Vol. 38(1), pp. 83-96, June 2019
ISSN 1821-536X (print)
ISSN 2619-8789 (electronic)

Tanzania Journal of Engineering and Technology

Full Length Research Paper

Development of Improved Characteristic Equations for Lake Rukwa in Tanzania

Patrick C. Valimba

Department of Water Resources Engineering, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania.
E-mail: pvalimba@yahoo.com, pvalimba@hotmail.com

ABSTRACT

Often Lake Rukwa characteristics have been misreported in literature giving different volumes and surface areas at similar water surface elevations. This study aimed at establishing reliable lake characteristics elevation-area-storage equations for Lake Rukwa by utilising all available data and information to define the bathymetry and derive characteristic equations. A procedure was developed that combines historical lake extents, spot heights from topographical maps and surveyed lake bathymetry to define refined bathymetry to levels it has never reached. It combined spot heights around the lake and selected 13,934 surveyed points (from 107,938 available) within the lake confined by the 820 m land contour boundary and define topographical raster image, which was used to extract lake volumes and surface areas between the lowest point (778 m) and 820 m boundary. Change-point analysis was used to detect segmentation of the elevation-area and elevation-volume relationships, which were fitted to a shifted power model. Contours generated from a refined bathymetry raster indicated Lake Rukwa to comprise two north and south lake basins, which are separated by a ridge lying at an altitude of 794.3 m. The north and south lakes consist respectively of five (5) and three (3) deeper depressions (pools) paralleling the northwest-southeast Konongo Scarp, which are disconnected below altitudes 792 m (north) and 789.4 m (south). Characteristic elevation-area and elevation-volume equations are segmented for lake below ridge altitude (794.3 m) whereas single relationships prevail for a single Lake Rukwa. Comparison of lake volumes estimated by refined and old equations indicated underestimation of lake stored volumes between 782.2 m and 805.65 m altitudes and overestimation thereafter by the old equations although the under/over-estimation remained within 10% between 801 m and 812 m. Old elevation-area equations underestimate lake surface area of up to 796.8 m, thereafter overestimate the lake area up to an altitude of 804.85 m and above this altitude underestimation re-appear. The old equations under/over-estimation, however, remains within 11% for altitudes between 794.3 m and 810 m. The refined equations indicate surface areas of north and south lakes at ridge altitude to be 2,554.4 and 837.1 km^2, respectively forming a 3,391.5 km^2 lake while at its highest recorded historical elevation of 804.69 m, Lake Rukwa is 183 km long and 17-51 km wide occupying an area of 5,614.7 km^2 (north: 4,409.8 km^2; south: 1,204.9 km^2) and containing 58.243 km^3 of water (north: 44.318 km^3; south: 13.925 km^3). The developed characteristic equations can be used for water management studies of Lake Rukwa.

Keywords: *Lake bathymetry; lake characteristic equations; Lake Rukwa; lake surface area; lake stored volume; shifted power models.*

NTRODUCTION

Lake Rukwa Basin is an internally draining basin located in south-west Tanzania (Figure 1). The basin covering an area of about 88,000 km^2 within the Rift Valley, is bordered in the southeast by the Mbeya Range, in the west by the slopes of the Ufipa escarpment, and in the north-east by rocky cliffs and rolling hills which reach as high as 1,707 m at Mount Sange (Baker and Baker, 2002).

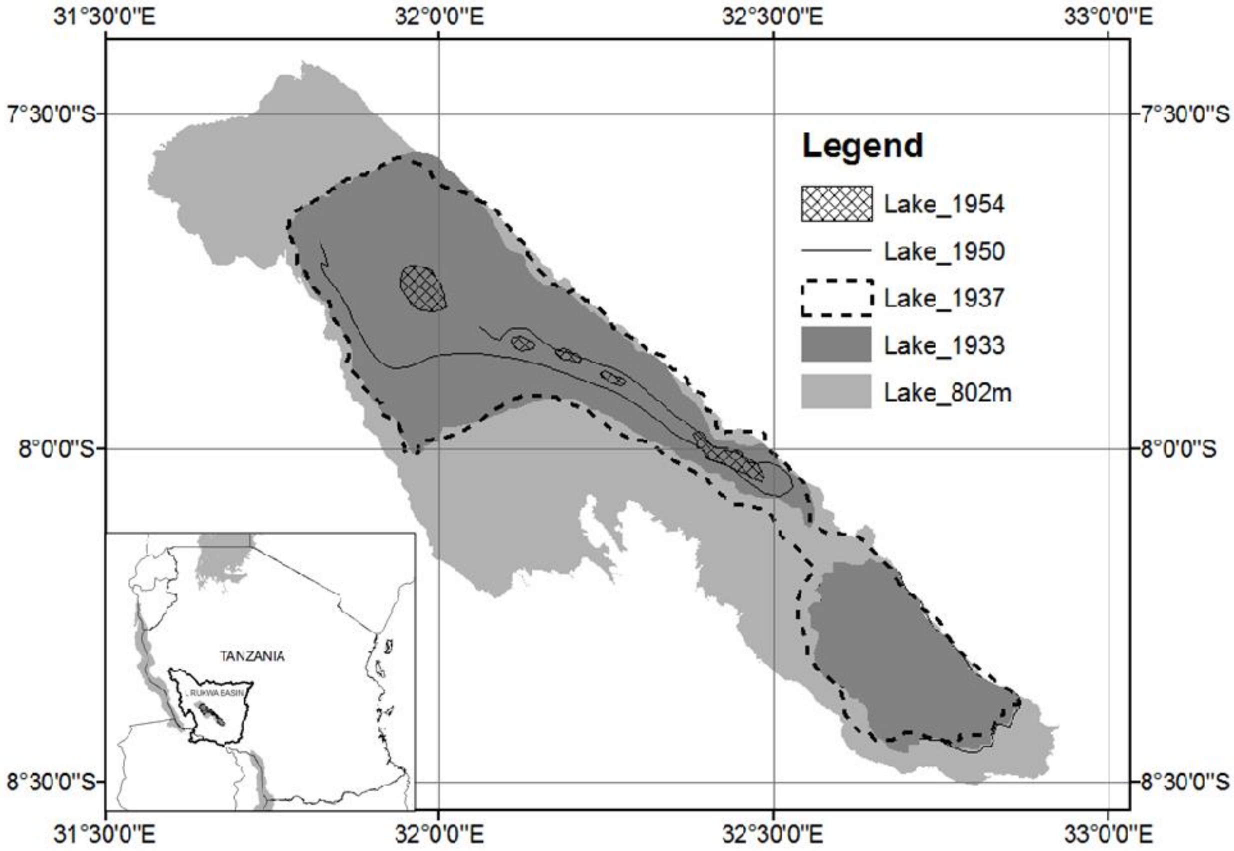

Figure 1: Documented extents of Lake Rukwa surface in the 1933-2018 period.

