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Impact of Sedimentation and Bathymetry of Selected Small Reservoirs on the Priority Water-Linked Sectors in the Zambezi River Basin

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Abstract

This study was conducted within the Zambezi River Basin to ascertain the bathymetry and sedimentation of selected reservoirs, evaluate their seasonal hydrological regimes, pinpoint the causes of reservoir siltation, and determine how the bathymetry and siltation impacted water-related industries and policy choices. Hydrological field measurements using a hydrographic survey boat, document studies, and interviews were used to collect the data. The 3D spatial analyst tools in ArcGIS 10.3 and hypsometric curves were used to analyze bathymetric data. Thematic analysis was used to analyze qualitative interview data. Findings indicated that sedimentation was a problematic phenomenon spatial-temporally and, it triggered a significant decrease in the storage capacities of the reservoirs. The study noted that catchments with small reservoirs were vulnerable to severe water stress, particularly from July through the beginning of the next rainy season in December. Over 90% of the local population and water-related industries were facing substantial risks of economic water shortages and may continue to face more water challenges amidst escalating climatic changes. The problem could be addressed by coping mechanisms such as alternative livelihoods, water harvesting, and water shedding. This study proposes an Integrated Water Resources Management Framework, which may help incorporate water education to bring about behavioural change against drivers of sedimentation. The proposed sediment and water resources management model serves as a multidisciplinary and transdisciplinary tool that could be used to address siltation concerns. This work has also shown the significance of bathymetric surveys of small reservoirs as a basis for policy context and regulations on managing water resources.

Keywords: reservoir, sedimentation, climate change, bathymetry, water scarcity, water-linked sector, hydrological regime, Zambezi Basin

1. Introduction

A constant supply of sediment from runoff and river channel erosion is eventually deposited into reservoirs, causing fast sedimentation and an early loss of the storage capacity, usable life, and quantity and quality of the water in the reservoirs (Sichingabula, 2018). In order to detect significant changes in sediment accumulation or bed morphological change, the bathymetric approach is based on a straightforward comparison of reservoir morphology at various times, which, according to the United States Army Corp of Engineers (USACE, 2009) and (Ajith, 2016), should be at least ten years in duration. Since the Zambezi River Basin is one of the catchments where the Sustainable Development Goals (SDGs) will be implemented by 2030, it is essential to comprehend processes like sedimentation that affect water quantity and quality. Two-thirds of the 17 Sustainable Development Goals (SDGs) (1, 2, 3, 13, 14, and 15) are dependent on water (United Nations Development Programme, 2018). Hence, factual scientific insights are constantly required to guide policy decisions. Moreover, this will improve water-dependent economic sectors like pastoral and agricultural farming by ensuring a steady supply of decisions for use in industry. Although reservoir sedimentation is a natural process in places such as the Zambezi River Basin, it is worsened by anthropogenic activities such as deforestation, riparian area mismanagement, and bad agricultural practices, particularly near reservoirs (Gharehkhani, 2011). Neglect of land, particularly in reservoir and river buffer zones causes sedimentation and rapid loss of storage capacity. Sand mining along rivers substantially influences sedimentation, morphological changes, and channel evolution over time. Sedimentation is an inherent phenomenon in all reservoirs; if left unchecked, sediment deposition diminishes reservoir storage capacities, leading to water scarcity (Sichingabula, 1997). Sediment accumulation in a reservoir limits its depth and usable life, as well as interfering with its functionalities. With many reservoirs quickly losing depth due to sedimentation and approaching the end of their original design usable life, sedimentation and bathymetric evaluation are becoming more relevant issues in reservoir operation and management (USACE, 2009). Reservoir sedimentation is a regionally dispersed problem that transcends a single catchment, and while various studies have been conducted, there is still a deficit, particularly in bathymetric research in Africa and Zambian settings. The Zambezi Basin has large sediment outputs, estimated to be between 50 and 500 tonnes km^{-2} yr^{-1}, providing a challenge to water resource availability and quality (Walling, & Webb, 1996) (De Sousa, *et al.*, 2020) (Chihombori *et al.*, 2012) (Alemaw *et al.*, 2013) (Sichingabula *et al.*, 2022). A quick survey of over 53 small reservoirs, including the Lukanga wetland, in various regions of the Zambezi Basin, revealed a sediment burden of over 1,201,654,842.57 m^3 with an average storage loss of nearly 26% (De Sousa *et al.,* 2020). The overall sediment load for measured water bodies in the Zambezi Basin varied from 34,000 m^3 to 1.2 billion m^3 (Chihombori *et al.,* 2012) (Alemaw *et al.*, 2013) (Sichingabula *et al.,* 2022).

River systems and reservoirs respond diversely to changing inputs of water, sediment, vegetation cover change, and human interference. It is worth mentioning that adjustments on reservoirs and channel morphology may range from small-scale to large-scale changes of reach morphology. It is worth mentioning that when a river channel is altered under naturally dynamic hydrologic conditions, the river re-adjusts itself with respect to dimension and profile to restore its former equilibrium state. However, this process is disturbed by anthropogenic influence and eventually, all reservoirs that are linked to such systems are also destabilized leading to various water stresses and shortages, especially for livestock. Through understanding such processes and how they are interlinked, strategic solutions could be found to address the challenge (Figure 1). Based on the foregoing, the study's objective was to assess how the bathymetry and siltation of the reservoirs affect water-linked sectors and policy decisions.

