KALEYA RIVER CATCHMENT REGIONAL ESTIMATION OF RESERVOIR CAPACITIES USING SONAR AND GIS APPROACHES

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ABSTRACT

Small reservoirs in arid and semi-arid areas help rural communities cope with prolonged dry spells and hence, the need for their continuous monitoring and assessments. However, it is challenging to survey many reservoirs using the traditional sounding methods. In this regard, bathymetric information could be used as a tool to monitor the available surface water to provide data for water allocation decisions and sustainable management of reservoirs. Despite the availability of new remote sensing-based methods for bathymetric surveys, their utilization in Africa in general and, Zambia in particular, remained low by the time this study was conducted. This paper presents modern bathymetric survey and analysis techniques applied for quantifying the capacities of small reservoirs, using the case of the Kaleya River Basin in southern Zambia. The objectives of the survey were to: i) create a database of reservoir storage capacities; and ii) introduce an efficient modern approach of monitoring small reservoir storage capacities. A remote-controlled Coden hydrographic survey boat equipped with a SONAR device mounted with Trimble OmniSTAR VBS providing DGPS was used to capture and record hydrographic data with a millimeter accuracy. Data was analyzed using Surfer 13 Golden software to produce contoured bathymetric maps of surveyed reservoirs. From this information, the reservoir capacities were computed, thus providing information on water stored in reservoirs in the basin. A regional model was also developed for faster and simpler estimation of reservoir capacities from their surface areas. The study concluded that the quantification of storage capacity of small reservoirs using SONAR and GIS provides a quicker and cost-effective way of obtaining accurate bathymetric data. Such data is important in guiding water allocation decisions at farm level and water permit allocation decisions at a catchment scale.

Keywords: *Bathymetric Survey; GIS; Small Reservoirs; SONAR; Storage Capacity*

INTRODUCTION

Small reservoirs play an important role in supporting food security and improving livelihoods of many communities in semi – arid parts of Africa. However, these reservoirs are threatened by loss of capacities due to sedimentation. Despite reservoirs being constructed by different stakeholders, most of them have one thing in common – lack of baseline bathymetric data. This is partly due to operational challenges associated with traditional methods of bathymetric surveys and analysis in that they are laborious, expensive and time consuming (Ran and Lu, 2011). Additionally, reliable databases of small reservoirs including their storage volumes are often lacking in most African developing countries due to lack of inventorying and coordination during reservoir planning and construction (Liebe *et al*., 2007). The lack of bathymetric data thus constrains effective monitoring, management and utilization of small reservoirs in the developing world (Liebe *et al*., 2005).

To address the operational challenges posed by the traditional methods of bathymetric survey, methods have been developed that use Sound Navigation and Ranging (SONAR) and Geographical Information Systems (GIS) techniques. These methods involve the use of echo sounders or SONAR for depth measurements, while Time Kinematic Global Positioning System (RTK-GPS) (Ceylan and Ekizoglu, 2014) or Differential Global Positioning System (DGPS) (Lopes and Smith, 2007) are used for horizontal location measurements. The modern methods can be used even in difficult to reach sites in any hydrographic area (both shallow and very deep areas), provide real-time data collection, and can help save on time, labour and costs (Table 1).

Table 1. Traditional vs the Modern hydrographic survey method

No	Attribute	Traditional methods	Modern methods
1	Equipment	*Multi-frequency single beam echo-sounder, digital printer data (tabular), time tagging machine, mini rangers, theodolites, power batteries, wireless radio, control station (Burgee), Motorised boat	*Multi-frequency single beam echo-sounder, Differential GPS, Power source, Laptop, Motorised boat
2	Software	GIS / Surfer	GIS / Surfer
3	Survey crew	About 5 persons	1-3 persons
4	Data points	Hundreds	Thousands
5	Time	2 days per small reservoir (about 40 ha in size)	2 hours per small reservoirs (about 40 ha in size)
6	Post processing/ Calculations/Analysis	1 hour per small reservoir (about 40 ha in size)	1 hour per small reservoir (about 40 ha in size)
7	Preparation of maps and other products	1 hour	1 hour
8	Accuracy of products	Less accurate due to sparse distribution of XYZ used	More accurate due to dense distribution of XYZ data used
9	Product type	*Contour map of reservoir surface, Area-storage relationship, stage-storage relationship, reservoir capacity	*Reservoir's under water terrain, storage capacity, Area-storage relationship, stage-storage relationship, three dimensional reservoir surface*

Source: Authors field experience and *Munir *et al*. (2014).

