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Bathymetric survey of Lake Naivasha and its satellite Lake Oloiden in Kenya; using acoustic profiling system

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Abstract

Lakes and reservoirs play important roles as freshwater sources for domestic, industrial, agricultural, fisheries and recreational purposes. However, for the lakes to be sustainably exploited, there is need to understand their bathymetric characteristics by conducting bathymetric surveys. This aids in generating information that can guide lakes stakeholders and managers in establishing the volume of available water. It is recommended, therefore, that bathymetric surveys be conducted at ten-year intervals. Such continuous bathymetric information is lacking in many lakes, especially in developing countries. One example is Lake Naivasha in Kenya, which is largely exploited for various socio-economic purposes. Despite its importance, its most recent published bathymetric data were collected in 1991. The goal of the present study, therefore, was to conduct a bathymetric survey of Lake Naivasha and its satellite Lake Oloiden, using an Acoustic Profiling System (APS) to generate Depth–Area–Volume relationships for the lakes. The survey results indicate the in the year 2016 mean depth, volume and surface area of the lake were 4.68 m, 722×10^6 m^3 and 154.17×10^6 m^2, respectively. Because of limited information from the 1991 survey, the 2016 survey results were comparable with those of 1983. The difference in the lakes mean, and maximum depth for the 1983 and 2016 survey was less by 0.23 and 2 m, respectively. This could be an indicator the lake is being affected by anthropogenic activities or environmental changes. The established Depth–Area–Volume relationships are crucial since they provide invaluable information to lake and water resources managers for making informed decisions regarding management of the lake's water resources.

KEYWORDS
Acoustic Profiling System, bathymetric survey, Depth–Area–Volume relationship, Lake Naivasha

1 | INTRODUCTION

Globally, freshwater is a fundamental requirement to support flora, fauna, human life and socio-economic activities. Freshwater is estimated to be 2.5% of the total water volume on our planet, with lakes representing about 0.29% of this water (Gleick, 1996). Surface waterbodies, such as lakes and reservoirs, are largely being exploited as readily available freshwater sources for domestic and industrial water supply, agriculture, fisheries and recreation purposes (Dost & Mannaerts, 2008; Pagliari et al., 2017). To properly manage the water supply from lakes and reservoirs, the current bathymetric characteristics and changes in the water storage capacity of these waterbodies should be determined (Dunbar, Allen, & Higley, 1999). Decision-making in water resources management would greatly benefit from the available information on storage capacity loss of lakes and reservoirs (McAlister, Fox, Wilcox, & Srinivasan, 2013).

Bathymetric surveys are conducted when detailed information of lakes, dams and/or ocean bed levels are required (Odhiambo & Boss, 2004). They are useful in deriving information on water depth, surface areas and reservoir volumes relationships. In addition, environmental changes such as lake/reservoir sedimentation, biodiversity and anthropogenic activities can be assessed from bathymetric surveys. These changes can be evaluated by comparing multi-temporal bathymetric survey data (Dost & Mannaerts, 2008). Such multi-temporal bathymetric survey data can also provide estimates of water capacity loss due to sedimentation (Furnans & Austin, 2008; Lachhab, Booterbaugh, & Beren, 2015). Thus, there is need to monitor the depth and storage capacity of lakes and reservoirs by conducting bathymetric surveys at predetermined intervals (Dunbar et al., 1999). The information derived from such surveys can be used to improve water resource management. One such Lake that would greatly benefit from multi-temporal bathymetric survey is Lake Naivasha, and its satellite Lake Oloiden, in Kenya.

Lake Naivasha is the second largest lake in Kenya after Lake Victoria. It is the larger of two freshwater lakes in Kenya's Rift Valley, which is dominated by alkaline-soda lakes (Harper, Morrison, Macharia, Mavuti, & Upton, 2011; Yihdego & Becht, 2013). Lake Naivasha was designated a Ramsar site (i.e., a wetland of international importance; https://www.ramsar.org/wetland/kenya) from 1995. The lake also supports agro-industrial-based economy (Becht, Odada, & Higgins, 2005). It is greatly valued as a reliable freshwater source, being exploited for floriculture and horticulture, a highly profitable and booming sector in the region (Harper et al., 2011). It is also used for tourism, fishing and pastoralism. The lake's water resources also support varied species of water birds, hundreds of hippopotamuses and other species of large mammals (e.g., buffaloes; waterbucks) that live in the riparian zone. Further, it supports unique habitats, especially the fringing papyrus swamps located mainly in the shallow waters of the lake edges. These papyrus swamps sometimes form floating islands in the lake when the papyrus has been moved by wind (Becht et al., 2005; Harper et al., 2011). Although the lake supports many activities, there is a concern regarding over abstraction of the water coupled, with threats of sedimentation from the changing land uses within the catchment (Becht & Harper, 2002). Thus, there is a need to establish the current bathymetric characteristics of Lake Naivasha, particularly because of its economic values, despite the changes and fluctuations of its water levels.

