface area of the Toshka Lakes. This method of classification, already discussed in Abd Ellah (2021), helps to distinguish accurately the water boundary of the study area.

The above-mentioned RS data were introduced in GIS, such as the bathymetric data. GIS software was used to process the edited XYZ data collected from the survey. The used GIS software was ArcGIS Desktop and ArcMap version 10.7.1 from the Environmental System Research Institute (ESRI). The edited data points in the XYZ text file format were converted into a point feature class in the ArcGIS file geo-database. The point feature class contained

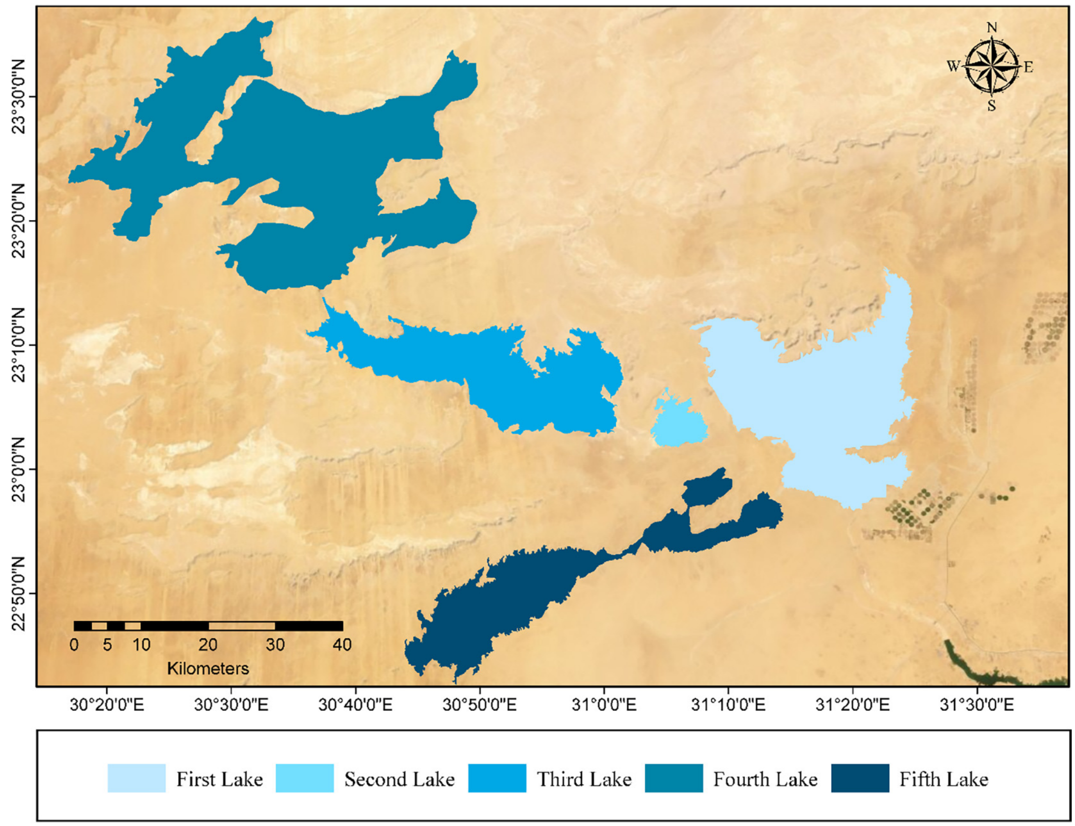

Fig. 3. The surface of the Toshka Lakes, using image satellite data (Landsat 8) and the GIS program.