While these new approaches have been applied widely in developed countries, and in a few other African countries like Ethiopia (Yesuf *et al*., 2012) and Burkina Faso (Schmengler and Vlek, 2015), their use in developing countries particularly in relation to depth measurements in small reservoirs is still very limited. Yet the need for water storage information is needed more than ever before due to climate change and siltation. As such continuous up to date bathymetric data is needed at farm level to guide farmers who use reservoirs for irrigation on what crops to grow given the available water in storage at various times of the year. Beyond the farm level, water storage in reservoirs is needed to guide future water allocation decisions so that catchments are not over abstracted. Against this background, this paper presents the application of SONAR and GIS techniques in generating storage capacities and characteristics of small reservoirs using the case of Kaleya River Basin in southern Zambia.

The goal is to adapt a methodology for cost-effective collection and analysis of bathymetry data for small reservoirs in Zambia. The study has benefited from the work of several scholars (Liebe et al., 2005; Brown *et al*., 2011; Lopes and Smith, 2007; McPherson *et al*., 2009; Ceylan and Ekizoglu, 2014; Muchanga *et al.* 2019) localy and mainly from other parts of the world. Additionally, the paper presents baseline bathymetric data on small reservoirs in Kaleya River Basin where conflicts over water use have emerged due to reservoir management. Hence reservoir data is critical not only for assessing the availability of surface water in this basin, but also in decision making especially on water permits allocation and integrated catchment management. Specifically, the objectives were to create a database of reservoir storage capacities; and introduce an efficient modern approach of monitoring small reservoir storage capacities.

STUDY AREA

Kaleya River Basin lies between latitude 15°40’0’’ S to 16°20’0’’ S and longitude 27°30’0’’ E to 28°10’0’’ E. Originating from the Chikankata hills, the Kaleya River flows in the southwest direction and joins the Kafue River north of Mazabuka town (Chisola *et al.* 2020) (Figure 1). It has several tributaries and a total catchment area of 743.52 km^2. Irrigated agriculture is heavily practiced in the basin with sugar cane as the main crop. The catchment is home to Zambia’s largest sugar producer – the Zambia Sugar Company. Other major economic activities include livestock (cattle) rearing such that the Kaleya River has been extensively dammed to support irrigation and livestock development. This study surveyed ten (10) small reservoirs in the basin (Figure 1).

Following the emerging water use challenges in the basin, Sichingabula *et al*. (2012) conducted a preliminary water balance analysis, but results were inconclusive due to lack of data on volume of water stored in reservoirs for computation of available surface water. Due to the large number of reservoirs in the basin, available resources could not allow for the volumetric assessment of water available as reservoir storage. This was due to the challenges posed by traditional sounding methods that were at the disposal of the study team at that time.

MATERIALS AND METHODS

Equipment

The equipment used in this study included the Remote Controlled (RC) Coden hydrographic survey boat that has an in-built echo sounder and DGPS. The methodological description on how to use this equipment was informed by a detailed description provided by Muchanga (2020). Other materials used included Google Earth satellite imagery.