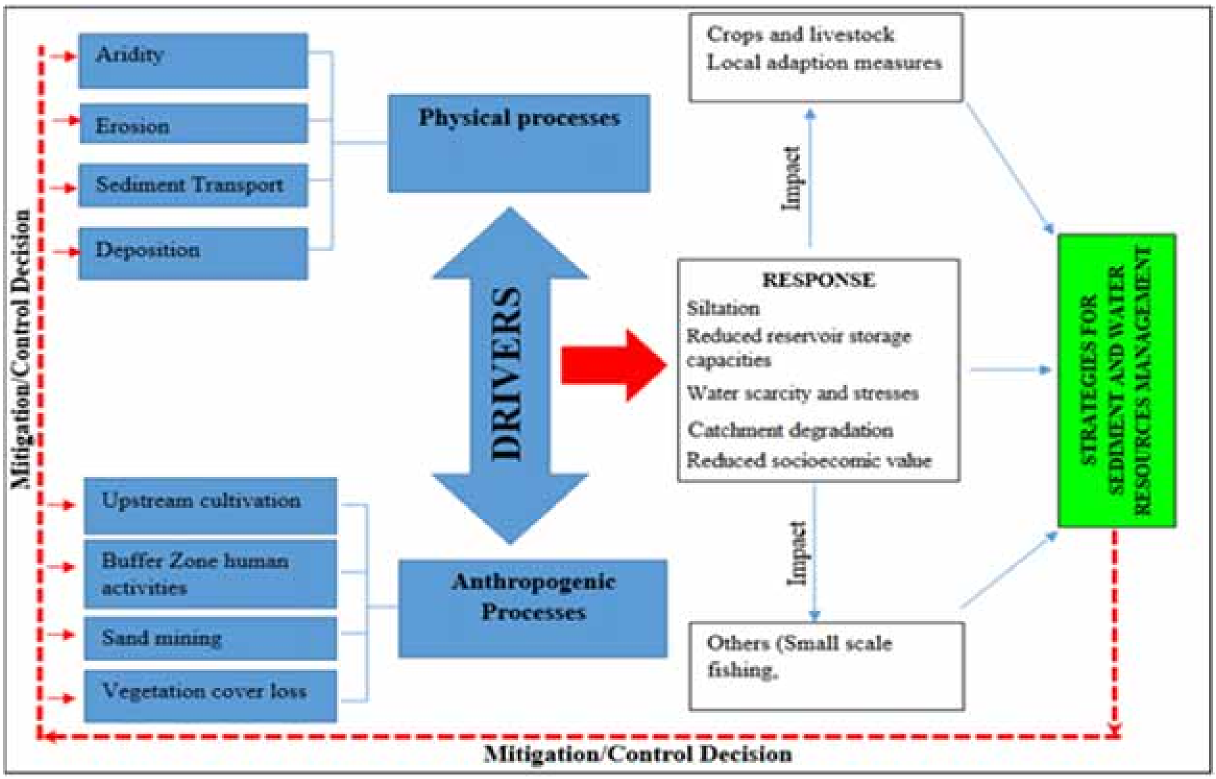


Figure 1. Conceptual Framework of the Study

2. Materials and Methods

2.1 Description of the Study Site

Zimba and Kazungula Districts are located in Southern Zambia between 15° 00"-18° 30" South and 25° 00"-27° 30" East (Figure 2). The total areas of the districts of Zimba and Kazungula are around 5,245.01 km^2 and 19,519 km^2, respectively. A decrease in rainfall has had a significant influence on agricultural, nutrition, surface water, and groundwater processes in these two districts (Zimba District Council, 2015). The three distinct seasons in the districts are the hot season (August to October), the rainy season (November to April), and the cold season (May to July). The relative humidity is quite low, and the temperature ranges from 15 to 27^{o}C. Nonetheless, the temperature may increase to around 32°C from October to November. The geomorphology of the study areas is explained by tectonic movement and rift valley faulting that existed in the Proterozoic era, more than 550 years ago (Zimba District Council, 2015).

The region has undergone extensive faulting, bending, and metamorphosis in addition to erosion and weathering, leaving behind broad plains and the surface of the most durable materials that have eventually undergone granitic and gneissic metamorphism. The existence of deep and shallow valleys, wide plateaus, and steep and flat river profiles is explained by the area's diverse topography. The Karroo Complex, a group of sedimentary rocks from the Palaeozoic and Mesozoic, underlies the regions (Zimba District Council, 2015). In Zimba and Kazungula, agriculture provides a significant portion of the population's socioeconomic support. In periods of water stress the community receives important environmental benefits from the reservoirs in addition to water for food security and animal hydration (Central Statistical Office, 2010).