According to literature, Lake Rukwa has historically changed its size and shape significantly in the past. The changes in shape have indicated existence of pools, two separate large north and small south lake basins and a recent single lake. The lake has varied (Figure 1) between its smallest surface area as recently as in 1954 (Gunn, 1956) to its largest extent in the early 1990s. The length reported to vary between 135 and 180 km with an average width of 32 km (Lakepedia, 2016) with no details of its width provided. The pre 1955 information largely available in Gunn (1956) indicated in much of the 1873-1954 period, Lake Rukwa existed as two separate lake basins (the 1933 extent), which occasionally joined (the 1937 extent). The largest lake in the pre-1960s period was in 1937 followed perhaps by the 1882 and 1905 extents while small surface areas correspond to very low or complete dry north lake basin in 1889-1899, 1920 and 1948-1954. A complete dry lake Rukwa (north & south lakes) has been reported around 1770 and a dry north lake basin in 1815-1835 (Nicholson, 1999) while a dry north lake was observed in 1954 corresponded to small 5 pools (Figure 1). Moreover, low lake depths have been reported in several other years including 1873, 1889-1899, 1914, 1929, 1948-1951, 1953 (Nicholson, 1999; Gunn, 1956). The lake had also experienced notable periods of high stand including the 1875-1882, 1904-1905 and 1937-1942. Since the dry mid-1950s, the lake has constantly risen to its highest level in 1989-1995 and decrease thereafter.

Available limited literature on Lake Rukwa indicates variable lake characteristics (length, width, depth, surface area) of the lake in the historical times. The average lake depth is reported at 3-5 m while the maximum depth in the south basin is reported at 15 m (World Lakes, 2016). However, the total surface area of Lake Rukwa at 800 m is differently reported in the literature (2,600 km^2 – Britannica, 2016; 5,760 km^2 in February 2007 – Wikipedia, 2016; 1,966 km^2 – Lakepedia, 2016 and 5,200 km^2 – MoW-URT, 2014).

Bathymetric survey of the lake has been carried out in March 2014 by the Lake Rukwa Basin Office in collaboration with the Department of Water Resources Engineering of the University of Dar es Salaam and iWASH programme (Tanzania) and it provides, for the first time ever, information of lake bottom topography although at a coarse spacing of surveyed transects. LRBWB-MoW (2014) used bathymetric data to develop characteristic elevation-area-volume equations for Lake Rukwa, which are given by equations (1a) and 1(b).

$$V = \begin{cases} 0.00354\,(EL - 785.9852)^{2.8154} & 786.3 \le EL \le 789.5\ m \\ 0.000019685\,(EL - 784.5818)^{5.43221} & 789.5 < EL \le 792.6\ m \\ 1.1865\,(EL - 791.38525)^{1.49868} & EL > 792.6\ m \end{cases} \qquad (1a)$$

$$A = \begin{cases} 6.616182\,(EL - 785.729)^{2.04543} & 786.3 < EL \le 789.3\ m \\ 98.5706\,(EL - 788.497)^{1.54732} & 789.3 < EL \le 791.7\ m \\ 1796.858\,(EL - 791.699)^{0.51187} & 791.7 < EL \le 800.9\ m \\ 5634.984 + 0.12418\,(EL - 786.3) & 801.0 < EL \le 803.8\ m \end{cases} \qquad (1b)$$

where *EL* is the water surface elevation above mean sea level (m).

The above developed characteristic elevation-area and elevation-volume equations for Lake Rukwa suffer from two major setbacks in their usage. The first problem is that the equations have been developed for a single Lake Rukwa and therefore are inapplicable at times of low lake stands when the lake divides into its separate north and south basins.

The second problem arises from interpretation of no water altitude (h_o) as estimated in developed elevation-area and elevation-volume relationships. The relationships closely predict this to be around 785.73-785.99 m indicating the lowest bottom point as 785.7 m. However, re-analysis of all available bathymetric data for each transect revealed that the two lake basins have different deepest sounded points, which were 784.36 m (north) and 778.37 m (south). Consequently, the depicted h_o of the developed relationships could be indicating the lowest point of the north basin. This resulted from the weakness of the selected 2,605 bathymetric data points used in developing these equations (deepest point: 15.6 m) (LRBWB-MoW, 2014) against a total of 107,938 available soundings (deepest: 22.5 m).

Moreover, lake surface areas estimated from developed elevation-area equations differ from those digitized from maps. Lake shoreline at 802 m altitude digitized from available 1:50,000 topographical maps of 1985 gives a total lake surface area of 5,259.81 km^2 while estimated by the equations as 5,636.93 km^2. The boundary shoreline used in developing these early study equations was digitized from Google Earth image and assumed to correspond to the 800.8 m lake surface altitude recorded during the March 2014 bathymetric survey, the fact that could not be verified. Elevation-area equations are further inapplicable for altitudes exceeding 803.8 m and consequently lake surface areas at higher lake stands of 1989-1995 and 1998 cannot be estimated using these equations.

Owing to availability of bathymetric sounding data within the lake and inadequacy of developed characteristic equations for the lake, this study aimed at improving lake bathymetric analysis by incorporating lake shorelines digitised from different existing maps and spot heights to a higher altitude of 820 m. Moreover, this study uses improved lake bathymetry to establish of new elevation-area and elevation-volume equations for Lake Rukwa taking into consideration existence of multiple lake basins at low stands.

METHODS AND MATERIALS

Lake Boundaries and Bathymetric Data

Lake boundaries were obtained from available digitised and geo-referenced 1:50,000 topographical maps and the December 1954 Lake Rukwa map of the Directorate of Colonial Survey (DCS) (Gunn, 1956). Topographical maps gave the 802 m lake shoreline and 820 m first land contour from the lake shoreline. The DCS hardcopy map in the Gunn (1956) gave several lake surface extents between 1933 and 1954. The map was extracted, converted to an image file and geo-referenced using coordinates of several locations on the map. The 1947, 1950 and 1954 extents were directly digitised from the map while the 1933 and 1937 lake surface extents were extracted from the map following descriptions in the accompanying text (Gunn, 1956).

The two types of data required for development of lake elevation-area-volume relationships were lake water depths (converted to surface water elevations) and lake shoreline boundaries. Water depths of Lake Rukwa were primarily obtained from lake bathymetric survey carried out in March 2014. Bathymetric (depth sounding) data covers only the current inundated part of the lake below 800.8 m altitude (Figure 2) and were converted to lake bottom altitudes using a known benchmark at the Lake Mbangala gauging station and lake stage measurements at Mbangala during the survey.