1.1 | Previous bathymetric surveys

Bathymetric surveys of Lake Naivasha have been carried over different periods in the last century by various researchers. The lake was originally surveyed in 1927 with the goal of generating a depth map (Ase, Sernbo, & Syren, 1986; Thompson & Dodson, 1963). As observed by Thompson and Dodson (1963), the survey conducted in 1927 had poor coverage of the southwest corner of the lake. A bathymetric survey of the lake was subsequently conducted in 1983 using an echo sounding technique. The sounder had a 20° transducer beam and the echo sounder operated at a frequency of 192 kHz (Ase et al., 1986). On the other hand, the coordinates were determined using theodolite measurements. The 1983 survey, however, only used 38 sounding sections of varying lengths because of the time and cost required to conduct a more detailed survey (Ase et al., 1986).

A bathymetric survey of Lake Naivasha was subsequently conducted in August 1991 to improve the 1983 survey using a chart recording echo sounder, similar to what was used in 1983 survey (Hickley et al., 2002). The 1991 survey focused on areas in the lake not surveyed in 1983, with the results presented as a depth contour map generated on the basis of both the 1991 and 1983 survey data.

Based on this review of past bathymetric data, it was determined the most recent bathymetric survey of Lake Naivasha was conducted in 1991, and reported in 2002 by Hickley et al. (2002). There is a recommendation by Dunbar et al. (1999) that bathymetric surveys of lakes and reservoirs should be conducted at 10-year intervals. Thus, the present study conducted a bathymetric survey of Lake Naivasha, together with its satellite Lake Oloiden, using acoustic profiling system (APS). This facilitated the generation of recent bathymetric map and Depth–Area–Volume relationships for the lake, as well as helping identify changes in lake surface area and volume by comparing multi-temporal results between the bathymetric surveys.

To ensure a complete bottom coverage during the bathymetric survey, the use of an echo sounder such as APS is paramount (Cross & Moore, 2014; Dunbar et al., 1999). The accuracy of the results obtained from reservoir surveys using APS, however, is greatly dependent on transects spacing (Wilson & Richards, 2006). According to Cross and Moore (2014), the sampling resolution for complex and steep areas is improved by using closer transect spacing. On the other hand, a challenge exists in using APS on shallow water (e.g., water depth of 50 cm and less; Dunbar, Higley, & Bennett, 2002). As a result, these regions are not surveyed, and the depths are usually generated with interpolation techniques, or by conducting direct water depth measurements at some predetermined points. As a result, interpolation was undertaken to address shallow and inaccessible parts of Lake Naivasha and its satellite Lake Oloiden. To further ensure high quality data are collected, surveying must be conducted during periods in which there is no wave action in the lake, mainly because APS does not have a pitch and roll sensor.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was conducted in Lake Naivasha and its satellite Lake Oloiden (Figure 1). The lakes are located about 100 km northwest of Nairobi (Hickley et al., 2002; Njuguna, 1988). For the present study, Lake Naivasha refers to a combination of the Main Lake

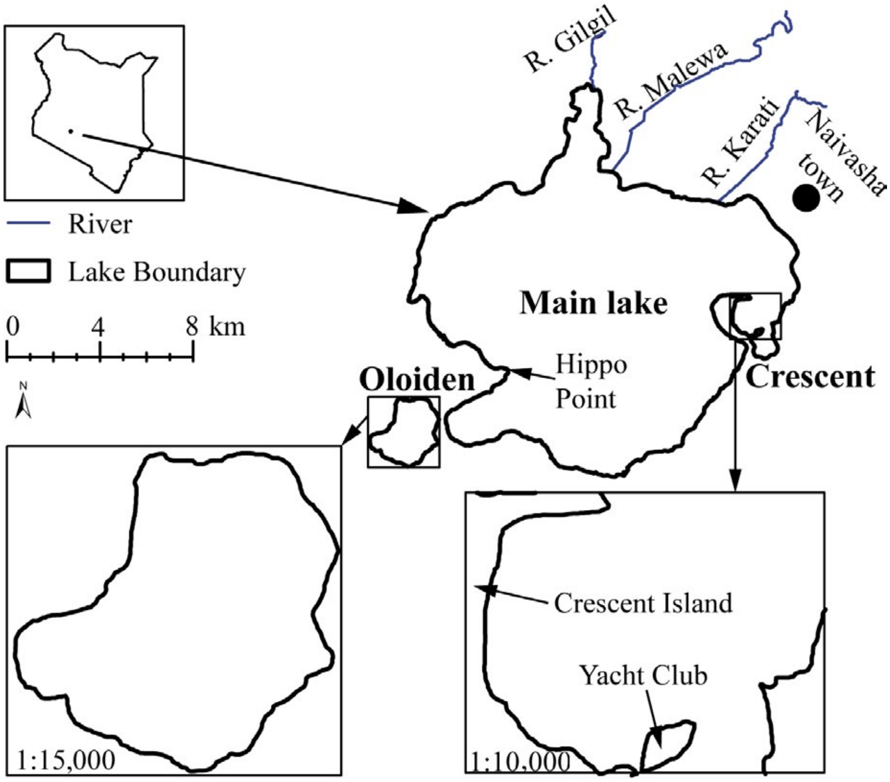

FIGURE 1 Location of Lake Naivasha, Kenya, showing Main, Crescent Island Lake and satellite Lake Oloiden and main inflow rivers (official gauging station of Lake Naivasha at yacht club also shown)