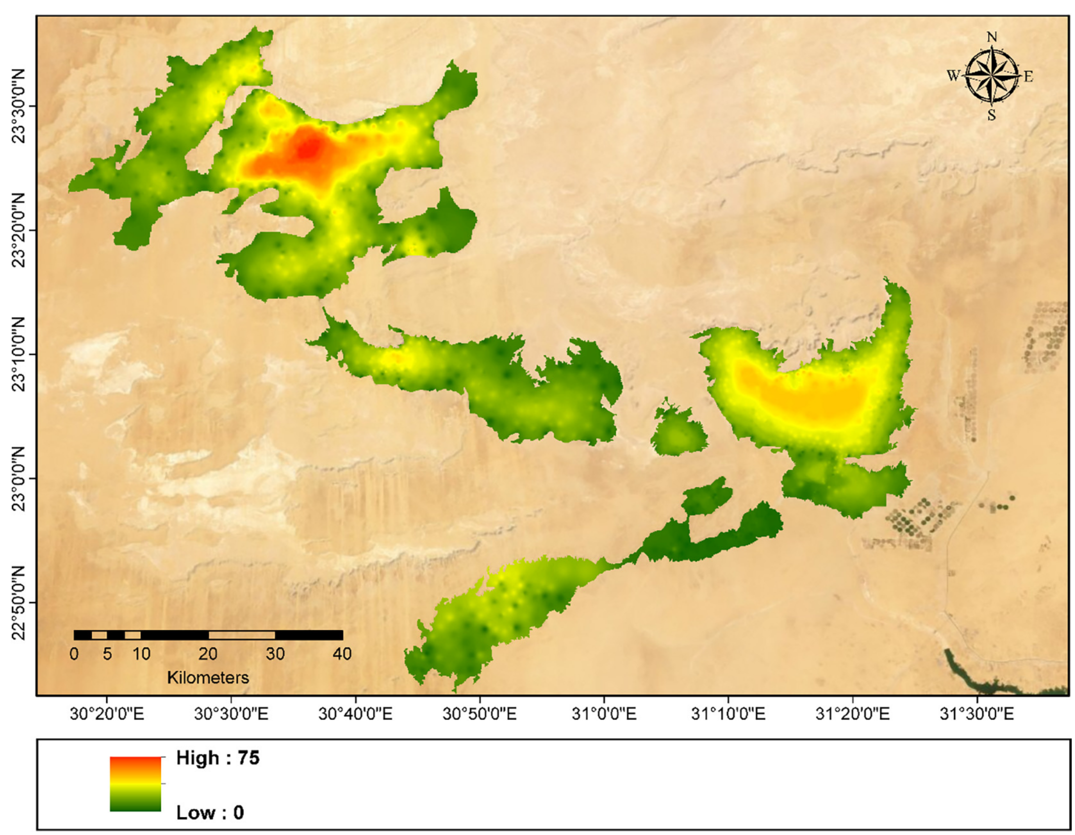

Fig. 4. Bathymetric maps of the five Toshka Lakes obtained using the proposed combination of lake bathymetric measurements, RS and GIS technologies.

the horizontal coordinates and elevation and depth values associated with each collection point. Toshka Lakes were coupled to the GIS-derived geographical and topographical parameters. The correction procedure followed all recommended corrections, such as geometric/radiometric correction using the Universal Transverse Mercator (UTM) projection. In UTM, the specific azimuth was Zone 36 North and the World Geodetic System 1984 data.

Depth–area–volume relationships

The area of each lake and that between two consecutive contour lines were determined from the GIS database of lake bathymetric maps. As previously mentioned, the GIS database was prepared using ArcInfo and ArcView software. Then, the volume of each lake was calculated using the measured area and average depth. Hypsographic curves have been used to provide a visual representation of the relationship between the surface area and water volume of a lake basin and its depth (Rout et al., 2020). From these graphs, we could predict more accurately how the lake's surface area changes, according to changes in the water depth.

Results and discussions

Bathymetry

After in situ measurements, the bathymetric results were analyzed, using the surface analysis tool of GIS, and bathymetric maps were prepared. The Toshka Depression contains five sub-basins, which extend from the southern to the northern basin (Fig. 3). A three-dimensional shaded rendered map was created from the grid file. The surface height corresponded to the *Z* value of the associated grid node. The green color in the color scale represented the lake surface, whereas the red color indicated the deepest layer of the lake (Fig. 4). The geographic central part of the first lake (its measured maximum depth was 48 m) denoted the deepest part, whereas the shallow water was in the southern part of the lake. Larger depths were recorded in the middle of the second lake (its measured maximum depth was 23 m), with gentle water slopes along the shoreline. The third lake (its measured maximum depth was 45 m) exhibited a sudden change in the slope angle and larger depths along the northwestern region. The bathymetric map of the fourth lake (its measured maximum depth was 75 m) showed that the maximum water depth was at the central part of the lake and that the lake bottom was characterized by an undulating topography. The bottom topography of the fifth lake (its measured maximum depth was 37 m) revealed the dominance of shallow depth in the water basin.