Water depth variation along shoreline transects parallel to the Konongo scarp indicated consistent deep-water producing lake shorelines parallel to the scarp and therefore additional points were generated by linear interpolation of lake surface altitudes between adjacent transects along the unsurveyed shoreline (Figure 2). Spots heights of random land points between the 802 m lake shoreline and the first 820 m land contour line were read from 1:50,000 topographical maps and recorded (Figure 3). Gunn (1956) gave spot measured depths of Lake Rukwa at different locations between 1934 and 1954, which were used in verification of interpolated lake bathymetry.

Improving Lake Bathymetry

The 2014 bathymetric survey of Lake Rukwa used an echo sounder mounted at the rear bottom of the boat to record water depths every second. The boat cruising speed was maintained at 10-12 km/hr providing soundings at an approximately interval of 2 – 4 m. At some instances when the sounder went out of water due to high waves, the soundings were not recorded. A total number of 107,938 good soundings were finally retained. Owing to this large number of closely sounded depths of the lake, it was necessary to select few sounded depths representing lake bottom altitudinal variations, which were combined with spot heights to define an improved lake topography raster. The selection process of representative lake bathymetric points used three criteria for each surveyed transect i) minimum and maximum sounded depths were selected, ii) sounded depths taken for points in which depths differences equalled or exceeded 0.2 m and iii) selected points were constrained to stretch the entire length of the transect across the lake. In cases when the second criterion eliminated a certain portion of the transect, few points were retained at a specified interval to bridge the gap. These selection criteria were applied to each of the 12 perpendicular and 12 parallel to shoreline transects. These criteria retained 13,934 sounded depths (Figure 3). The selected bathymetric points show the deepest locations lie mostly close to the eastern shore coinciding with locations of the 1954 pools in the north lake basin. The elevation at these points were combined with spot heights to define land altitudes to 820 m (Figure 3).

Improvement of the bathymetry was necessary in order to improve quality of the contours defining shapes of lake surface. This required constraining of interpolation by introduction of manually interpolated depths between the adjacent transects in northwest and southeast parts of the lake and along the eastern shore along the Konongo Scarp (Figure 3). The aim was to rectify unrealistic inward curves in contour shapes at these locations revealing themselves as arcs from shoreline along the Konongo scarp (Figure 4a) at places were the lake surface shorelines depicted in historical parallel to the scarpment. This was done by constraining interpolation to improve representation of the shoreline shape as in historical digitised maps (Figure 4b).

Assessing adequacy of improved bathymetry to define lake shapes

Assessment of adequacy of improved lake bathymetry was carried out by comparison of shapes and areas of the lake from contour generated lake extents against digitised historical extents. Different interpolation methods included in the ArcGIS Spatial Analyst Tool were used to develop raster data from these point altitudes and contours created at an interval of 0.1 m from the rasters to define shapes of lake surface. A comparison was then made by plotting on the same map contours and digitised lake surfaces and comparing shapes of contours closest to historical lake shapes.

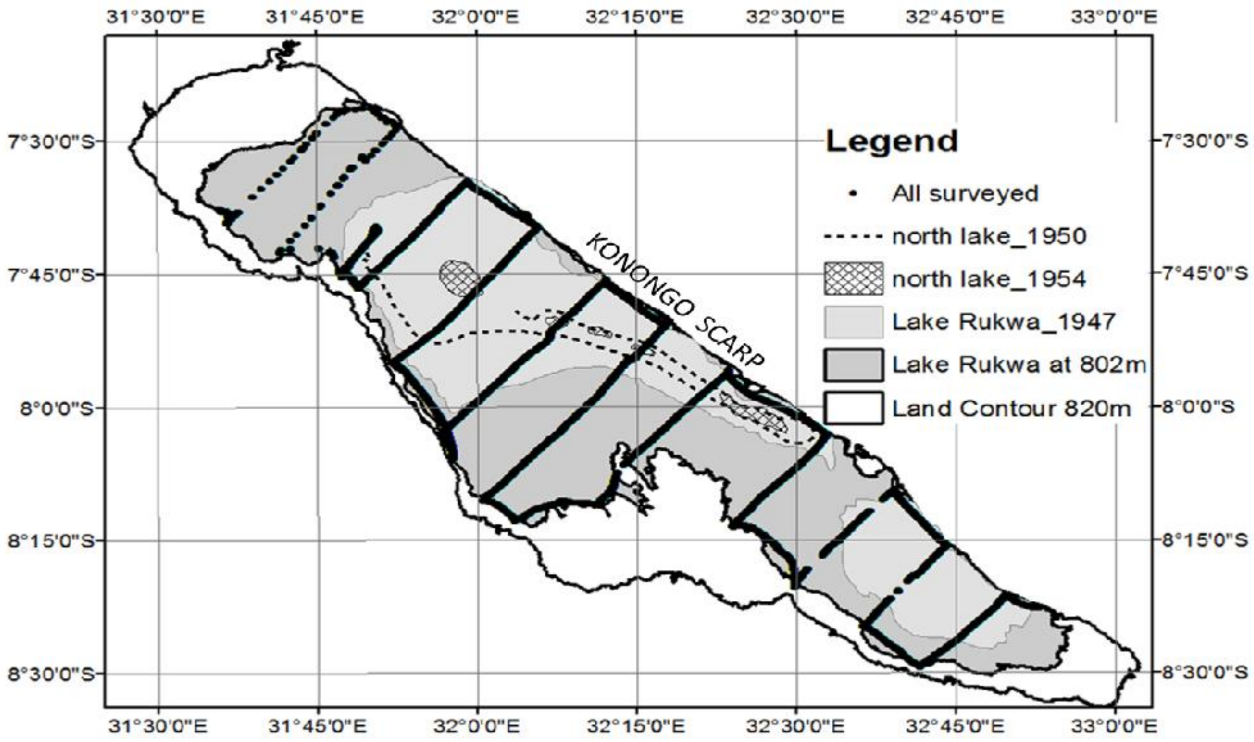

Figure 2: Bathymetric sounded data at surveyed transects in Lake Rukwa.