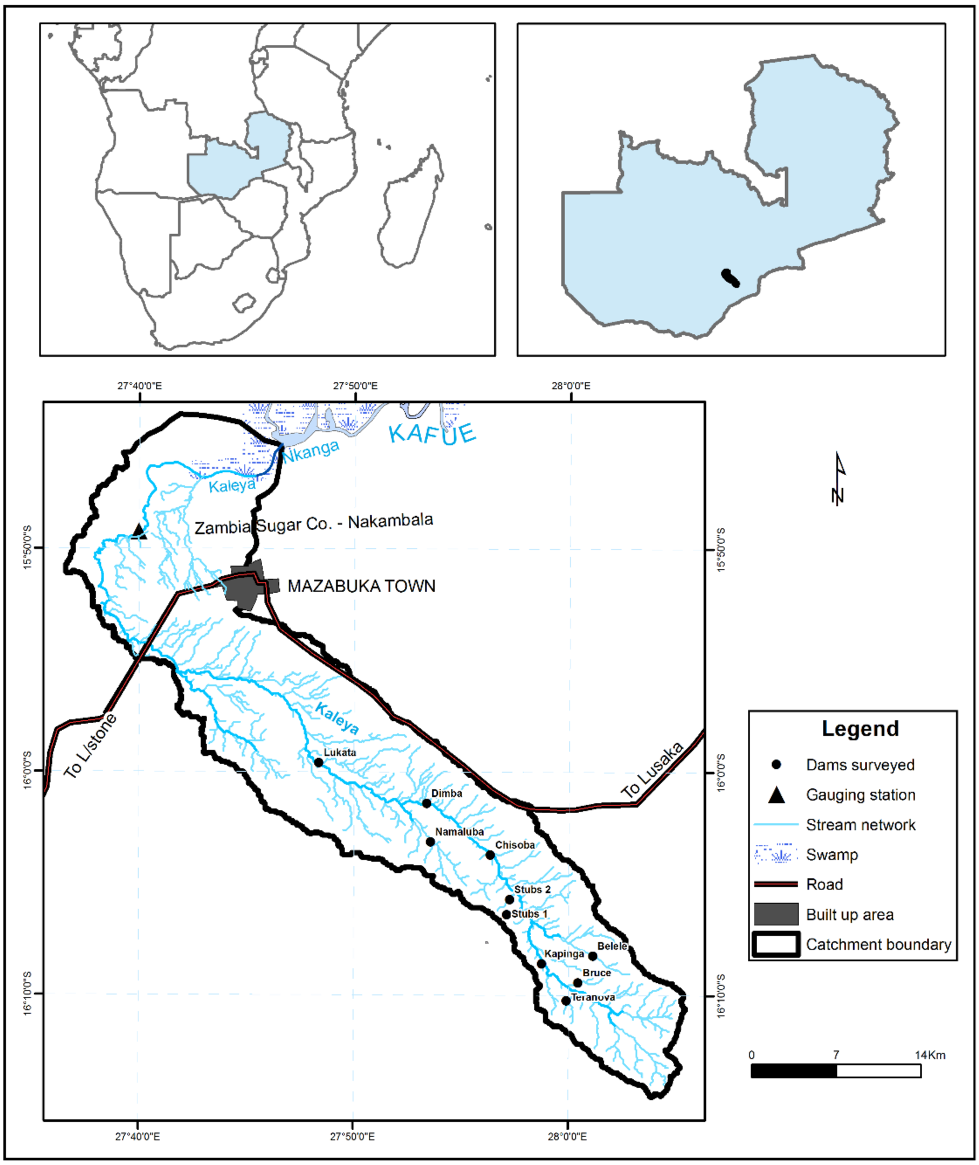

Figure 1. Kaleya River Basin, Zambia.

Data Collection

Inventory of small reservoirs

Due to lack of up-to-date database on small reservoirs, a reconnaissance survey was undertaken to map the spatial distribution of reservoirs. Given the small size of reservoirs, open-source Google Earth satellite imagery was used to identify the reservoirs because of its higher spatial resolution (15 m) compared to Landsat imagery (30 m). Ran and Lu (2011) also found Google earth imagery to perform better in identifying and delineating surface areas of small reservoirs especially the reservoir tails.

The limitation of using Google earth imagery in our study area was its low temporal resolution, hence it was difficult to identify reservoirs if the only available image was on a cloudy day. This challenge was overcome by asking community members to in identifying reservoirs that could have been missed from the satellite imagery. However, for future studies, we recommend the integration of Synthetic Aperture Radar (SAR) imagery due to their all-weather capability. Once reservoirs were identified on the image, field visits were conducted to physically map the location of each identified reservoir using a hand-held GPS. This helped to build a geodatabase of the reservoirs with a total of 208 reservoirs mapped in Southern Province of Zambia, 10 of which fall in the Kaleya River basin.

Collection of bathymetric data

Bathymetric data (location and water depth point data) were collected using the remote-controlled Coden hydrographic survey boat (Figure 2a). The hydrographic survey boat simultaneously measured and recorded the depth (Z data) and location (XY data) of each depth measurement. In this way, thousands of XYZ data for each reservoir were recorded and stored in a csv file called *Back data*.