Morphometry

Although Toshka Lakes are wide and extend long distances into the desert, the morphological elements in each of the five lakes are different. Morphometry is a process that is directly and closely related to the bathymetry of the lakes. The results of using the combined evaluation methods of RS and GIS technologies for bathymetric measurements in Toshka Lakes are listed in Table 1. The first lake having a cup shape represents the nearest water basin connected to the Toshka spillway. It has an area of 549.02 km^2 and stores water of 15.33 billion m^3. The second lake, which has a circular shape and is considered the smallest lake in Toshka Depression, occupies an area of 40.49 km^2 and stores water of 0.61 billion m^3. The third lake having a funnel shape covers an area of 387.69 km^2 and contains 6.62 billion m^3 of water. The fourth lake, which has an octopus shape, has the largest water size in Toshka Depression. It has an area of 997.94 km^2 and stores water of 25.55 billion m^3. The fifth lake having a tuning-fork shape represents the newest water basin formed in Toshka Depression. It covers an area of 346.5 km^2 and is filled with 5.17 billion m^3 of water. The determined surface area of the entire Toshka Lakes is 2321.64 km^2 and holds a cumulative water capacity of 53.28 billion m^3.

The lake morphometry data are very useful for anticipating any changes in the lake system and predicting the effects on the water basins, being therefore fundamental for any water balance analysis (Ahmadi et al., 2015). The morphometry of lakes determines their physical, chemical, and biological properties, namely; water retention time, nutrient dynamics, primary production, organic matter mineralization, and sedimentation (Jeppesen et al., 2005). From the scientific or lake management perspectives, changes revealed by morphometry can help in forecasting the behavior of the volume of water in the lakes' system. Therefore, proper morphometry increases the chances of mitigating any undesirable effects, through the use of carefully planned management techniques.

Hypsographic curves of the area and volume of Toshka Lakes

When the surface area in each of the contour lines (Fig. 4) is calculated and plotted on a graph, a hypsographic curve can be obtained, thus, providing accurate information at a glance (Farhan et al., 2016). In particular, the hypsographic curve reveals the relationship between the surface area or volume and the depth of the lakes.

In Fig. 5, the hypsographic curves are proposed for the five Toshka Lakes. Using them, assuming a hypothetical change in the lake depth (*y*-axis), it is possible to estimate the corresponding change of surface or volume (*x*-axis). The hypsometric analysis of Toshka Lakes shows that the rate of morphological changes in the five Lakes is very large. Today, the Toshka Lakes are in a mature stage (100 %). In the future, the result of the given hypsometry analysis will be able to estimate any shrinkage of the water basins and predict the best time for implementing any lake management strategy. Generally, the comparison of hypsometric curves from different lakes can help explain why some basins are more suscep-

Table 1
Summary of significant morphometric characteristics of the Toshka Lakes.

Lake			First Lake	Second Lake	Third Lake	Fourth Lake	Fifth Lake	Total Lakes
Location	**Lat. (N)**	**From**	22°56′40.3″	23° 01′42.6″	23° 02′34.4″	23°14′25.3″	22°42′34.4″	22°42′34.4″
		To	23°16′15.3″	23° 06′34.2″	23°13′5.2″	23°36′33.4″	23° 00′13.1″	23°36′33.4″
	Long. (E)	**From**	31° 6′39.7″	31° 03′48.8″	30°36′0.8″	30°20′53.3″	30°44′5.6″	30°20′53.3″
		To	31°24′46.3″	31° 08′27.4″	31° 01′36.6″	30°49′50.6″	31°14′14.0″	31°24′46.3″
Altitude (m a.m.s.l.)			156	156	144	144	149	
Max. length (km)			35.0	08.5	43.1	50.0	56.0	118.1
Max. width (km)			27.4	08.0	17.2	37.1	12.5	90.4
Mean width (km)			15.7	04.8	09.0	20.0	06.2	19.7
Max. depth (m)			48.0	23.0	45.0	75.0	37.0	75.0
Mean depth (m)			27.9	15.1	17.1	25.6	14.9	23.0
Lake area (km^2)			549.02	40.49	387.69	997.94	346.5	2321.64
Volume (billion m^3)			15.33	0.61	6.62	25.55	5.17	53.28