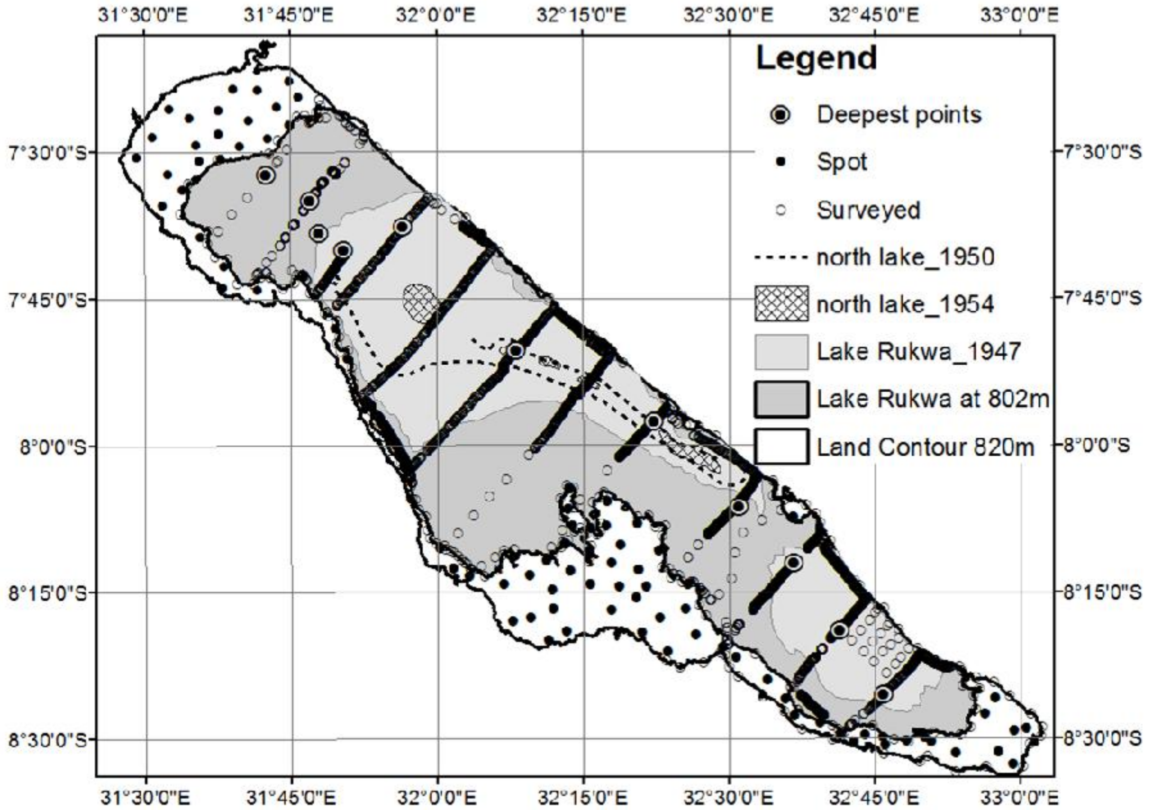

Figure 3: Selected bathymetric points, spot heights and lake boundaries for analysis.

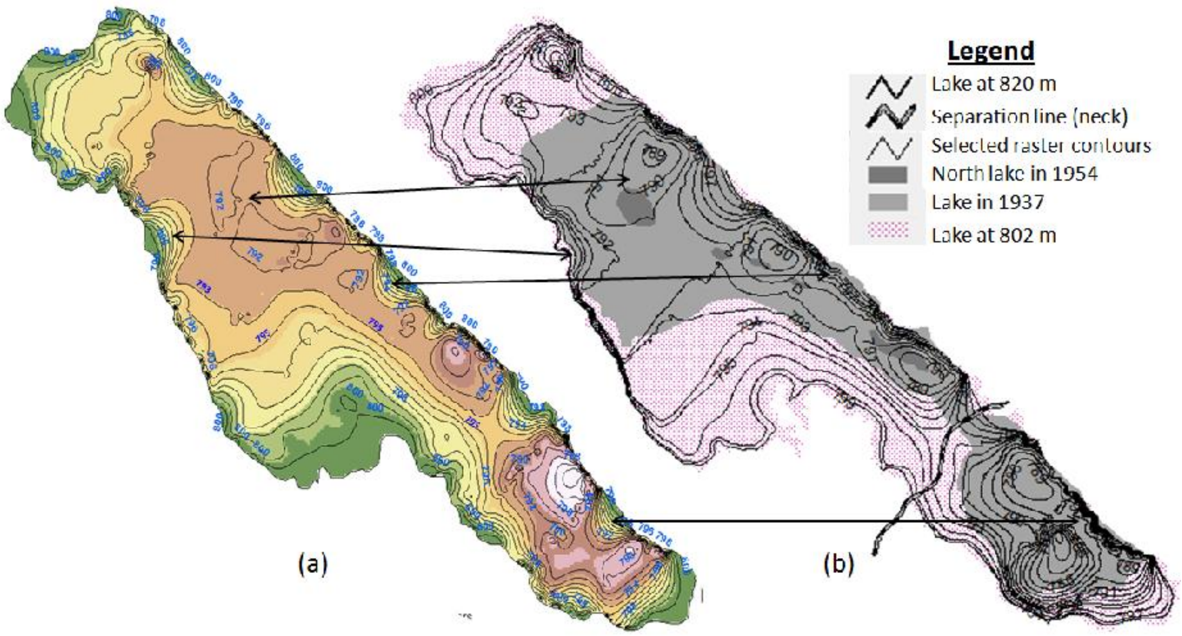

Figure 4: a) Original and b) refined lake bathymetry of Lake Rukwa.

An assessment further compared lake areas of digitised lake shapes and closest contours in which closeness was evaluated by the magnitude of standardised difference (*Di*) proposed by URT-MoW (2017), which provides finer classes of D_i than Ritcher *et al.*

(1998). The standardised difference was computed as the ratio of the surface area difference between model estimated and digitised surface area of the lake to digitised lake surface area. It is considered small when its absolute value is below 10%, moderate between 10% and 20%, slightly large between 20% and 30% and large above 30%. Raster generating method resulting into contours approaching digitised lake shapes and producing the least difference between areas was retained for extraction of lake surface areas and volumes using a Surface Volume of the Functional Surface (3D Analyst Tools) in ArcGIS. Extraction of surface areas and volumes of lake basins (north, south) before joining into a single lake involved defining a ridge altitude from the contours of the selected raster, clipping the raster to represent south and north basins and extraction of their respective surface areas and volumes.

Lake characteristic equations

Change-point analysis using Pettitt test, Lee and Heighinian test and Hubert autosegmentation procedure included in the Khronostat Software (IRD-HSM, 2002) was carried on extracted elevation-area and elevation-volume data pairs for lake basins and entire lake to identify change points and segmentation of the data sets. Shifted power model was fitted to each segment to obtain the best fit mathematical models. The shifted power model used is shown by equation (2).

$$y = k(h - h_o)^x \quad \text{.......................... (2)}$$

where *y* is dependent variable (lake surface area, volume), *h* is independent variable (lake water surface altitude), h_o is the no water altitude for a given lake segment, *k* is the obtained from the intercept on the log *y*-axis and *x* is the slope of the logy log(h-h_o) plot. CurveExpert Professional software (Hyams, 2011) was used to obtain values of parameters *k*, h_o and *x* of the best fitting curve to data. Model fitting efficiency was assessed by maximising the Nash-Sutcliffe coefficient of efficiency (NSE) comparing observed and estimated lake areas or volumes.