(a) **(b)**

(c)

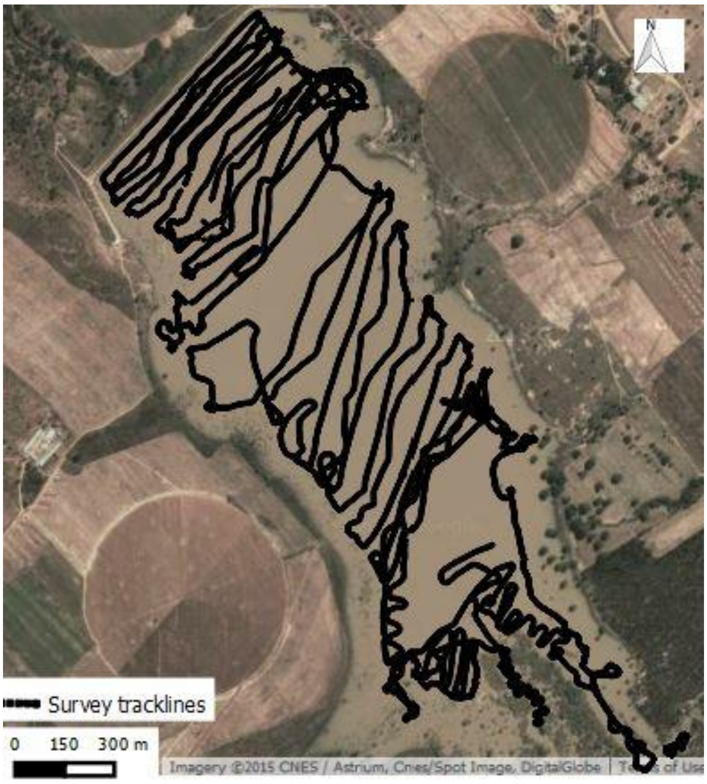

Figure 2. Coden Hydrographic boat (a) and motorized inflatable boat (b) used for dragging survey boat on reservoirs with weeds; and an overlay on Google image of survey path lines (c) showing the distribution of XYZ data points on Chisoba reservoir.

The hydrographic survey boat used in this study could be navigated around the reservoir using the remote control or could operate on its own by programming it with predetermined survey lines thus significantly reducing the size of the survey crew. However, its use for bathymetric mapping of small reservoirs is faced with a challenge in that most of the small reservoirs in our study area had weeds, rendering these functions ineffective as the boat would be entangled in weeds especially the propeller. Hence, the inflatable boat powered by an out-board engine (Figure 2b), was used for navigating on the reservoirs while dragging the hydrographic survey boat. To improve the accuracy of DGPS location measurements (XY data) for the soundings, a subscription to the Trimble OmniSTAR VBS service was made.

In this paper, we used Chisoba reservoir to illustrate the method that was used for all the surveyed small reservoirs. This reservoir was surveyed in April 2015 at the time when the dam spillway was over-spilling and the results obtained gave the total volume of the reservoir at full capacity (Liebe *et al*., 2005). A total of 25,523 xyz data points were recorded by the hydrographic boat and mapped (Figure 2c).

Data Analysis

Creating a blanking file

Where the banks of the reservoir were accessible, the reservoir boundary was obtained by walking around the reservoir with the hydrographic survey boat and the boat recorded zero depth values associated with the reservoir boundary. Google Earth images were used to obtain the shape and surface areas of bigger reservoirs with rough banks where it was not possible to walk around the reservoir to obtain the reservoir boundary. From this reservoir boundary data, a blanking file was created in Surfer 13 Golden software in order to confine the grid interpolation and volume calculation to within the reservoir boundary.

Selecting the interpolation technique

With the aid of the random expression in Microsoft Excel 2010, the dataset was randomly split into two, with each set containing about 50% of the observations (Yesuf *et al*., 2012). One dataset was used to interpolate a bathymetric map to the removed observation locations using different interpolation techniques (Topo to Raster, Kriging, Natural Neighbour and the Inverse Distance Weighted (IDW) all at 1×1 m cell size) in Surfer Golden software. The removed dataset was used as observed values to determine the error variance by cross validation (McPherson *et al.*, 2009; Dost and Mannaerts, 2008; Isaaks and Srivastava, 1989). Thus, the interpolation error was taken as the difference between the interpolated value and the observed value, explained by the coefficient of determination (r^2) (Table 2). Based on the cross-validation exercise, the interpolation method that gave the best coefficient of determination was selected for each reservoir. In case of Chisoba reservoir, Natural neighbour was chosen for final interpolation as it provided the lowest error variance.