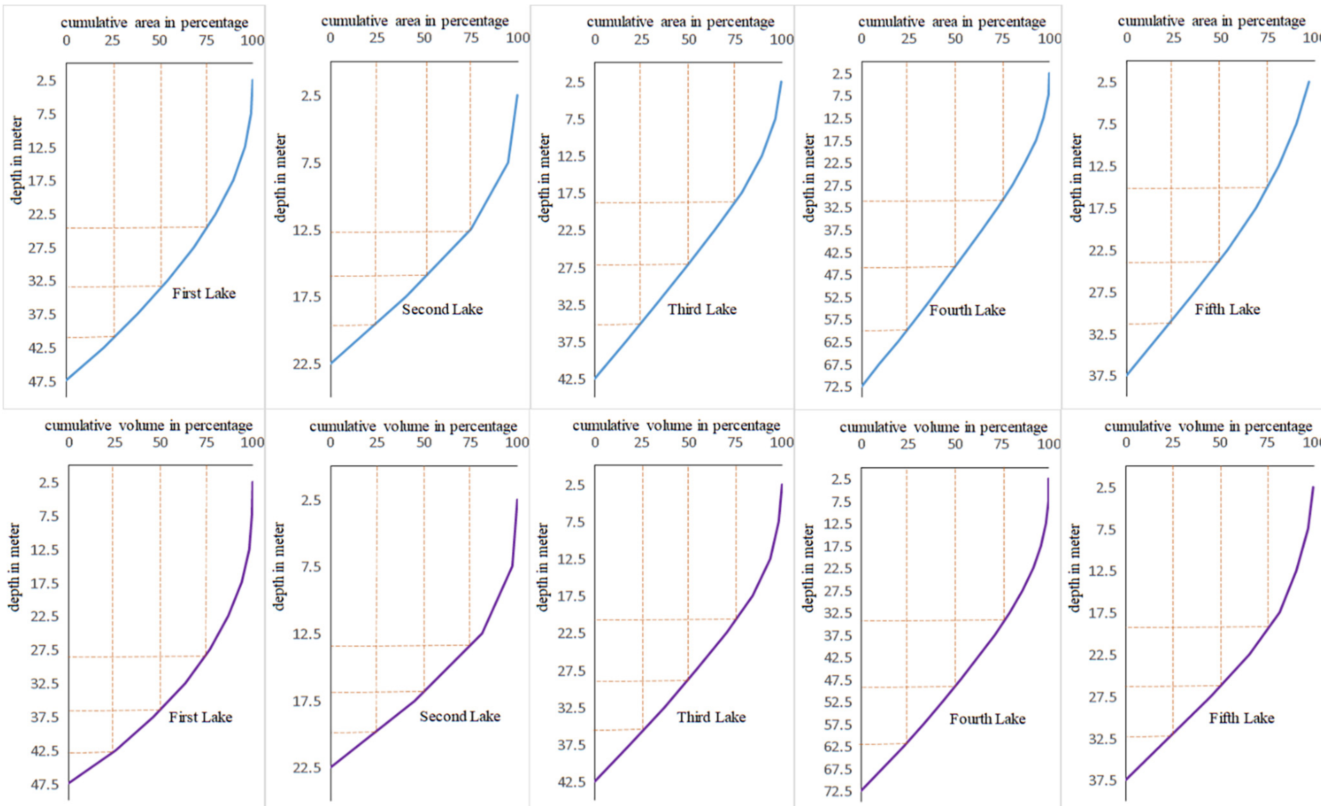

Fig. 5. Hypsographic curves for Toshka Lakes. Notice that the x-axis is located at the top of the figure in the common format for this type of graphic curve, which allows the depth measurements to be displayed in a downward direction.