RESULTS AND DISCUSSION

Improved Lake Bathymetry and its Features

Adequacy of the bathymetry

Contours generated from a refined raster bathymetry of Lake Rukwa (Figure 4b) shows an improvement in the way bathymetry is presented for the lake compared to lake shapes from contours generated using an old bathymetry (Figure 4a). Assessment of the lake shapes depiction by raster generated contours considered improvements in capturing main features of Lake Rukwa including the north lake pools, straight lake shore along the Konongo Scarp, dividing ridge between north and south lake basins and westward linear expansion of the lake on its northwest side. The refined bathymetry largely reduced curves in the northwest and southeast parts of the lake as well as straightening lake shores along the Konongo Scarp as in old maps (Gunn, 1956). Generated contours representing lake surface extents at different altitudes largely reproduced the 802 m shoreline of Lake Rukwa (Figure 4b).

The new bathymetry captures lake altitudes below 792 m in the north and 790 m in the south (Figure 4b), which were not captured by the original bathymetry (Figure 4a). The north lake is portrayed as disconnected lake by the 792 m altitude of the old bathymetry while connected in the refined bathymetry. Despite capturing locations of the 1954 pools as reported in Gunn (1956), refined bathymetry could not capture their sizes particularly of three small central pools (Figure 4b) giving larger pools than recorded fact reflected in a slightly large difference between digitised and raster generated lake sizes (Table 1). This calls for improvement of bathymetric data along the NW-SE direction within the pool area. Comparison of the contours and digitised lake surface further indicates 792 m, 792.7 m and 793.2 m contours to approximately represent the 1950, 1947 and 1933 extents of Lake

Rukwa while the 1954 pools correspond to a altitude contour of 788.5 m.

Contours indicates Lake Rukwa is separated into north and south basins at 794.3 m, above which a single lake prevails and the altitude was considered to represent altitude of the separation ridge between the lake basins. The ridge was then adjusted to follow the dry crest between north and south lake basins defined by the passing route up to old right bank of River Momba on the old maps reported in Gunn (1956). The separation ridge was thereafter used to partition the bathymetry raster of Lake Rukwa into north and south lakes from which shapes, surface areas and volumes of the two lake basins were extracted.

Raster generated lake surface areas for altitudes 792 m, 792.7 m, 793.2 m and 802 m defining historical lake extents and 820 m land contour remarkably matched digitised historical lake sizes (Table 1). Better matching raster generated lake surface areas at altitudes above the 1954 pool level suggests refined lake bathymetry is capable of depicting lake characteristics above such an altitude (788.5 m) and below which bathymetry needs more refinements.

Lake characteristic sizes

Resulting lake surface contours developed from topography raster indicate that Lake Rukwa is about 184 km long and 17-51.2 km wide at its historical highest elevation (Surface water altitude: 804.7 m) having a surface area of 5,611.75 km^2 and average depth of 10.37 m (max depth: 22.49 m, south basin). The lake is currently at 800.8 m, 16-49 km wide extending 177 km with a total surface area of 4,993.92 km^2 and an average depth of 7.48 m (max interpolated depth: 18.6 m, south basin). Length of Lake Rukwa reported in literature (Lakepedia, 2016) lies within the measured and raster generated lake extent. However, lake depths and surface areas have been largely underestimated. The average lake depth has been reported at 3-5 m while the maximum depth in the south basin reported at 15 m (World Lakes, 2016). The reported average depth range is almost half that derived from bathymetric measurements and analyses in this study while the maximum depth of the north basin is given for the first time.

Of the two lake basins, the north basin is the largest being 127 km long and 23-51 km wide at 804.7 m altitude having a surface area of 4,406.85 km^2 and average depth of 10.04 m (max interpolated depth: 17.7 m). The south basin is small, 17-31 km wide extending 57 km at 804.7 m altitude with a surface area of 1,205 km^2 and average depth of 11.6 m (max interpolated depth: 22.49 m). At the current surface altitude of 800.8 m, north and south basins are 3,925 and 1,082 km^2 large respectively with average depths of 7.15 m (north) and 8.9 m (south) and maximum depths of 13.8 m (north) and 18.6 m (south). The 800 m altitude contour gives total area of Lake Rukwa of 4,846.4 km^2, which is reported as 2,600 km^2 (Britannica, 2016), 5,760 km^2 in February 2007 (Wikipedia, 2016), 1,966 km^2 (Lakepedia, 2016) and closely estimated from the graphical relationship as 5,200 km^2 (MoW-URT, 2014). The area given by Wikipedia corresponds to an estimated lake surface altitude of 805.7 m, which is outside the February 2007 observed altitude range of 800-801 m (LEGOS/GEOS, 2016) and estimated as 801.0 m (Valimba, 2015).

Table 1: Comparison of measured and estimated lake surface areas.

Lake	**Year**		**1933**	**1937**	**1950**	**1954**	
	Alt (m)	**802**	**792.7**	**793.2**	**792**	**788.5**	**820**
North	Digitised	4,131.6	1,860.8	1,985.9	-	41.1	5,763.6
	Contour	4,081.6	1,782.2	2,082.6	1,305.9	53.4	5,597.0
	Equation	4,079.6	1,793.0	2,095.0	1,249.9	52.6	5,700.3
	D_i	***-1.3%***	***-3.6%***	***5.5%***		***28.1%***	***-1.1%***
South	Digitised	1,128.2	625.8	715.0	576.9	-	1,599.6
	Contour	1,114.6	660.2	718.2	588.4	288.4	1,566.9
	Equation	1,120.6	680.3	716.7	591.0	234.5	1,563.4
	D_i	***-0.7%***	***8.7%***	***0.3%***			***-2.3%***
Entire lake	Digitised	5,259.8	2,486.6	2,700.8	-		7,363.2
	Contour	5,196.2	2,442.4	2,800.8	1,894.2	341.8	7,164.0
	Equation	5,204.3	-	2,811.7	-	-	7,248.2
	D_i	***-1.1%***		***4.1%***			***-1.6%***

Lake Characteristic Equations

Single lake

According to bathymetric analysis, a single Lake Rukwa exists above an altitude of 794.3 m and lake water surface areas and volumes were extracted for elevations above this altitude (Figure 5). Change-point analyses were carried out on these data and by data fitting revealed single relationships between elevation (*h*) and area (*A*) or volume (*V*) depicted to be

$$A = 2407.94(h - 791.6)^{0.32937} \quad \text{........ (3a)}$$

$$V = 1.537436(h - 790.5)^{1.369103} \quad \text{........ (3b)}$$

The fitted models reproduced well lake surface areas and volumes (Figure 5) giving fitting efficiencies (NSE) of 99.9% for both lake surface area and lake volumes and are considered adequate. At an altitude of 794.3 m and below, Lake Rukwa exists as two separate lakes, the north and south lake basins with the former being the largest.