Generating Bathymetric maps

For each reservoir, a grid was interpolated using the interpolation technique that gives the best coefficient of determination (r^2). The interpolated grid file was then blanked (clipped) using the blanking files to generate the blanked grid (Grid confined to the reservoir area only). Composite maps (contour maps) were drawn based on the blanked grid file. Contour lines were drawn at different intervals depending on the morphometric characteristics of respective reservoirs. Bathymetric maps showing the depth variations in each of the surveyed reservoirs were thus generated.

Table 2. Accuracy assessment of the grid interpolation methods for Chisoba reservoir

Method	r^2
Kriging	0.9931
Inverse distance to a power	0.9897
Minimum curvature	0.9926
Natural neighbor	0.9933
Nearest neighbor	0.9885
Triangulation with linear interpolation	0.9928

Volume computation

The blanked grid was used as input in the grid volume calculation menu of the Surfer software, to calculate the reservoir volume. The software then reported the area and volume of the reservoir at the specified water surface (contour) level. Apart from computing the volumes by the Cut and Fill calculations, the Surfer software also calculates volume by the extended trapezoidal formula, extended Simpson's rule, and extended Simpson's 3/8 rule (Surfer User Guide, 2017).

Generation of Reservoir Bathymetric data and Bathymetric maps

The bathymetric maps for Chisoba (Figures 3), Bruce and Lukata (Figures 4) reservoirs are illustrated. The volume of Chisoba reservoir at full capacity was 6.53 million cubic meters with a surface area of 187.56 hectares (Table 3). The maximum depths for all the ten surveyed reservoirs in the Kaleya River basin ranged from 2.15 m (Namaluba) to a depth of 14.24 m (Chisoba).

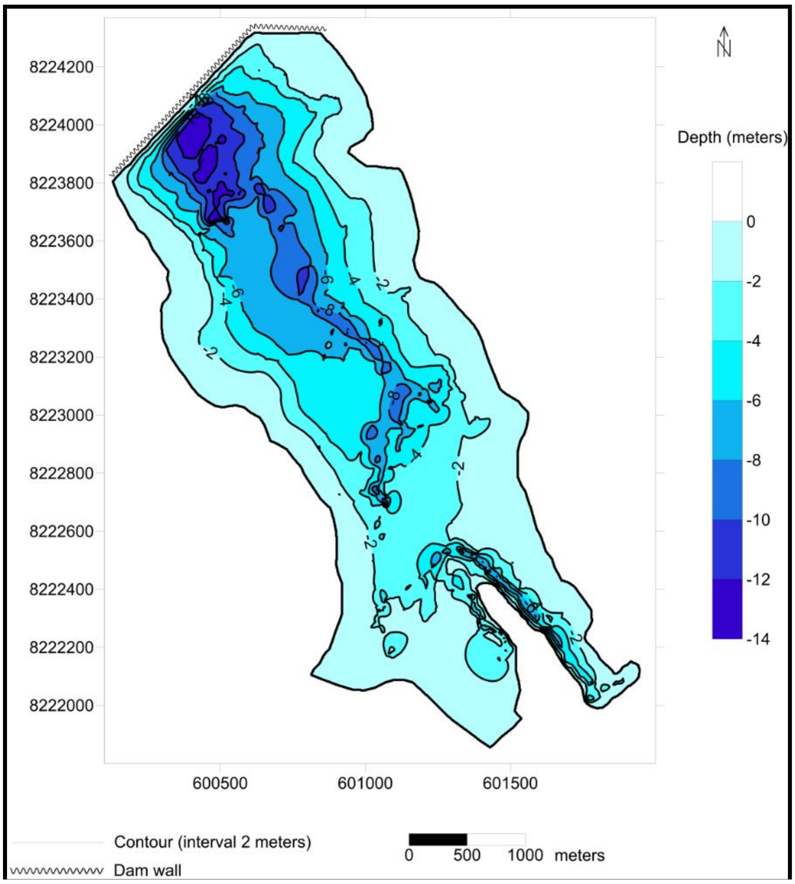

Figure 3. Bathymetric map of Chisoba reservoir.