and Crescent Island Lake. Lakes Naivasha and Oloiden are located approximately 0°10′ to 1°00′S and 36°10′ to 36°45′E (Yihdego & Becht, 2013), with an average elevation of 1,890 m above sea level, and water depth ranging between 3 and 6 m (Hickley et al., 2002). Crescent Island Lake, the deepest part of Lake Naivasha, is located on the eastern part (Figure 1). Moreover, lake water levels fluctuate greatly with season. Thus, the lake surface area varies from about 100 to 200 km^2, with Crescent Island Lake becoming isolated from the Main Lake in extreme cases (Verschuren, 1999).

Surface inflows into the lake are mainly from the Gilgil, Malewa and Karati Rivers (Figure 1; Everard, Vale, Harper, & Tarras-Wahlberg, 2002). Perennial rivers Malewa and Gilgil contribute about 90% of the inflow to Lake Naivasha (Becht & Harper, 2002), with the remaining inflow being from groundwater seepage, direct precipitation and seasonal streams, especially the Karati River, which flows for about 100 days per year (Boar & Harper, 2002). Lake Naivasha has no visible surface outlet, however, has outflows through the permeable volcanic subsurface rocks that allows it to remain a fresh water lake (Bergner & Trauth, 2004).

According to Ase et al. (1986) and Verschuren (1999), the average annual rainfall and evaporation in Lake Naivasha are 680 and 1,865 mm, respectively. For the lake water mass to exist, Lake Naivasha relies on perennial rivers, which flow from the Aberdare ranges, where average rainfall is 2,500 mm (Becht & Harper, 2002).

The satellite Lake Oloiden located at the southern end of Lake Naivasha (Figure 1), being hydrologically closed. Thus, water loss from the lake can only be attributed to evaporation (Verschuren, 1999). Lake Oloiden depth and surface area ranges between 4–19 m and 4–7.5 km^2, respectively. During periods in which the Lake Oloiden lake level is high, the lake is confluent with Lake Naivasha. In such cases, water in Lake Oloiden is freshwater. On the other hand, when the lake water level is low, the two lakes are separated, with the water in Lake Oloiden being saline (Verschuren, 1999).

2.2 | Pre-bathymetric survey of Lake Naivasha

Prior to the Lake Naivasha and Oloiden survey, the lake boundaries were digitized from Digital Globe images accessed via Google Earth. A series of transects and tie lines for guiding the survey also were created as shapefiles in ArcGIS. The spacing between the transects were 50, 100–200 m and 2 km (Figure 2) in the shallow, medium and deep (middle of lake) parts of the lake, respectively. These spacings were based on previous surveys indicating there was less variation in the bottom topography in the middle part of the Main Lake. To improve data collection accuracy, tie lines were created with an orientation of 90° to transect lines. The predetermined transects and tie lines facilitated elaborate coverage of the lake during the survey.

According to Sekellick and Banks (2010), tie lines provide independent measurements of depth, and can also be used to check the measured water depth at their intersections with the transect lines. A similar procedure was previously used by Dunbar et al. (1999); Odhiambo and Boss (2004) and Sang et al. (2017) in reservoir surveys. The lake boundaries, together with transects and tie lines, were projected into Universal Traverse Mercator (UTM) zone 37S, and then loaded in APS.