North lake basin

Lake water surface areas and volumes were extracted from north lake basin raster at an interval of 0.1 m from 787 m to 794.3 m altitudes. Changing shapes from concave (787-792 m) to convex (between 792 and 794 m) of the elevation-area plot indicates double curvature suggesting two different relationships (Figure 6). Change-point analysis confirmed the existence of two segments in the elevation-area relationship with a change in the relationship occurring at 792.0 m altitude. Despite visual analysis of elevation-volume plot indicating rather a single curve, change point analysis segmented elevation-volume relationship into two segments with a change at 792.0 m altitude. This is the altitude representing a single north lake basin below which north lake exists into constituent pools. The best fitted power models with NSE exceeding 95% representing the segmented relations as shown by equations 4(a) and 4(b).

$$A = 18.0937717(h - 787.0)^{2.6315008} \quad (4a)$$
$$= 1912.332852(h - 791.9)^{0.3273438}$$
$$V = 0.002743216(h - 786.7)^{3.879379} \quad (4b)$$
$$V = 0.037598033(h - 788.2)^{2.8454124}$$

Alt	Area (m²)		Volume (m³)	
	Measured	Fitted	Measured	Fitted
820.0	7,163.963	7,248.200	158.238	158.396
815.0	6,849.038	6,799.999	123.054	122.869
810.0	6,320.264	6,281.909	90.045	89.931
806.0	5,809.284	5,794.119	65.753	65.712
805.5	5,741.677	5,726.978	62.866	62.833
805.0	5,672.815	5,658.196	60.012	59.989
804.5	5,603.892	5,587.667	57.193	57.180
804.0	5,535.577	5,515.277	54.407	54.409
803.5	5,456.998	5,440.900	51.660	51.675
803.0	5,372.905	5,364.393	48.952	48.980
802.5	5,289.031	5,285.597	46.285	46.324
802.0	5,196.228	5,204.334	43.664	43.708
801.5	5,103.135	5,120.401	41.087	41.134
801.0	5,016.231	5,033.570	38.557	38.603
800.5	4,930.059	4,943.577	36.073	36.116
800.0	4,840.440	4,850.119	33.630	33.674
799.5	4,742.748	4,752.843	31.234	31.279
799.0	4,643.579	4,651.335	28.889	28.932
798.5	4,540.196	4,545.104	26.593	26.636
798.0	4,428.397	4,433.562	24.351	24.392
797.5	4,304.138	4,315.993	22.169	22.202
797.0	4,174.117	4,191.514	20.049	20.069
796.5	4,044.227	4,059.016	17.996	17.995
796.0	3,895.478	3,917.073	16.011	15.984
795.5	3,757.624	3,763.805	14.099	14.039
795.0	3,611.870	3,596.653	12.257	12.165
794.5	3,448.767	3,411.982	10.491	10.365
794.0	3,240.538	3,204.354	8.817	8.646

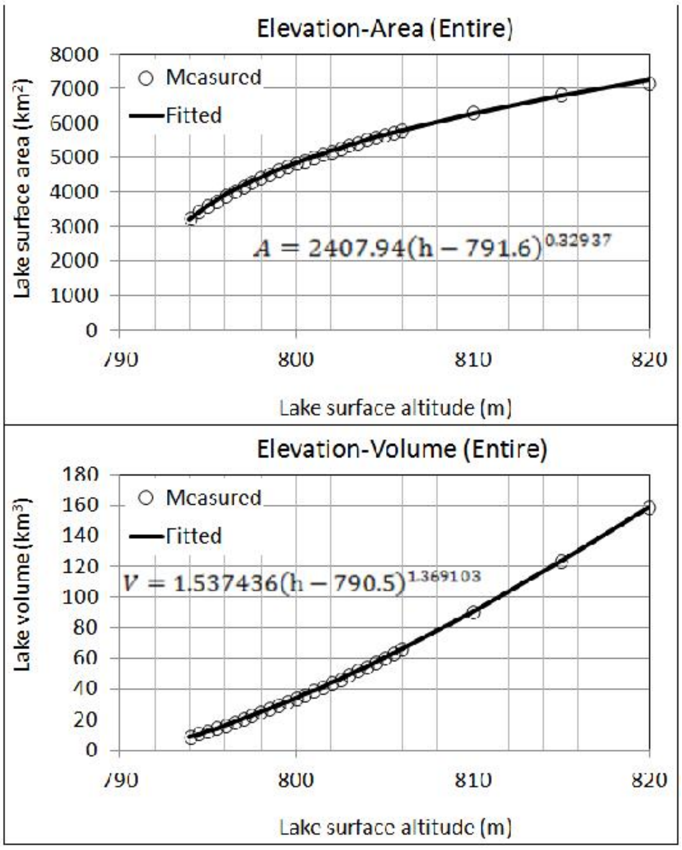

Figure 5: Elevation-area-volume data and equations for Lake Rukwa above 794.3 m.

South lake basin

Lake water surface areas and volumes were extracted from south lake basin raster at an interval of 0.1 m from 782.0 m to 794.3 m altitudes. Elevation-area plot indicates double curvature suggesting existence of two or more relationships (Figure 7). Change-point analysis identified four segments in the elevation-area relationship with changes in the relationship at 785.5 m, 787.0 m and 789.5 m altitudes. Despite visual analysis of elevation-volume plot indicating rather a single curve, change point analysis identified two segments in the elevation-volume relationship with a change occurring at 789.3 m altitude.

The south lake basin exists as an oval single lake up to 785.1 m altitude when this single central lake pool changes its shape to a bowl like with a large increase at its southern part. This single pool exists up to an altitude of 787.0 m above which a north pool forms within the south lake basin and the two north and central pools combine at 788.9 m to form a larger pool of the south lake. At 788.7 m, the third south pool starts forming and combines with the rest at 789.3 m to form a single south lake basin. Therefore, the three change points define the three critical stages of formation of a single south basin of Lake Rukwa. The best fitted power models with NSE exceeding 96% representing the segmented relations as shown by equations 5(a) and 5(b).

$$A = 4.45986304(h - 782.2)^{2.03351915} \quad h \leq 785.1\,m \tag{5a}$$
$$= 19.545048(h - 783.3)^{1.2083659} \quad 785.1\,m < h \leq 787.0\,m$$
$$= 0.24381281(h - 781.6)^{3.52270204} \quad 787.1\,m < h \leq 789.3\,m$$
$$= 8.324284656(h - 781.4)^{1.80129237} \quad h > 789.3\,m$$
$$V = 0.000244721(h - 781.2)^{3.71515183} \; h \leq 789.3\,m \tag{5b}$$
$$V = 0.029526229(h - 785.2)^{2.16089088} \; h > 789.3\,m$$

Comparison of old and refined characteristic equations for lake surface areas and volumes

Comparison of lake surface areas and volumes estimated using old equation (LRBWB-MoW, 2014) (see equation 1) and refined characteristics equations (see equations 3 to 5) indicates large differences of lake areas and volumes below a ridge altitude (794.3 m) (Table 2). Old equations give a lake volume of 0.004 km^3 (4 Mm^3) while it is over 40 times as estimated by refined equations (163 Mm^3). The percent difference of estimated stored volumes between the old and refined equations decreases with increasing lake surface altitude to below 2% at the historical highest lake surface altitude of 804.69 m (volume is 58.2 km^3) in early 1990s. This decreasing difference persists up to an altitude of 805.7 m above which underestimation re-appear. Despite being developed using data up to an altitude of 803.8 m, the old elevation-volume equation can estimate lake stored volume between 801 m and 812 m to within 10% of error making them equally useful. Between high stand of the early 1990s and current stand (~ 800 m, volume is 33.7 km^3), Lake Rukwa has lost about 24.5 km^3 of water.