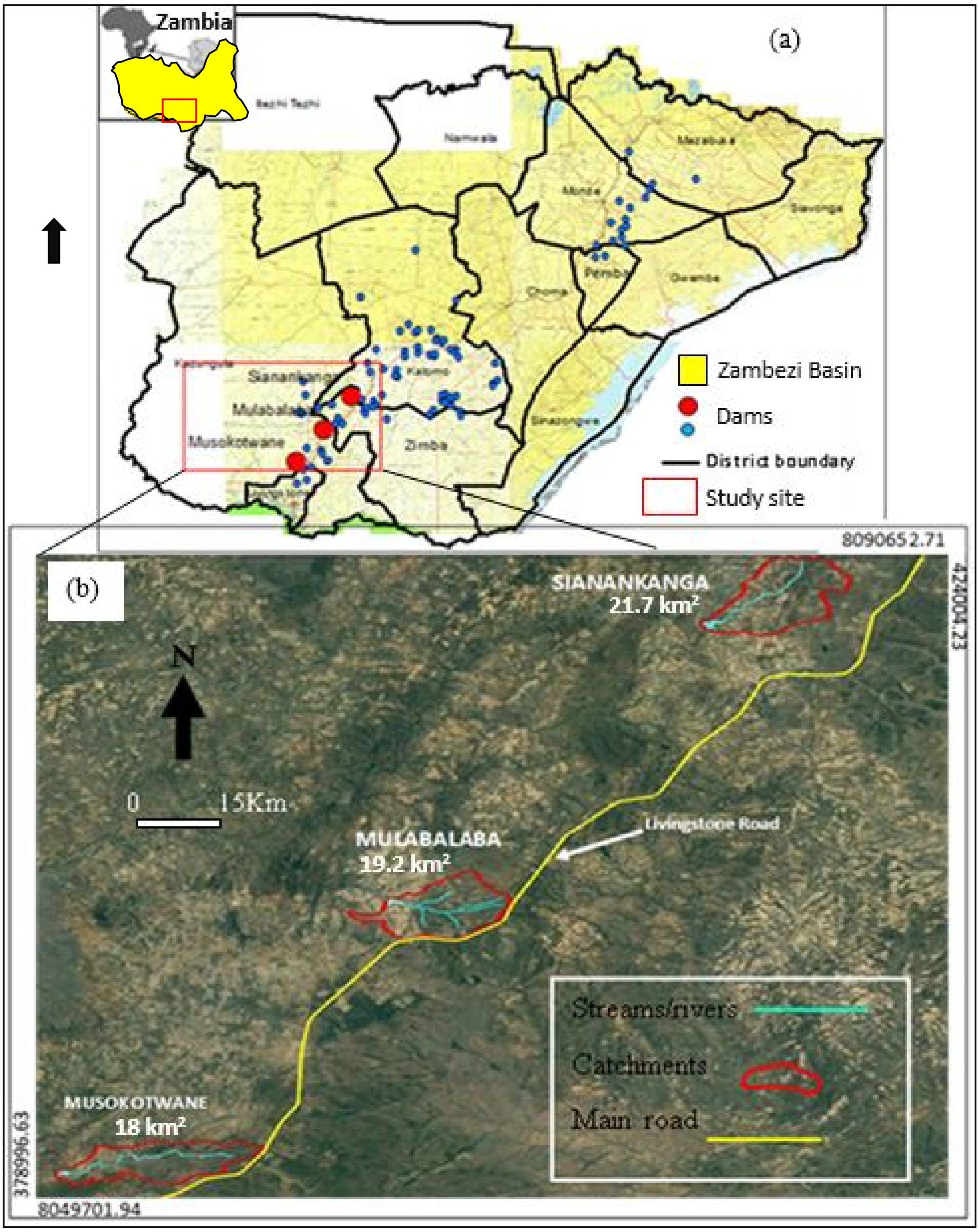


Figure 2. (a) General Location Map of the study area and (b) distribution of specific study sites

2.2 Data Sources, Collection, and Analysis

Bathymetric surveys were used to gather bathymetric data. The reservoirs of Sianankanga, Mulabalaba, and Musokotwane were bathymetrically surveyed using a Remote-Controlled Hydrographic Survey Boat (RCHSB) Model RC-S2 fitted with a Trimble Hemisphere OmniSTAR VBS for Differential Geographic Positioning System (DGPS). Water levels, bed profiles, wetted perimeters, and XY coordinates in UTM were among the datasets gathered. The processes shown in Figure 3 were used to build up the RCHSB.

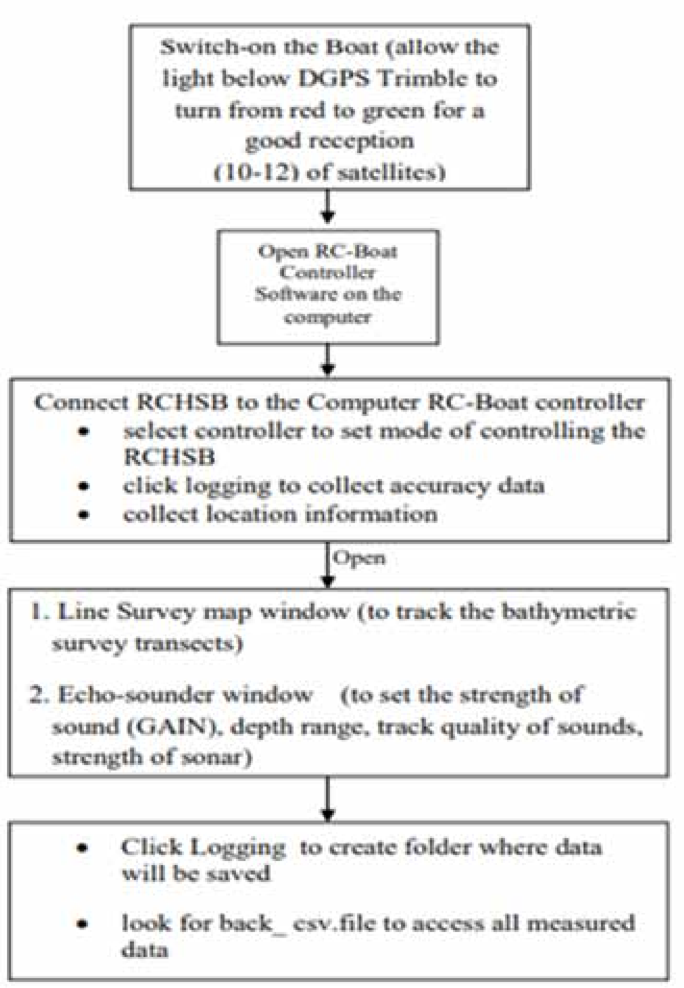


Figure 3. Process of setting up the equipment before deployment for the bathymetric survey. Adapted with permission from (Muchanga, M., 2020)

After assembling the RCHSB model RC-S2 boat, XY coordinates were verified for ground accuracy using Equation 1.

$$A = \sum_{i=1}^{N} \sqrt{((X_{i...nth} - \bar{X})^2 + (Y_{i...nth} - \bar{Y})^2)/N} \qquad \text{Equation 1}$$

Where: A, $X_i...n_{th}$, $Y_i...n_{th}$, and N stand for ground accuracy, all individual X coordinates in UTM, mean for X coordinates, all individual Y coordinates in UTM, mean for Y coordinates, and a total sample of paired X and Y values, respectively.

The RCHSB-Model RC-S2 was towed across the reservoir while attached to an inflatable boat powered by an outboard engine to conduct a bathymetric survey. Paddling was used where the inflatable boat's engine was unable to move, and where paddling was not possible due to accessibility, the RC-S2 was connected to the boat controller software on the tough book laptop, allowing it to be remotely controlled to reach areas that were not physically accessible. The RC-built-in S2's SONAR automatically recorded data on water depths, which were registered in the back_csv file. Wetted perimeters were measured by walking around the reservoir holding the DGPS on the RCHSB-Model RC-S2, which was transmitting records of perimeter coordinates automatically to the generated folder on the laptop computer, after each bathymetric survey.