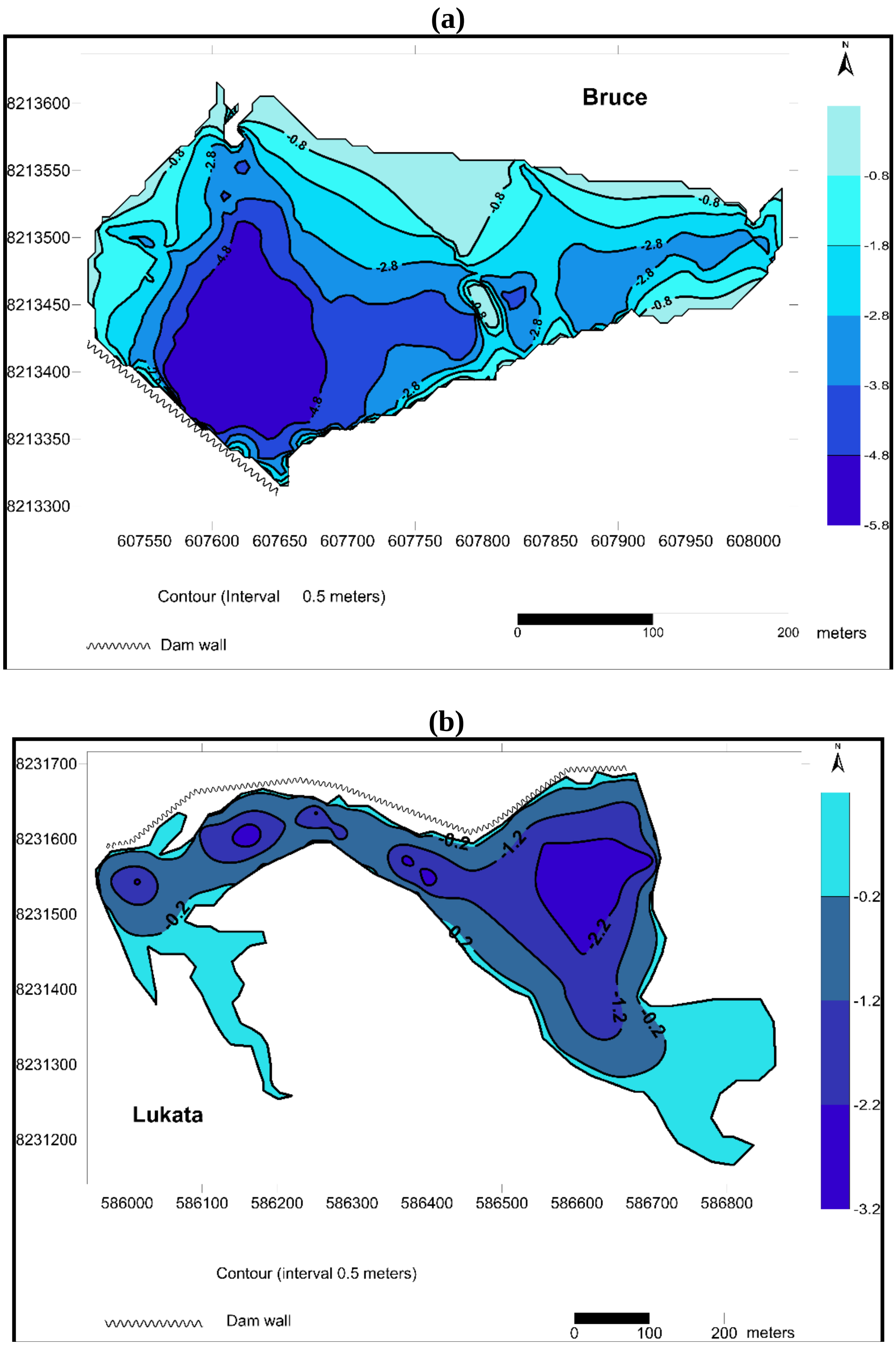

Figure 4. Bathymetry maps for (a) Bruce and (b) Lukata reservoirs.

The capacities, surface areas and other hydrographic data for all the 10 surveyed reservoirs in the Kaleya River Catchment are given Table 3.