Old characteristic equations largely underestimate lake surface areas below the 792 m altitude and generally underestimation reduces with increasing altitude of the lake surface (Table 2) up to an altitude of 796.8 m where the difference becomes zero. Thereafter, old equations start overestimating lake surface area to an altitude of 804.85 m above which underestimations restart. However, the under/over estimation of the lake surface area by the old equation is within 11% for altitudes between 794.3 m and 810 m indicating their usefulness when Lake Rukwa exists as a single lake.

Alt	Area (m^2)		Volume (m^3)	
	Measured	Fitted	Measured	Fitted
793.5	2,228.853	2,240.096	4.413	4.473
793.0	1,961.997	1,985.399	3.362	3.344
792.5	1,663.587	1,636.504	2.457	2.452
792.0	1,305.881	1,249.883	1.715	1.731
791.5	955.790	947.236	1.151	1.167
791.0	667.676	694.785	0.751	0.759
790.5	477.827	488.928	0.467	0.467
790.0	323.938	325.892	0.270	0.269
789.5	201.677	201.701	0.140	0.141
789.0	112.153	112.122	0.064	0.065
788.5	53.429	52.591	0.025	0.025
788.0	21.014	18.094	0.008	0.007
787.5	7.456	2.920	0.001	0.001
787.0	-	-	0.000	0.000

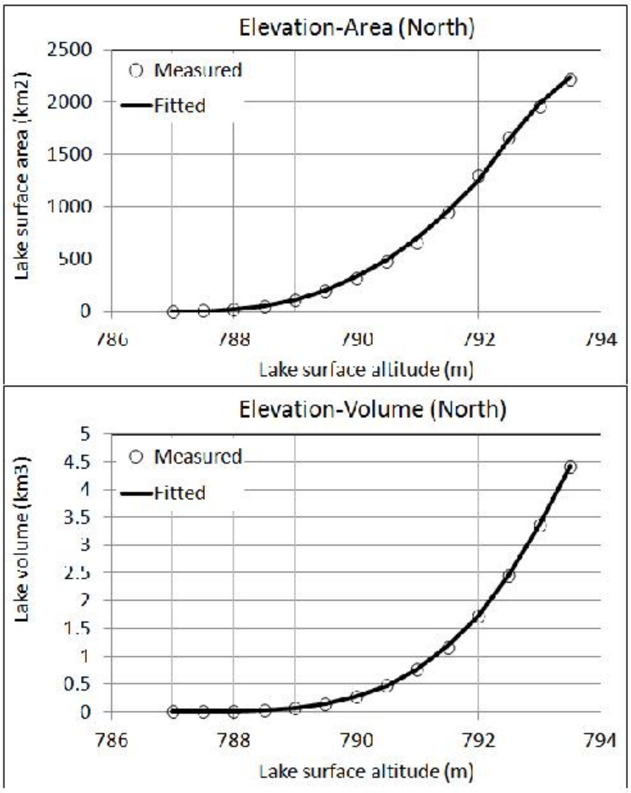

Figure 6: Elevation-area-volume data and equations for north basin of Lake Rukwa.

Alt	Area (m^2)		Volume (m^3)	
	Measured	Fitted	Measured	Fitted
793.5	743.475	746.171	2.850	2.848
793.0	696.270	691.696	2.489	2.490
792.5	639.389	639.065	2.156	2.157
792.0	588.351	588.295	1.849	1.850
791.5	536.081	539.403	1.569	1.568
791.0	491.750	492.407	1.312	1.311
790.5	449.379	447.326	1.077	1.078
790.0	404.043	404.181	0.863	0.870
789.5	354.239	355.403	0.673	0.685
789.0	288.404	282.358	0.512	0.524
788.5	213.840	220.747	0.388	0.386
788.0	169.851	169.416	0.293	0.295
787.5	129.597	127.254	0.218	0.222
787.0	94.445	94.445	0.163	0.163
786.5	79.178	79.178	0.119	0.116
786.0	64.405	64.405	0.083	0.080
785.5	50.151	50.551	0.055	0.053
785.0	36.640	36.193	0.033	0.033
784.5	24.618	24.261	0.018	0.020
784.0	14.764	14.737	0.008	0.011
783.5	7.271	7.604	0.003	0.005
783.0	2.256	2.833	0.001	0.002
782.5	0.461	0.386	0.000	0.001
782.4	0.292	0.169	0.000	0.000
782.3	0.166	0.041	0.000	0.000
782.2	0.075	0.000	0.000	0.000
782.1	0.000	0.000	0.000	0.000

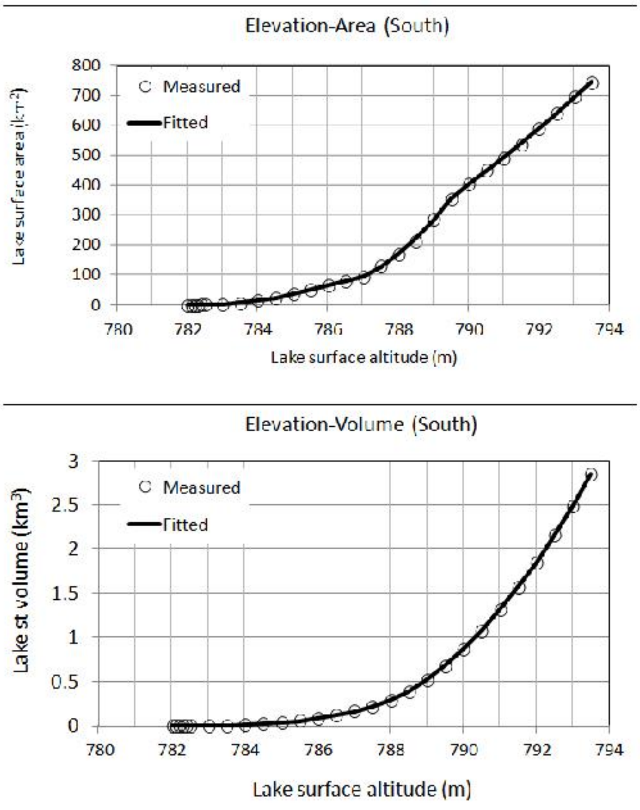

Figure 7: Elevation-area-volume data and equations for south basin of Lake Rukwa.