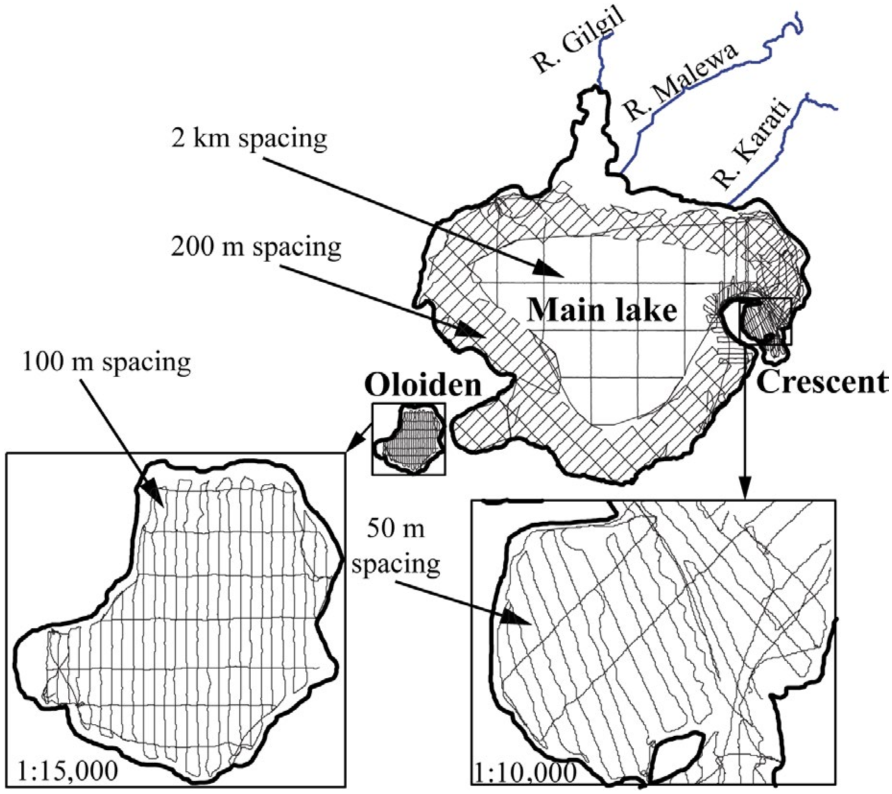

FIGURE 2 Transects, tie lines and spacings as used during bathymetric survey in Lake Naivasha and satellite Lake Oloiden

2.3 | Bathymetric survey of Lake Naivasha

The bathymetric survey was conducted for a total of 42 days between July and October 2016. It was conducted with an APS mounted on a motor-driven dual Jon boat driven at a constant speed of 6 km/hr. The use of a 6 km/hr speed was to avoid cavitation and turbulence around the depth of transducer, ensuring the data collected were of high quality. The same speed was used by Sang et al. (2017) in a bathymetric survey of Ruiru Reservoir in Kenya. The boat was driven along the predetermined transects and tie lines (Figure 2), except where there were obstructions by water hyacinth, papyrus, fishing nets, partially submerged trees, shallow waters and hippopotamus.

Since the survey equipment has an in-built navigation system, the data obtained during bathymetric survey included coordinates and corresponding water depths at each point. These data were recorded and stored for post-survey processing.

2.4 | Post-survey processing of bathymetric data

For post-survey processing of the collected data, acoustic images were traced along a profile using the post processing and editing program, DepthPic (Specialty Devices, Inc., Wyle, Texas), which aided in extracting XYZ (latitude, longitude and water depth) values for all the surveyed points. The resulting three-dimensional XYZ data were imported into a Surfer 14, Golden software (Golden Software, Inc. Golden, CO, USA) worksheet and saved as a surfer data file. Data cleaning was undertaken to remove duplicates and any outliers caused by poor GPS responses. Yesuf, Alamirew, Melesse, and Assen (2013) and Sang et al. (2017) used a similar data cleaning procedure in their bathymetric data processing. The next step involved creating a grid file from the point data through interpolation. For the present study, ordinary Kriging interpolation method was used because it creates smoother contours than those generated from the Triangulated Irregular Network (TIN) model, as reported by Dost and Mannaerts (2008) and Aykut, Akpinar, and Aydin (2013).

Contours and bathymetric surface were generated from the grid, and then cartographically edited for presentation using a procedure of Yesuf et al. (2013). The volume and surface area corresponding to different water depth contours were calculated, aiding in generating depth–area–volume relationships. Volume and area calculations were performed from the grid file using the Surfer in-built mathematical functions. The lake lower surface represented by the respective water depth contours and upper surface defined by the grid were specified. The volume and area were calculated at 1 m depth intervals starting from $Z = 0$ to 17 m, where 0 depicted the surface of the lake. Volume is calculated in Surfer 14 software using Trapezoidal, Simpson's and Simpson's 3/8 Rule. From the volume calculated with the three methods, the relative error was estimated (Yesuf et al., 2013) and used as an indicator as to whether or not the three total volume calculations were close together or not, as follows:

$$RE = \frac{LR - SR}{Avg_{volm}} \times 100 \quad (1)$$

where, RE = relative error; LR = largest result among the three methods; SR = smallest result among the three methods; and Avg_{Volm} = average volume of the three methods. According to Yesuf et al. (2013), an RE ≤ 0.9 indicates the variation of the volume and area calculated from the three methods is insignificant, meaning the computed lake volume and area are acceptable. For all the volumes calculated by varying water depths, the computed lake volume and area were found acceptable for the present study. The established volumes and areas values were plotted against the depth, resulting to in Depth–Area–Volume relationship, which illustrated the variations between lake volumes, surface areas and various water depths.

In generating the Depth–Area–Volume relationship, calculations were done with a bathymetric surface model (representing the raw grid), rather than from the cartographically edited contour maps. This was to eliminate chances of introducing errors to the calculated volumes and areas. A similar procedure was followed by Wilson and Richards (2006) and Sekellick and Banks (2010), wherein they generated Depth–Area–Volume relationships from the original bathymetric surface model other than the edited contours.