The remotely sensed Sentinel-2 images were accessed from https://dataspace.copernicus.eu/ for 6-year period for each reservoir from 2016 to 2021 to supplement the bathymetric data that was physically measured. They were then analyzed in ArcMap using the image processing tool to determine how the water surface areas changed over the year for each chosen reservoir. The regression models created using the hydro-hypsometric rating curves were utilized to estimate the water volumes using the water surface areas that were acquired. It was anticipated that the little difference between data obtained physically and data obtained remotely might be extrapolated to subsequent seasons for which there were no data obtained physically. The hydrological regimes for each reservoir were built using the expected quantities of available water, which aided in the analysis of water stress times and potential consequences for water shortage issues in the context of climate change. With the aid of 3D Spatial Analyst Tools in ArcMap 10.2 and bathymetric data from the hydrographic boat, it was possible to determine the surface area and water storage capacity for each reservoir. The boat program downloaded the point data (XY-Z (depth)) from the back data file. The water's surface was used as the reference level, and the surface volume 3D analyst tool estimated depth values as elevations rather than depths if the negative sign had not been provided. Also, the reservoir shoreline's XY coordinates were imported, with each point's default depth value set to zero.

After that, an interpolated surface was created using Inverse Weighted Distance in ArcMap (IWD). The Area-Volume plugin was used to compute the reservoir's volume and surface area using this raster surface. The plane height was set to zero and all reservoir depths were assumed to be negative using meters as the unit of measurement since the reservoir border had zero values indicating the reservoir surface. In order to illustrate the correlations between water surface area and depth, volume and depth, and surface area and volume, hydro-hypsometric rating curves were created. A table with a summary of the data was used to illustrate the hydrological regimes for the reservoirs and show the inter-seasonal dynamics of water availability. Bathymetric maps were created from the data sets to visualize the spatial changes in depth throughout the reservoirs. ArcMap 10.2's IDW tool was used for this. Using Equation 2 following the guideline in (Muchanga, 2020), the Elevation Change Method (ECM) was used to calculate the long-term Total sediment accumulation from the construction date to the most current date (2022).

$$SV = A\frac{[(W_e - D_{se}) - M_{wd}]}{3} \qquad \text{Equation 2}$$

Where: SV, A, W_e, D_{se}, $M_{wd,}$ and *3* are; Total Sediment Volume (m^3), Surface area of the Bed (m^2), Water surface elevation of the reservoir (m), Downstream elevation nearest to the Crest (m), Maximum Water depth near the crest (m) and Constant, respectively.

The main premises of this formula are that the reservoir has a trapezoidal shape and that there are no substantial differences between the water surface area and the bed area. This formula was initially tested on a reservoir in the Magoye Catchment (Muchanga, 2020) with a 6% accuracy from the volume that was physically measured. Letter testing was done in the Mushibemba area, with the best minimal error at 5% and the worst scenario at about 15%. With errors ranging from 3% to 25%, it was later tested on a larger sample of reservoirs (MWDS, 2021). Onsite observations and interviews with 45 purposively chosen informants were used to gather information on the primary drivers of sedimentation and strategies for policy decision-making. The data was analyzed using thematic analysis.

3. Results

Musokotwane reservoir's full storage capacity was estimated at 380,264.8 m^3, with a matching water surface area of 103,052.79 m^2, as of April 2022. The physical bathymetric measurement, which was made while the reservoir was at full capacity served as the foundation for these estimates. Figure 4 displays the survey transects and bathymetric map that illustrate the changes in water depths.

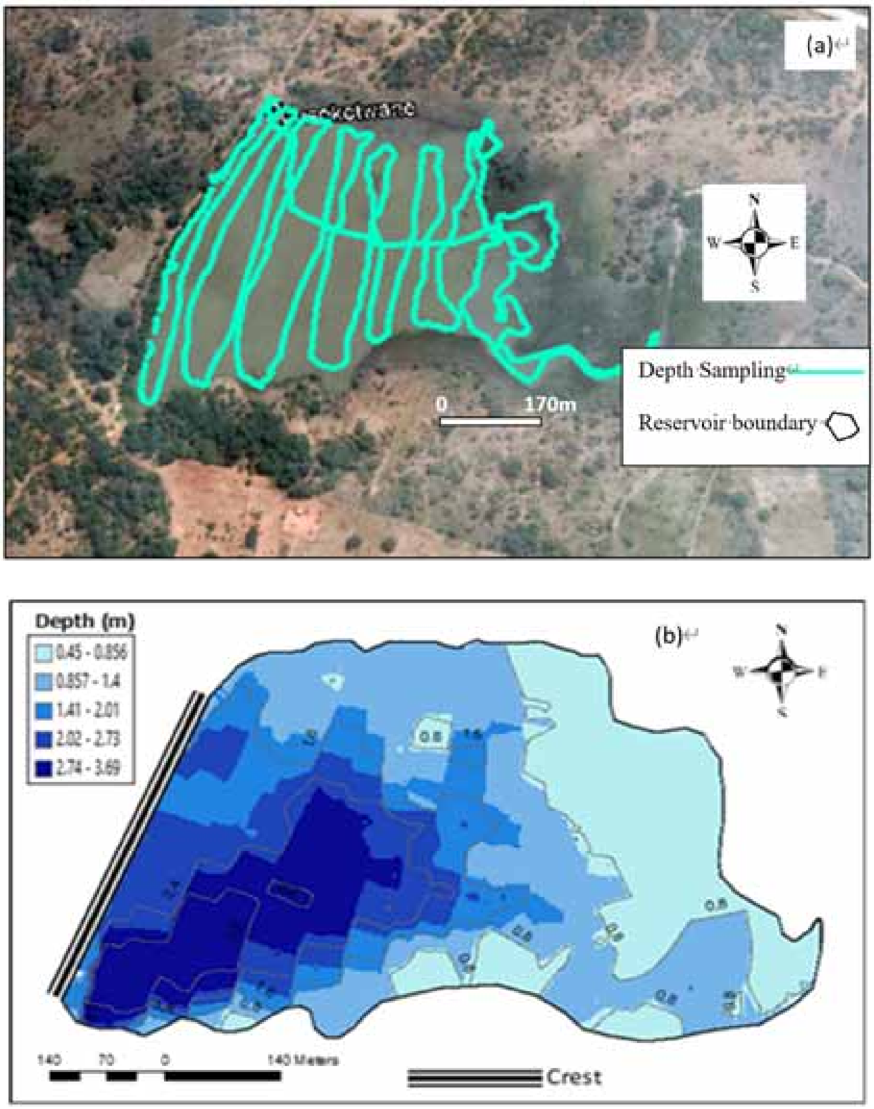


Figure 4. (a) Satellite image overlaid with survey transects
and (b) Bathymetric Map of the Musokotwane Reservoir (Field data, April 2022)

Details of how water volumes and water surfaces changed with changes in depth are shown in Table 1. The assessment showed a strong relationship between depth and volume as well as surface area and volume as indicated by high r^2 values of 0.96 and 0.97, respectively (Figure 5).