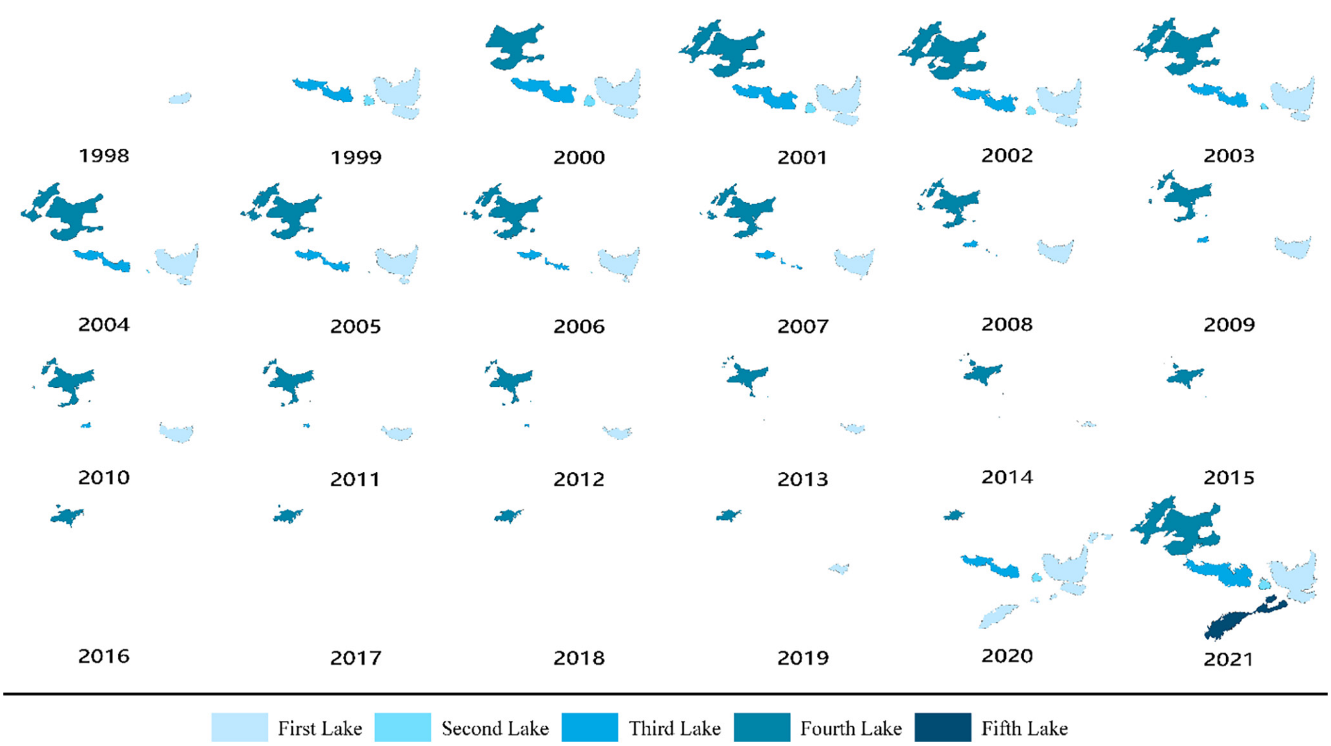

Fig. 6. Differences in the Toshka Lakes morphology from the year 1998 to 2021, images (1998–2020) were taken in December while images (2021) were taken in late November.

tible to changes in their surface area, while others are displaying very few changes (Harsha et al., 2020). The related dynamic behaviors are particularly important because they are correlated to the concentration of nutrients and the biological productivity of the lakes (Pérez-Ruzafa et al., 2019).

Past, present, and future of Toshka Lakes

The inland lakes created in Toshka Depression have repeatedly been flooded and desiccated over the last 24 years. Fig. 6 shows that the surface areas of Toshka Lakes appear to vary greatly over time. The Lakes date back to 1998, and the first sine curve extended from 1998 to 2018 (Abd Ellah, 2021), with four lakes appearing during this interval. Because of low water discharges from Lake Nasser, and the natural evaporation and percolation through seepage, the Toshka Lakes subsequently shrank, and most of them completely dried up except for the fourth lake, which is the deepest of them. As shown by the satellite imagery, in the years 2020–21 relevant water flows through the Toshka spillway have reached and re-flooded the basins of the Toshka Depression. The Toshka Lakes reappeared where the inland lakes had been previously formed, but their morphology was drastically modified because the surface of the lakes has been consistently widened.

By observing the past behavior of the lakes shown in Fig. 6, one can forecast that Toshka Lakes will probably start to dry up in the next decade if the water flow from Lake Nasser decreases. Nevertheless, despite such a negative outlook, the hope for a complete recovery of Toshka Lakes should not be dismissed, because they have already recovered from their desiccation at the beginning of the current decade. Probably, periodic desiccation and reflooding of lakes in the Toshka Depression will continue in the future, according to the decrease and increase of the level of Lake Nasser. However, based on the above-mentioned results, in particular, the bathymetric maps obtained using specific in situ measurements, the future of Toshka Lakes becomes less uncertain as the predictive models are based on more reliable data.