The topography of the lake was established by using profiles that captured various sections of the lake. Depth profiles (Figure 3) were taken from the east to west direction of the lake represented by the profile from Hippo Point towards the town of Naivasha (Figure 1). The second profile was generated from the south to north direction of the lake. Profiles were also taken in Crescent Island Lake and Lake Oloiden.

3 | RESULTS AND DISCUSSION

During the Lake Naivasha survey, the tie lines used in checking the quality of water depth collected indicated the difference in depth measurements was in the range of ± 1–5 cm, where the transects and tie lines crossed. These findings agreed closely with those reported by Yutsis et al. (2014), wherein the water depth measured from the crossing lines did not exceed ± 2–5 cm in a bathymetric survey conducted in Cerro Prieto Dam, northeast Mexico. The accuracy of acoustic water depth measurements was also checked by randomly conducting direct depth measurements at some parts of the lake, with the results found to be within ± 1–3 cm.

3.1 | Lakes surface area and levels

The Lake Naivasha boundary created from the Google Earth images had a surface area of 154.17 km^2, while that of Lake Oloiden is 5.47 km^2. Although the lake boundary was created in March 2016, and a survey conducted between July and October 2016, the lake had the same surface area during the two periods. This was also confirmed by the fact that within the two periods the lakes level was 1,889 m, as recorded from an official gauge at a yacht club (Figure 1). Comparing these results with those from previous surveys (summarized in Table 1), the surface area of the lake varies.

To compare the surface area of the lake over time, the same lake level of 1,889 m was chosen. The lakes surface area in 1927, 1983 and 2016 was 162, 180 and 154.17 km^2, respectively. The differences in

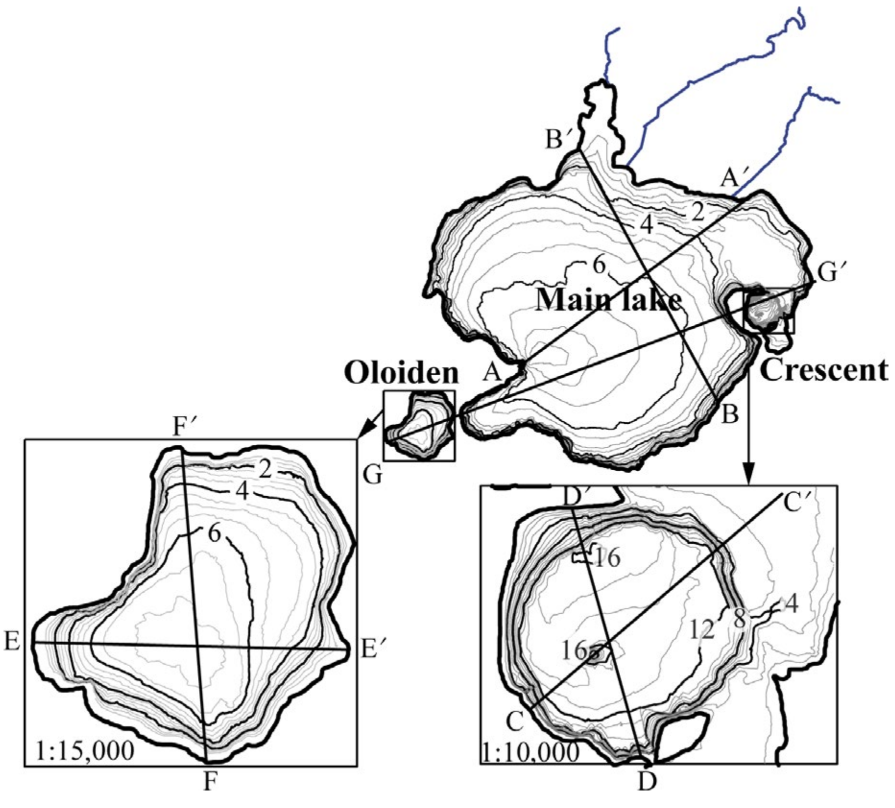

FIGURE 3 Profile tracks and water depth contour map of Lake Naivasha and Satellite Lake Oloiden

the lake surface area under constant lake levels could be attributable to different methodologies used in computing the lake boundary or area. Thompson and Dodson (1963) and Ase et al. (1986) did not indicate whether or not the surface area presented for 1927 and 1983 surveys only represented Lake Naivasha or was the combined areas of Lake Naivasha and Lake Oloiden. This information was necessary in comparing the surface area, since there are certain periods of the year when Lake Oloiden is confluent with Lake Naivasha.

3.2 | Depth of Lake Naivasha

A water depth contour map of Lake Naivasha and Lake Oloiden was generated (Figure 3). Comparing Figure 3 with the contour maps of 1927, 1983 and 1991, the 1927 map exhibited major differences, where the shape of Lake Oloiden map as presented by Ase et al. (1986) is different. The difference in Lake Oloiden's shape could be attributed to the fact that the 1927 survey had a poor survey coverage at the southwestern part of the lake. Another observed difference on the contour maps drawn for the various bathymetric survey is the presence of a delta on the northern part of the lake. This delta was not distinct from 1927 contour map presented by Ase et al. (1986), compared with the resulting 1983, 1991 and 2016 contour maps in which the delta is distinct. The presence of delta from 1983 to 2016 can be associated with a build-up of sediment loads deposited by the main inflows.