Table 1. Water Depth, Surface area, and Volume data for Musokotwane Reservoir

Depth (m)	Area (m^2)	Volume (m^3)
0	0	0
0.05	41713.14	47688.46
0.19	43852.08	52029.17
0.33	46522.64	56738.33
0.47	49082.85	61861.07
0.61	52657.22	67511.37
0.75	56055.28	73777.97
0.89	58121.62	80505.57
1.03	60636.88	87656.1
1.17	63027.6	95328.64
1.31	65796.2	103531.38
1.45	68364.87	112339.92
1.59	70782.97	121742.24
1.73	78705.2	143143.85
1.87	83503.48	155876.66
2.01	83727.74	169009.82
2.15	843345	169949.82
2.29	85233	185359.15
2.43	86872	202657.24
2.57	86504	222619.46
2.71	87330.39	244020.72
2.85	87413.34	265452.37
2.99	91323.2	286884.02
3.13	91502.23	308315.68
3.27	95233.07	329747.33
3.41	97383.18	351178.98
3.55	99142.93	372610.64
3.69	103052.79	380264.8

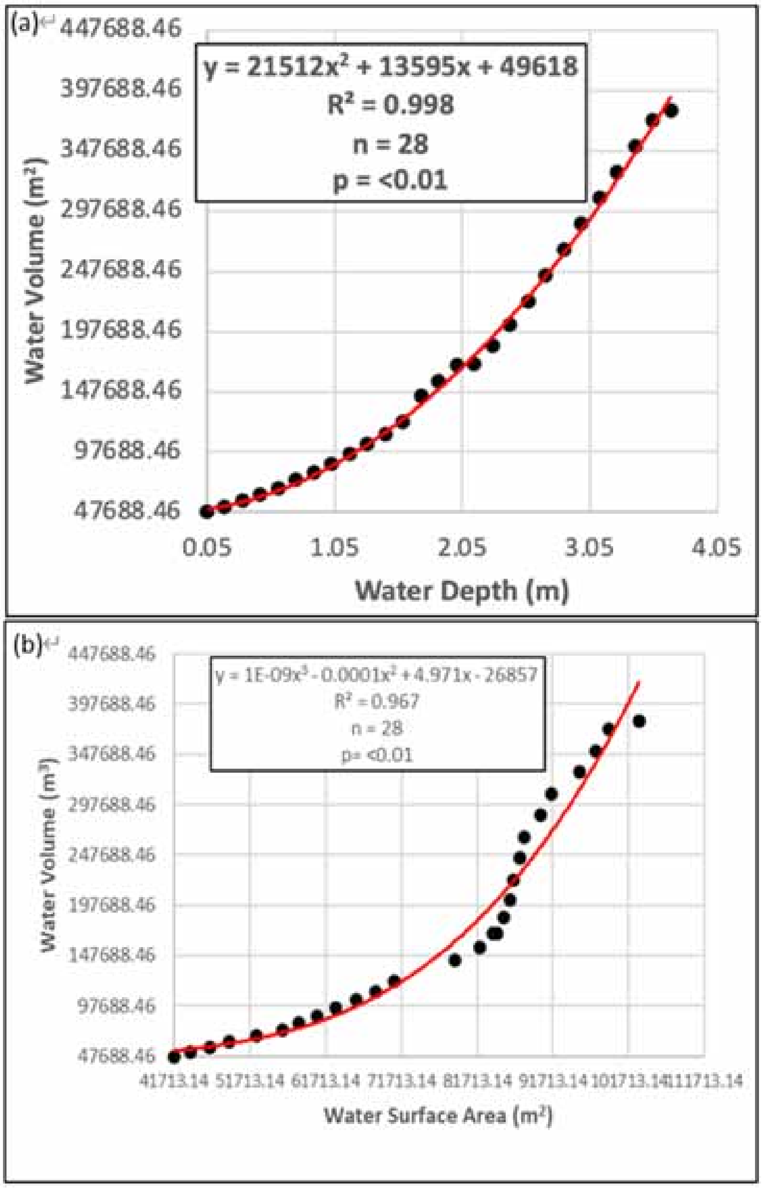


Figure 5. (a) Water depth-Volume relationship

and (b) water surface area-volume relationship for Musokotwane Reservoir (Field data, April 2022)

A bathymetric survey for the Mulabalaba reservoir was done when it was at full capacity in April 2022. At that time, the measured volume of water was 621,737.16 m^3 inundating the surface area of 117,087.98 m^2. Figure 6 presents the survey transects and bathymetric map of Mulabalaba Reservoir whose depth oscillated between 0.13 and 5.31 m.