Table 3. Hydro-Morphometric characteristics of the reservoirs in Kaleya River basin

No.	Reservoir Name	Date Surveyed	Reservoir Catchment area (km^2)	Water Surface elevation (m.a.s.l)	Maximum measured depth (m)	Mean depth (m)	Throw-back (m)	Crest length (m)	Reservoir surface area (ha)	Volume (MCM)
1	Belele	17/04/2015	6.81	1,248.0	6.15	2.45	594.17	446.66	13.20	0.3232
2	Bruce	12/08/2015	3.36	1,240.5	5.67	2.87	472.85	176.35	7.95	0.2278
3	Teranova	16/04/2015	3.47	1,250.8	11.18	3.72	420.34	377.87	15.25	0.5674
4	Kapinga	18/04/2015	0.55	1,216.8	6.65	3.66	917.10	733.8	48.56	1.1408
5	**Chisoba**	**21/04/2015**	**177.74**	**1,171.3**	**14.24**	**3.47**	**2,485.44**	**718.28**	**187.56**	**6.5126**
6	Stubs 1	23/04/2015	1.05	1,182.0	12.47	3.00	670.95	309.47	18.33	0.5512
7	Stubs 2	13/10/2015	1.77	1,198.0	2.40	1.65	681.06	321.69	11.35	0.4015
8	Namaluba	13/10/2015	14.48	1,148.0	2.15	1.55	457.00	231.13	5.10	0.0575
9	Dimba	12/10/2015	215.31	1,140.0	2.58	1.54	327.30	26.30	0.67	0.0082
10	Lukata	12/10/2015	319.39	1,084.0	3.09	1.36	606.36	749.83	29.96	0.4073
	Total								**337.93**	**10.2189**

MCM: Million Cubic Meter; m.a.s.l – meters above sea level

Hydro-Morphometric parameters

Reservoir storage characteristics

Reservoir areas and capacity curves are useful in assessing the spatial and temporal variations in reservoir storage characteristics. To develop the area-capacity curves, we first computed the surface area and the corresponding volume of the reservoir at each depth using the blanked interpolated surface (grid) with the aid of a script called *contaarea.bas* developed by Golden Surfer. A power relationship between the reservoir surface area and the corresponding volume was then derived and the results compiled in Table 4. The coefficients of determination (r^2) are all above 0.96 indicating a strong relationship between reservoir volume and area for each reservoir. The derived equations are valid for 0 ≤ surface area ≤ surface area at full capacity (m^2) all significant at $p = 0.001$.

From the equations in Table 4, the reservoir surface area is the only parameter needed to estimate the volume of the reservoir. The water surface area could be obtained by walking around the reservoir with a hand-held GPS where possible or from remote sensing imagery (Rodrigues and Liebe, 2013). Similar relationships involving depth versus volume were also developed (not presented here) for each reservoir and showed strong relationships between the two variables. This means, by installing gauge plates in the reservoirs, dam owners could easily monitor the changes in volumes of their reservoirs and thus better allocate water to competing demands.

Table 4. Area – Volume relationships for Kaleya River basin reservoirs.

Reservoir	Equation	r^2	n	p value	SE
Belele	$Volume = 0.0020 \times Area^{1.5927}$	0.9965	13	0.001	0.0652
Bruce	$Volume = 0.00004 \times Area^{1.9937}$	0.9914	12	0.001	0.0619
Terranova	$Volume = 0.0021 \times Area^{1.6265}$	0.9985	20	0.001	0.0377
Kapinga	$Volume = 0.0006 \times Area^{1.6358}$	0.9969	13	0.001	0.0402
Chisoba	$Volume = 0.0789 \times Area^{1.2656}$	0.9971	22	0.001	0.0328
Stubs 1	$Volume = 0.0041 \times Area^{1.5492}$	0.9983	14	0.001	0.0209
Stubs 2	$Volume = 0.0004 \times Area^{1.7869}$	0.9949	23	0.001	0.0753
Namaluba	$Volume = 0.0018 \times Area^{1.5942}$	0.9981	21	0.001	0.0401
Dimba weir	$Volume = 0.0050 \times Area^{1.6262}$	0.9971	20	0.001	0.0327
Lukata	$Volume = 0.0023 \times Area^{1.5068}$	0.9620	26	0.001	0.1913

SE: Standard error

Regional estimation of reservoir storage characteristics

It is also possible to produce regional equations or models for ease prediction and monitoring of all the reservoirs in the basin, including those that were not part of the bathymetric survey.

For easy estimation of capacities of unmeasured reservoirs within the Kaleya River basin, a regional basin level Equation (4) is presented in the Area-Volume curve (Figure 4).

$$Y = 0.7267 \times A^{1.1064} \quad (4)$$

where Y = reservoir volume in m^3, and A = water surface area (m^2).