The 2016 survey confirmed that the middle part of the lake was generally flat, with the maximum depth of Lake Naivasha being at the Crescent Island Lake, with a similar finding reported by Thompson and Dodson (1963) and Ase et al. (1986). A general reduced depth across the three lakes between 1983 and 2016 was observed, since the maximum depth in the Main Lake (located at Hippo point), Crescent and Oloiden Lake has been reduced in depth by 2, 0.6 and 1.75 m, respectively. The variation, however, may be attributable to the differences in the adopted survey methodologies. The effect of the methodologies used to the results of a bathymetric survey were also reported by Yesuf et al. (2013). A difference of 44 cm on maximum depth of the lake between two surveys was reported in that study.

Although the 1983 and 2016 survey water levels were the same, the mean depth of Lake Naivasha in 2016 was 0.23 m lower than that recorded in the 1983 survey (Table 1). Further, according to Hickley et al. (2004), Lake Naivasha had a mean depth of 3.35 m in the 1991 bathymetric survey, being 1.33 m lower than that recorded in the 2016 survey. The difference in the lake mean depths between the 2016 and 1991 surveys could be attributed to different water levels in the lake. The water level in 1991 was 1,887.5 m, compared to the water level of 1,889 m during the 2016 survey. The reduced mean water depth, while the surface water level remained constant, could indicate sedimentation has occurred in Lake Naivasha and its satellite lake over time.

The lake bottom topography variations, depth profiles of the 2016 study for the Main Lake, Crescent Island Lake and Lake Oloiden are summarized in Figure 4. The deepest part of the Main Lake (Section A – A′ of the profile) is close to the Hippo Point on the southwestern section of the lake. Based on the profiles, the Main Lake is relatively flat at its middle parts, while the deepest section is at Crescent Island Lake (Figure 4), with Ase et al. (1986) reporting a similar finding. Due to close spacing during the survey, the changes in lakes bottom topography were especially noted at Crescent Island Lake (Section C – C′ profile in Figure 4). A continuous profile cutting through Lake Oloiden, Main Lake and Crescent Island Lake is presented in Section G – G′, which indicates a discontinuous line indicating regions not in the water. From the profiles, it also was observed that gentler slopes exist towards the northern parts of Lake Naivasha (Figure 4), which covers the inflow area of the lake. This part could have gentler slope because of sediment deposition taking place in the zone, with a similar observation of the inflow part of the lake having gentler slope also observed by Hassan, Al-Ansari, Ali, Ali, and Knutsson (2017).

3.3 | Lake Naivasha volume

The combined volume of Lake Naivasha and its satellite Lake Oloiden was 748.2 × 10^6 m^3 (Table 1). The computed lake volumes for bathymetric surveys conducted in 1927, 1983 and 2016 at a constant water level of 1,889 masl are 730 × 10^6, 900 × 10^6 and

TABLE 1 Summary of bathymetric parameters of Lake Naivasha, and satellite Lake Oloiden for the year 1927 (Thompson & Dodson, 1963), 1983 (Ase et al., 1986), 1991 (Hickley et al., 2002) and 2016

	Years			
Parameters	1927	1983	1991	2016
Volume (× 10^6 m^3)	870[a]	900	–	722 (748.2)[b]
Surface area (km^2)	171 (162)[a]	180	–	154.17 (159.64)[b]
Lake level (m)	1,892	1,889	1887.5	1,889
Mean depth (m)	–	4.91	3.35	4.68
Maximum depth (m)				
Main Lake (hippo point)	–	9	–	7
Crescent	–	17	–	16.4
Oloiden	–	9	–	7.25

[a]The volume and area of Lake Naivasha from 1927 survey corresponding to lake level of 1,889 m.
[b]The volume and area represent Lake Naivasha and Lake Oloiden combined.