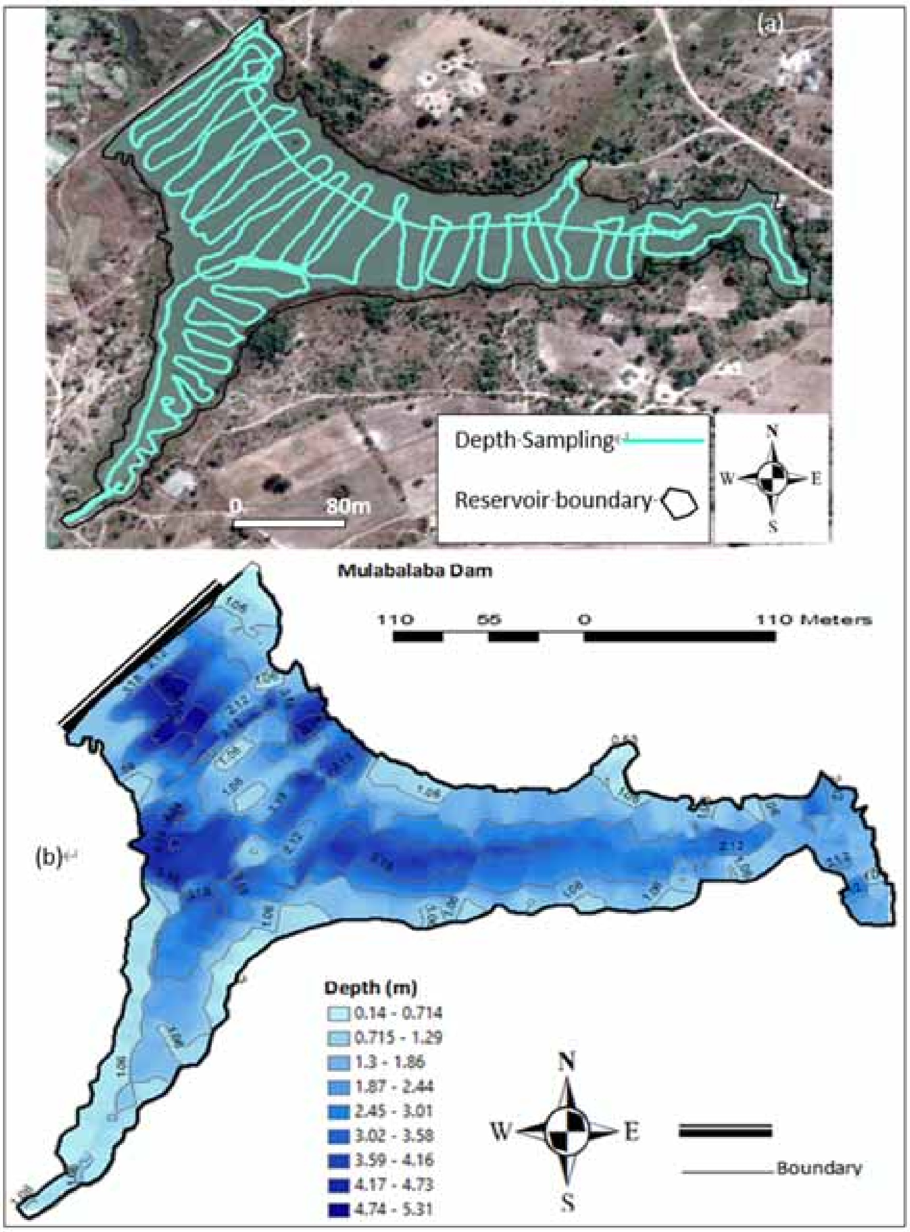


Figure 6. (a) Satellite image overlaid with survey transects
and (b) Bathymetric Map of Mulabalaba reservoir. (Field data, April 2022)

The research noted a statistically strong relationship between the amount of water and its surface area ($r^2 = 0.99$) in the Mulabalaba reservoir (Figure 8, Table 3). The depth-volume relationship followed a similar pattern (Figure 7, Table 2). It should, however, be noted that the size of the water surface area does not always equate to more water; it may indicate a silted reservoir. Hence, the strong correlation suggests that siltation levels could be in check.

Table 2. Water Depth, Surface and Volume relationship for Musokotwane Reservoir

Depth (m)	Area (m^2)	Volume (m^3)
5.31	117,087.98	621,737.16
5.17	115,067.98	587,630.12
5.03	113,057.97	553,523.09
4.89	111,047.96	519,416.06
4.75	110,037.96	485,309.03
4.61	109,027.94	451,201.99
4.47	108,017.93	417,094.93
4.33	107,007.91	382,987.93
4.19	106,668.89	348,968.89
4.05	104,874.85	315,531.34
3.91	102,498.66	283,894.00
3.77	100,431.30	255,097.53
3.63	97,532.81	229,393.31
3.49	91,385.40	206,664.19
3.35	85,045.76	186,519.33
3.21	79,281.17	168,608.69
3.07	73,839.33	152,745.86
2.93	69,138.15	138,612.79
2.79	65,260.08	125,786.92
2.65	61,541.77	114,086.40
2.51	61,541.77	114,086.40
2.37	57,334.28	103,479.29
2.23	53,611.25	93,931.42
2.09	49,509.11	85,426.14
1.95	46,330.29	77,768.51
1.81	43,622.73	70,802.13
1.67	40.878.79	64,426.14
1.53	37,639.01	58,689.93
1.39	34,709.82	53,577.45
1.25	32,688.65	48,952.42
1.11	31,042.19	44,686.53
0.97	29,219.94	40,748.64
0.83	26,905.25	37,166.39
0.69	24,937.67	33,960.13
0.55	23,331.19	31,028.48
0.41	21,720.71	28,354.15
0.27	20,398.13	25,916.77
0.13	18,104.19	21,607.01
0	0	0