Table 2: Differences between lake surface areas and volumes for various historical extents.

	Volume (km^3)			Area (km^2)		
Alt (m)	**Refined**	**Old**	**Difference (%)**	**Refined**	**Old**	**Difference (%)**
787	0.163	0.004	4316.3	94.44	10.8	774.1
792	3.569	1.051	239.4	1,838.18	971.9	89.1
794.3	10.055	5.896	70.5	3,391.50	2,931.0	15.7
795	12.165	8.140	49.4	3,596.65	3,311.3	8.6
796	15.984	11.739	36.2	3,917.07	3,791.6	3.3
796.3	17.183	12.9005	33.2	4,003.47	3,924.7	2.0
796.8	19.232	14.9165	28.9	4,139.55	4,137.5	0.0
797	20.069	15.750	27.4	4,191.51	4,219.8	-0.7
798	24.392	20.135	21.1	4,433.56	4,610.1	-3.8
799	28.932	24.865	16.4	4,651.33	4,971.1	-6.4
800	33.674	29.916	12.6	4,850.12	5,308.7	-8.6
800.8	37.603	34.174	10.0	4,997.97	5,564.7	-10.2
801	38.603	35.2677	9.5	5,033.57	5636.8	-10.7
802	43.708	40.9052	6.9	5,204.33	5636.9	-7.7
803	48.980	46.8141	4.6	5,364.39	5637.1	-4.8
804.69	58.243	57.384	1.5	5,614.68	5,637.3	-0.4
804.85	59.142	58.4218	1.2	5,637.23	5637.3	0.0
805	59.989	59.3999	1.0	5,658.20	5637.3	0.4
807	71.573	72.9449	-1.9	5,923.84	5637.6	5.1
808	77.566	80.0566	-3.1	6,048.03	5637.7	7.3

CONCLUSIONS

Contours generated from a refined bathymetry of Lake Rukwa constructed from a combination of sounded bathymetric points, spot heights in topographical maps, digitised lake shorelines from old maps and digitised land contour indicated Lake Rukwa to comprise two north and south lake basins, which are separated by a ridge lying at an altitude of 794.3 m. The north and south lakes consist respectively of five (5) and three (3) deeper depressions (pools) paralleling the northwest-southeast Konongo Scarp with deepest sounded points at 784.36 and 778.37 m for north and south lakes respectively. These pools are disconnected below altitudes 792 m (north) and 789.4 m (south).

Characteristic elevation-area and elevation-volume equations are segmented for lake below ridge altitude whereas single relationships prevail for a single lake. Comparison of lake volumes estimated by refined and old equations indicated underestimation of lake stored volumes between 782.2 m and 805.65 m altitudes and overestimation thereafter by the old equations although the under/over-estimation remained within 10% between 801 m and 812 m. Old elevation-area equations underestimate lake surface area up to 796.8 m, thereafter overestimates the lake area up to an altitude of 804.85 m and above this altitude underestimation re-appears. The old equations under/over-estimation, but remains within 11% for altitudes between 794.3 m and 810 m.

The refined equations indicate surface areas of north and south lakes at ridge altitude to be

2,554.4 km^2 and 837.1 km^2, respectively forming a 3,391.5 km^2 lake. At its highest recorded historical elevation of 804.69 m, Lake Rukwa is 183 km long and 17-51 km wide occupying an area of 5,614.7 km^2 (north: 4,409.8 km^2; south: 1,204.9 km^2) and containing 58.243 km^3 of water (north: 44.318 km^3; south: 13.925 km^3). At its recent March 2014 water surface altitude (~ 800.8 m), the lake was 177 km long and 16-49 km wide with a surface area of 4,997.7 km^2 (north: 3,918.3 km^2; south: 1,079.4 km^2) containing 37.603 km^3 of water (north: 28.055 km^3; south: 9.548 km^3). Whilst elevation-area and elevation-volume equations for the lake have been improved in this study, these characteristic equations for separated north and south lake basins are given for the first time. Although few additional bathymetric points are recommended for collection at strategic unsurveyed locations including pools in north lake basin for improving further the lake bathymetry, the developed characteristic equations can be used for water management studies of Lake Rukwa.

ACKNOWLEDGEMENTS

iWASH programme is highly acknowledged for funding the bathymetry survey of Lake Rukwa and Lake Rukwa Basin Water Board (LRBWB) for availing bathymetry data for this study.

REFERENCES

Baker N.E. and Baker E.M. (2002). Important bird areas in Tanzania. Wildlife Conservation Society of Tanzania. Dar es Salaam, Tanzania.

Britannica (2016). Lake Rukwa, Tanzania. Available online at www.britannica.com/place/Lake-Rukwa. Accessed on 24th February 2016.

Gunn D.L. (1956). History of Lake Rukwa and the Red Locust, Tanganyika Notes and Records, 42(1): 1 – 18.

Hyams D.G. (2011). CurveExpert Professional documentation. Release 1.5.0, 162p.

IRD-HSM (2013). Khronostat, logiciel statistique de series chronologiques. Copyright Orstom 1998-IRD 2002, Montpellier, France, 2002.

Lakepedia (2016). Lake Rukwa, Tanzania. Available online at www.lakepedia.com/lake/rukwa. Accessed on 24th February 2016.

LEGOS/GEOS (2015). Surface monitoring by satellite altimetry: Lake Rukwa. Available online at www.legos.obs-mip.fr/soa/hydrologie/hydroweb/StationsVirtuelles/SV_Lakes/Rukwa.html. Accessed on 15th January 2016.

LRBWB-MoW (2014). Lake Rukwa bathymetry report, Lake Rukwa Basin Water Board, Ministry of Water and Irrigation, Dar es Salaam, Tanzania, 54p.

Nicholson S.E. (1999). Historical and modern fluctuations of Lakes Tanganyika and Rukwa, Climatic Change, 41: 53 – 71.

Ritcher B.D., Baumgartner J.V., Braun D.P. and Powell J. (1998). A spatial assessment of hydrological alteration within a river network, Regul. Rivers: Res. Mgmt, 14: 329-340.

URT-MoW (2017). Environmental Water Requirements Assessment Guidelines for Tanzania, Final Draft. Ministry of Water and Irrigation, 144p.

Valimba P. (2015). Water balance study of Lake Rukwa. United Republic of Tanzania/Ministry of Water/Lake Rukwa Basin Water Board, 166p.

Wikipedia (2016). Lake Rukwa. Available online at https//en.m.wikipedia.org/wiki/Lake_Rukwa . Accessed on 24th February 2016.

World Lakes (2016). Lake profile Rukwa. Available online at www.worldlakes.org/lakedetails.asp?lakeid=8579. Accessed on 24th February 2016.