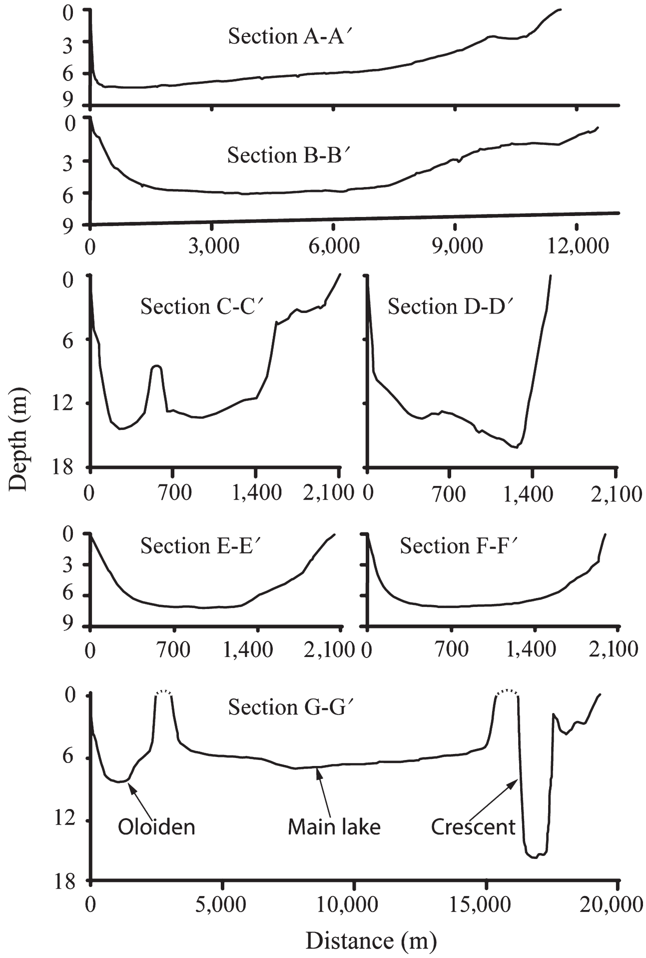

FIGURE 4 Cross section profiles of Main Lake (Section A-A′ and B-B′), Crescent Island Lake (Section C-C′ and D-D′), Lake Oloiden (Section E-E' and F-F') and combined cross section running from Oloiden, Main Lake and Crescent Island Lake (Section G-G′)

748.2×10^6 m^3, respectively. Table 1 indicates the 2016 combined volume of the lake is higher than that determined in 1927, and lower than that recorded in 1983. These volume changes translate to an increase of about 170×10^6 m^3 in 1927 and 1983. Similarly, a decreased volume of 151.8×10^6 m^3 was observed in the 1983 and 2016 study. Comparing the lake volumes for the 1927 and 2016 study (Lake Naivasha and Lake Oloiden combined), an 18.2×10^6 m^3 increase in volume was observed. In contrast, the Lake Naivasha volume was found to have decreased by 8×10^6 m^3 between the 1927 and 2016 survey findings. During previous surveys, Thompson and Dodson (1963) and Ase et al. (1986) reported poor transect coverage throughout the lake, which could have increased the errors of the calculated volumes. Accordingly, closer transects and tie lines spacings were followed during the 2016 Lake Naivasha survey (Figure 1) to improve the accuracy of the water volume calculation. A transect spacing of 50 m was followed in Crescent Island Lake since this section of lake was previously reported by Ase et al. (1986) to be more topographically complex. Cross and Moore (2014) and Furnans and Austin (2008) reported closer transect spacing during a bathymetric survey of waterbodies improved the confidence and accuracy of the estimated water volume. According to Moriasi, Steiner, Duke, Starks, and Verser (2018), the volume estimated from the 2016 study could have higher accuracy since bathymetric water volume measurements using APS usually have an error value of ± 4.2%.

Thompson and Dodson (1963) and Ase et al. (1986) did not specify whether the volumes observed in their studies represented only Lake Naivasha or the combined volume of Lake Naivasha and Lake Oloiden, thereby limiting the comparison of their findings with those of the 2016 survey. The reduced water volume at the same surface water level of 1,889 m, however, could be an indication of a drop in the water depth attributable to sedimentation. This possibility is supported by Solis et al. (2012), who reported that comparisons of lake/reservoir volumes from multi-temporal studies can aid in calculating volume loss rates.

The direct comparison of water volume changes from multi-temporal surveys can lead to determination of sediment accumulation rates. This is not always the case for some lakes, however, since the differences in methodologies used from one bathymetric survey to another may lead to major differences in computed lakes volumes than actual volume changes (Solis et al., 2012).

3.4 | Depth–Surface Area–Volume relationships

The resulting volumes and surface areas against depth at one-metre interval are presented in Figures 5 for Lakes Naivasha and Oloiden. The Depth–Area–Volume relationships present vital information on lakes and reservoirs that aid in their operation, prediction of sediment distribution, and understanding of seasonal variations in water storage capacities (McAlister et al., 2013), which are useful in determining temporal variations in lake surface areas and volumes at different depths (Yesuf et al., 2013).

The Depth–Area–Volume relationship from the 2016 survey was compared to those of the 1927 and 1983 surveys (Figure 6). In comparing the different Depth–Area–Volume curves of Lake Naivasha, it was noted that the 1927 and 1983 curves did not consider depths beyond 10 m. Thus, comparing the 2016 survey findings with those of previous surveys in deeper parts of the lake (Crescent Island Lake) is not possible. Further, fluctuations in lake surface area and volume were also noted where the volume curves of the 1927 survey closely agree with those of the 2016 study. The curves obtained in 1927, however, are different from those of 1983. It was observed that the volume and area occupied by the lake water are different between the five- and ten-metre contours for years 1927, 1983 and 2016. The difference in the curves could be attributed to autochthonous sedimentation, with the curves possibly being an indication of sediment deposition in various parts of the lake, rather than being restricted to the deepest sections (Crescent Island Lake) of the lake.