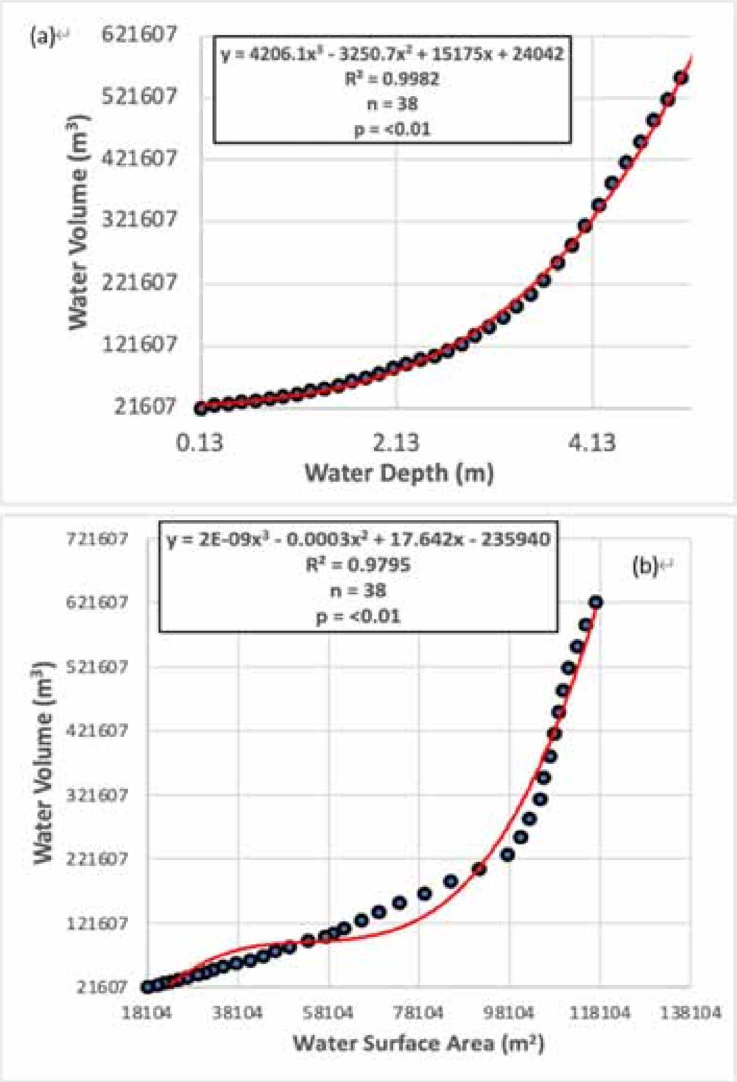


Figure 7. (a) Water depth-volume relationship
and (b) Water surface area-volume relationship for Mulabalaba Reservoir (April 2022)

About 1,111,497 m^3 of water was found to be accessible for diverse applications in Sianankanga Reservoir while it was operating at full capacity, primarily for municipal and agricultural needs. At a maximum depth of 4.5 m, this amount of water covered a surface area of 246,999.4 m2 (Figures 8 and 9, Table 3). Strong r^2 values of 0.99 and 0.98, respectively, show that there was a very strong relationship between water volume and depth as well as water surface area, just like in the cases of Musokotwane and Mulabalaba Reservoirs.

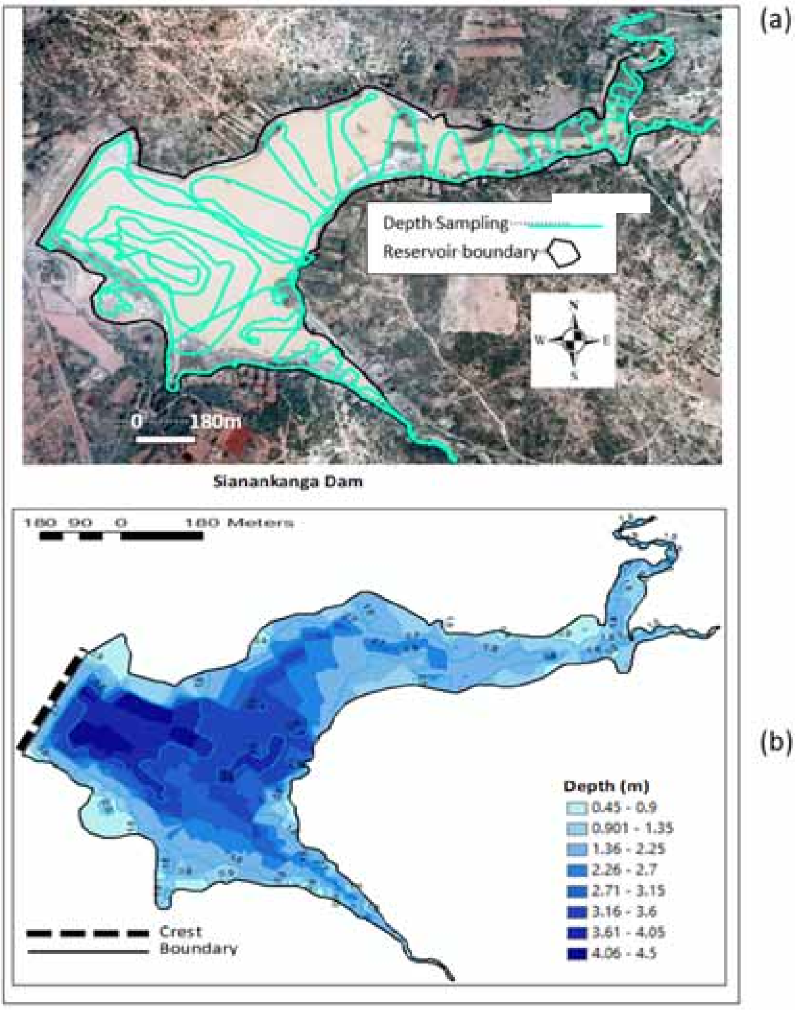


Figure 8. Satellite image overlaid with survey (a) pathways; and (b) Bathymetric Map of Sianankanga Reservoir. (Field data, 2016)

Table 3. Water depth, Water surface area and Volume for Siananganga Reservoir

Depth (m)	Area (m^2)	Volume (m^3)
4.5	246,999.4	1111497
4.37	246998.4	1076560
4.35	246996.4	1047446
4.3	246994.4	1012509
4.28	246990.4	977571.9
4.05	246989.4	849469.3
3.83	246979.3	715543.9
3.6	246969.3	587441.3
3.38	235587	455956.6
3.15	191820.5	354275
2.93	159773.6	280454.5
2.7	143576.7	224143.7
2.48	123865	175164.9
2.25	101471.9	139054.7
2.03	83687.96	110892.5
1.8	69742.77	90117.38
1.58	57701.26	73703.94
1.35	50205.49	61106.64
1.13	43072.79	50377.46
0.9	36804.72	41996.69
0.68	30052.44	35207.46
0.45	24882.11	30194.22
0	0	0