In this regard, equation (4) could be used by reservoir owners, catchment managers or researchers to obtain a good estimate of the reservoir volumes at any time of the year. The only input would be the reservoir surface area which could be obtained by either walking round the wetted boundary of the reservoir to map the water area of the reservoir with a handheld GPS, or estimating the surface are from sentinel satellite imagery (Rodrigues and Liebe, 2013, Ghansah *et al.* 2022).

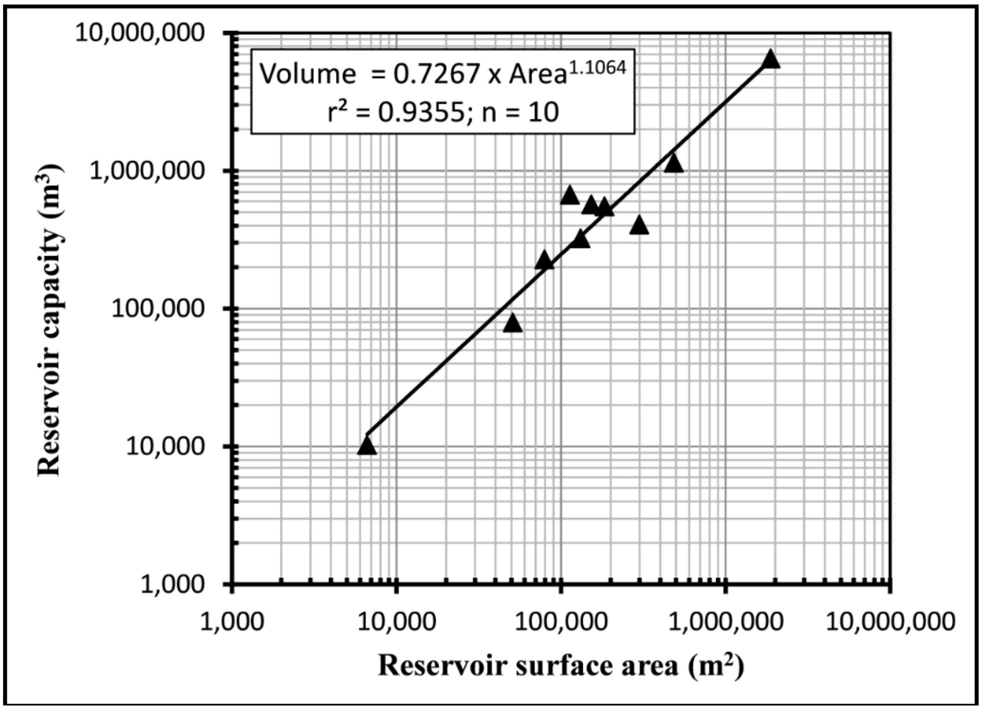

Figure 4. Power relationship between surface area and reservoir volume, Kaleya River basin.

Implications for monitoring sedimentation rates in surveyed reservoir

Previous studies (Sichingabula, 1997; Walling *et al*., 2001) in the upper part of the catchment) and Muchanga *et al.* (2019) in the Magoye Catchment have found that erosion and sedimentation pose a threat to water storage. In this regard, bathymetry information generated in this study could serve as baseline data for analysis of sedimentation rates in future studies. This is based on the premise that the volume of sedimentation in a reservoir could be considered equal to the loss in the reservoir storage capacity (McPherson *et al*., 2009). As such, sedimentation rates based on bathymetric data could be determined by comparing the new storage volume results with the previous baseline survey results. A reduction in storage capacity indicates the volume of accumulated sediment (Liebe *et al*., 2005; Ferrari and Collins, 2006). For measuring sedimentation rates, this approach is limited by the survey equipment and data-processing methods (McPherson *et al.*, 2009). Therefore, there is need to ensure replicability of the methods in future bathymetric surveys for example by using the same grid interpolation method and by conducting the bathymetric surveys when the reservoirs are at full supply level as was the case in the initial survey.

CONCLUSIONS AND REMARKS

This study successfully adapted the modern technology and software to assess the storage characteristics of small reservoirs in Kaleya River Catchment in Zambia. The generated bathymetric maps and morphometric characteristics of small reservoirs form valuable baseline information for water allocation decisions, and improved water resources management, water balance assessment, and analysis of sedimentation rates in the Kaleya River Catchment. Overall, the approach proposed is cost-effective in terms of bathymetric data collection and analysis and facilitates the delivery of accurate bathymetry data to users of small reservoirs and to the decision makers in Zambia.

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