On the other hand, the difference in curves could also be associated with different methods and technological approaches used during the 1927, 1983 and 2016 surveys. Ase et al. (1986), for example, observed that the theodolite equipment and the few sections sounded during the 1983 bathymetric survey could have resulted in some errors and uncertainty in the measurements, thereby affecting the Depth–Area–Volume relationship. The results of multi-temporal

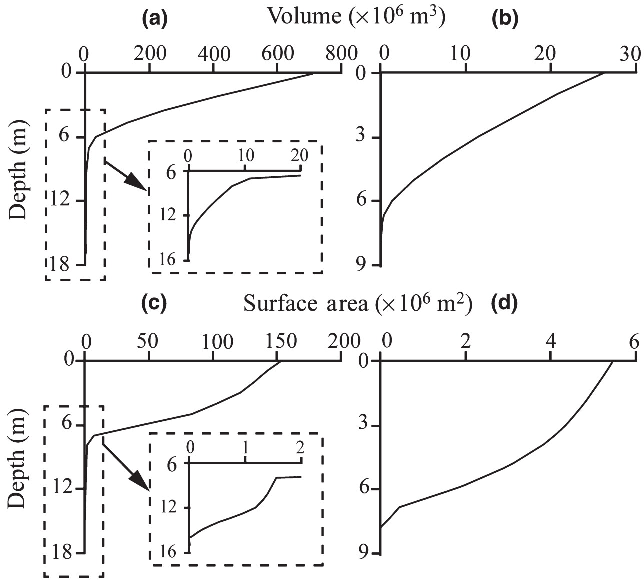

FIGURE 5 Depth, Surface area and volume relationship of Lake Naivasha and Lake Oloiden, respectively (a and b = depth volume relationship; c and d = Depth Surface area relationship)

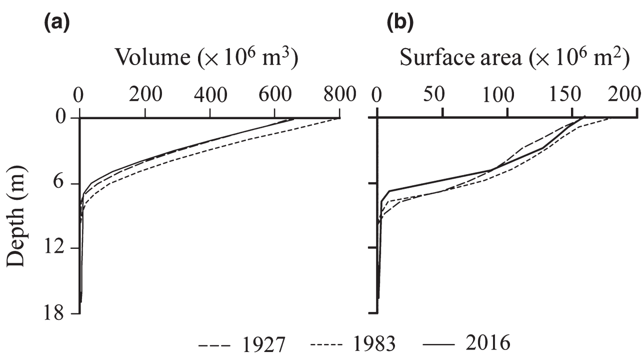

FIGURE 6 Comparison of Depth, Surface Area and Volume relationship of Lake Naivasha for 2016, 1983 and 1927 surveys

Lake Naivasha Depth–Area–Volume relationships indicate similar trends to those observed by Hassan et al. (2017) in a multi-temporal study conducted on Dokan Reservoir, Iraq.

The availability and assessment of these curves would be very useful to stakeholders and water managers in managing water withdrawals from Lake Naivasha. This is because the lake is a Ramsar site, as well as being highly exploited for water supply and irrigation (floriculture and horticulture) sectors (Becht & Harper, 2002; Everard et al., 2002; Harper & Mavuti, 2004; Mavuti & Harper, 2005; Mekonnen, Hoekstra, & Becht, 2012). The benefit of analysing the Depth–Area–Volume relationship was demonstrated by Hassan et al. (2017), who computed the quantity of trapped sediments over a given period by combining the new Depth–Area–Volume relationship with the previous ones on the same figure. Various authors such as Hickley et al. (2002), Bergner, Trauth, and Bookhagen (2003), Bergner and Trauth (2004), Becht et al. (2005), Harper et al. (2011), and Yihdego and Becht (2013) have reported the Lake Naivasha water levels fluctuate greatly. Thus, it is difficult to compare multi-temporal bathymetric surveys and correctly conclude the capacity loss is due to sedimentation.

4 | CONCLUSION

The bathymetric map of Lake Naivasha was generated using APS technology. The lake was found to have a mean depth, volume and surface area of 4.68 m, 722 × 10^6 m^3 and 154.17 × 10^6 m^2, respectively. Considering water levels at 1,889 masl, it can be concluded from the 1983 and 2016 survey that the maximum water depth was reduced by 2, 0.6 and 1.75 m in the Main Lake (hippo point), Crescent Island Lake and Lake Oloiden, respectively. This could be attributed to environmental changes and anthropogenic activities around the lake. The present study provides valuable information that can be utilized for various water resources management activities based on the current lake water capacity.

On the other hand, direct comparison of multi-temporal bathymetric data for Lake Naivasha and its satellite lake could lead to unreliable conclusions regarding the loss of the water storage capacity of the lake. This is because different methodologies were employed in the past surveys and the 2016 study. There is a need, therefore, to use a different approach to effectively determine the sedimentation status of the lake.

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