Outlook and proposal

Water resources in Egypt are limited. Furthermore, Egypt's population has experienced rapid growth, being today more than one hundred million, with an average increase of 2.7 % per year. This fact indicates that the country will face in the next future serious water scarcity. As a consequence, the Egyptian government is deeply concerned about a relevant increase and better management of its water resources. The recent announcement by the press (Al-Monitor, January 5, 2022) of the revival of the Toshka project, within the Western Desert agricultural project, is therefore very important for the future of Egypt. The government's strategic plans are embracing several development activities in the fields of agriculture, industry, transport, communication, and roads, as well as social aspects and services. The Toshka project is a part of this huge project, where the water from Lake Nasser is diverted into the Sheikh Zayed Canal and brought through a system of canals into the heart of the Western Desert, to eventually create a New Valley parallel to the River Nile Valley. The involved region starts from the western side of Lake Nasser near Khor Toshka, stretches across the Toshka Depression, and moves due north, along the old Darb elArba'in, through the oases of Baris and El-Kharga (El-Shabrawy and Dumont, 2009).

Today, the current overflow from Lake Nasser spillway is recreating and enlarging Toshka Lakes. But it is certain that their falling water level, due to evaporation and seepage, will cause these closed lakes to shrink again, with a rapid increase in their water salinity. Therefore, it is fundamental to optimize the use of this freshwater resource. A direct use, which depends on the diversion of the Toshka Lakes water, requires a massive employ of pipelines accompanied by an installation of modern irrigation systems. The Egyptian Government, in reclaiming a part of the desert, uses the surface waters to increase agricultural production and attract people from the over-populated Delta region. Therefore, Toshka Lakes can be related to the irrigation system of the New Valley Project, in particular for nearby lakeside direct irrigation projects, and for the surrounding area, along the old Darb elArba'in (≈150 m a.m.s.l.), through the oases of Baris (≈50 m a.m.s.l.) and El-Kharga (≈60 m a.m.s.l.). The Lakes' water can be also a water resource along Sheikh Zayed Canal of Toshka's new valley area.

Darb elArba'in, the oases of Baris and El-Kharga, and Toshka's new valley are very important areas for Egypt, because of the large presence of groundwater, which can be used for massive agricultural development. However, water and land resources are exposed to degradation because of the decrease in groundwater levels. Consequently, there would be an increasing cost of lifting water as well as dealing with its salinity. One of the various solutions for improving the water management conditions can be to consider Toshka Lakes as a water resource for aquifers of the surrounding area, and therefore to use the lakes for artificial aquifer recharge, at a rate that is faster than that obtained in natural conditions. The main advantages of this solution are the following: storage space available for free, negligible evaporation losses, and minimal temperature variation. Moreover, the solution has no adverse social effects, because it does not require any displacement of population or loss of agricultural land. Moreover, it is environment-friendly, provides water during water deficit conditions, and uses storage that is resistant to natural or anthropogenic hazards.

Conclusion

The bathymetric method proposed here, based on the combination of in situ measurements, RS, and GIS technologies, provides the possibility of an accurate determination of the three-dimensional morphology of Toshka Lakes. The presented bathymetric maps and morphometric parameters of the Lakes, including the depth, volume, area, width, and length, have been generated using state-of-the-art technologies, which can provide quick surveying with ease of use of equipment. Toshka Lakes are large inland basins based on specific morphometric characteristics, with areas that significantly vary with time. The estimation of the amount of stored water of 53.28 billion m^3 is significant (almost equal to Egypt's annual water income from the Nile). This highlights the importance of using this water rather than losing it to evaporation. The size of Toshka Lakes is expected to gradually shrink in the next future, similar to what had occurred in the past decades. The findings given in the present study are providing valuable information that can be used for water-related resource management systems and subsequent limnological and ecosystem research for Toshka Lakes. This knowledge can help in the development of the most effective methods for improving the ecological conditions of the water basins, and, of course, to find the most eco-friendly use of water from the Toshka Depression. Let us conclude by stressing that the proposed method for an accurate overview of morphometric characteristics can be generally applied to model the evolution of other water basins in the world.

The article documents the current status of Toshka Lakes and enables researchers and decision-makers to predict the change in volume and area with depth. Moreover, the study discusses the potential of utilizing the water briefly without proposing solutions or proving their validity. The present work already estimates a huge amount of water in Toshka Depression, which proves that the utilization of this water is a must.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical clearance

Not applicable.

Raw data

The raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

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