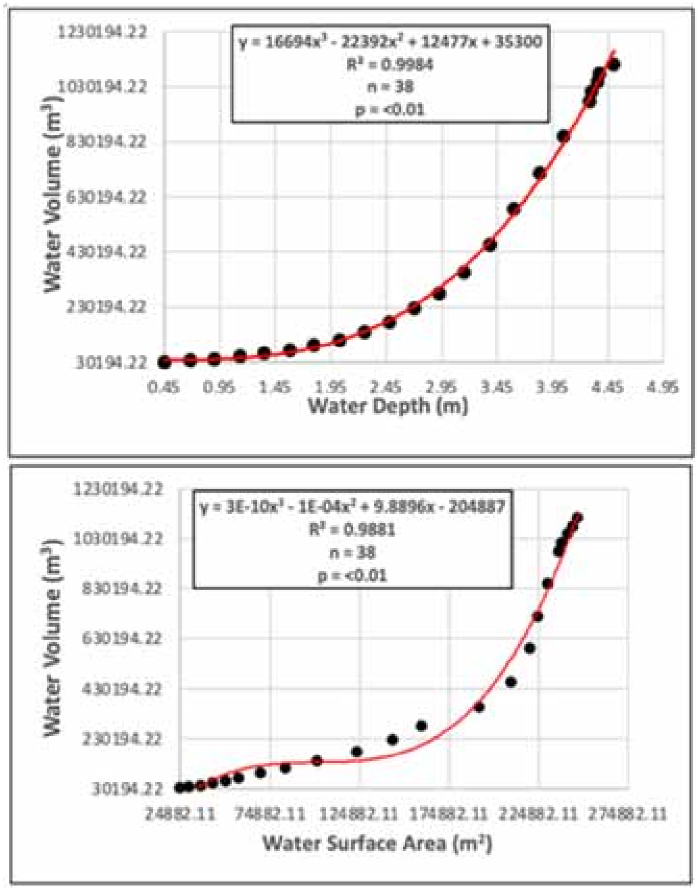
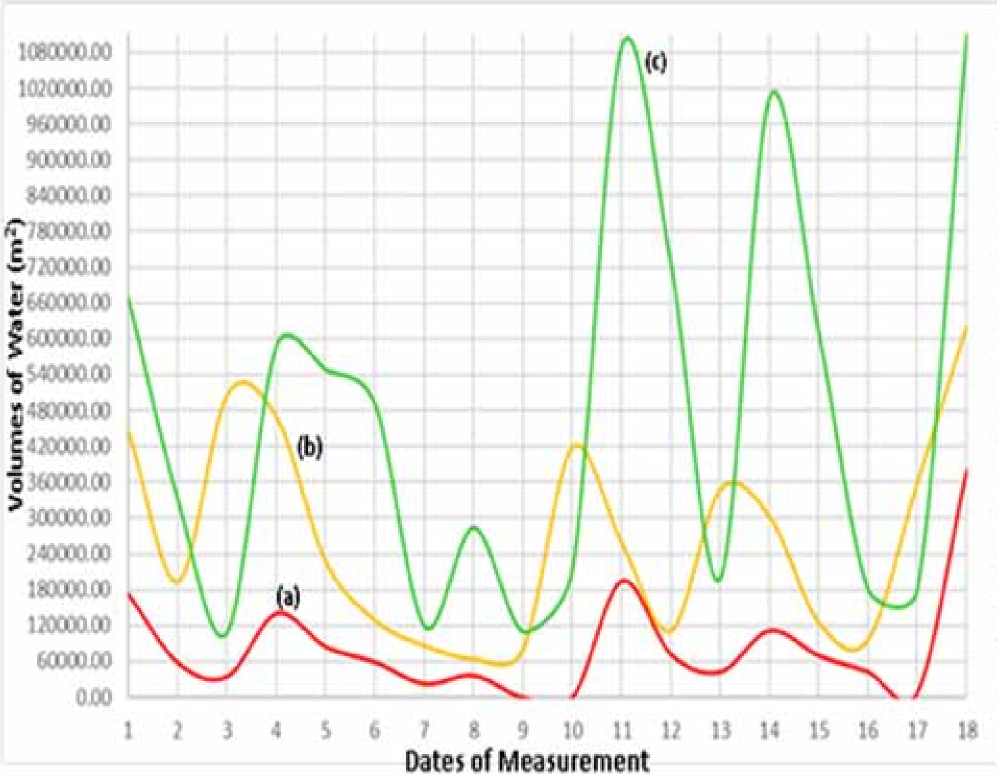


Figure 9. Water surface area-Volume (a) and Water depth-volume (b) relationships for Sianankanga reservoir. (Field data, April 2022)

The three reservoirs' water levels were found to be volumetrically unstable, with the Sianankanga reservoir being the most unstable and hence, most likely to face water scarcity and stress during dry seasons. Between December 2016 and mid-2022, the hydrological regimes also indicated that the Mulabalaba reservoir had receding flows between 2018 and 2019, but between 2019 and 2022, the results indicated consistent peak flows, particularly during rainy seasons. As opposed to other years, Sianankanga reservoir saw a dramatic rising and decreasing limbs between December 2019 and 2021 (Figure 10).



SN	Date
1	8/4/2017
2	15/10/2017
3	19/12/2017
4	18/04/2018
5	22/07/2018
6	10/10/2018
7	14/12/2018
8	12/7/2019
9	15/10/2019
10	19/12/2019
11	7/4/2020
12	16/07/2020
13	19/10/2020
14	12/4/2021
15	11/7/2021
16	14/10/2021
17	13/12/2021
18	10/4/2022

Figure 10. Hydrological regimes of (a) Musokotwane, (b) Mulabalaba, and (c) Sianankanga Reservoirs, 2017-2022 (computed based on remotely sensed water surface areas at different times from Sentinel A and B, 2022)

The ECM was used in the current study to estimate the amount of sediment load in the three reservoirs, and the results are shown in Table 4. The results demonstrated that siltation levels were within a low range since the capacity loss varied between 15% and 17% for each of the three reservoirs. This partly explains why there was a strong relationship between water surface area and water volume, the siltation levels were relatively low.

Table 4. Estimated Total Sediment Loaded in the Reservoirs

Variables	Musokotwane	Mulabalaba	Sianankanga
Area (m^2)	103,052.79	117,087.98	246,999.41
Water surface elevation (m)	1061.81	1144.37	1197.54
Downstream elevation (m)	1055.83	1136.21	1190.28
Max Water Depth Near Crest (m)	3.69	5.31	4.5
Constant	3	3	3
Maximum Sediment Depth Near Crest (m)	2.29	2.85	2.76
Total Sediment Volume (m^3)	78, 663.63	111, 233.58	227, 239.46
Estimated original Storage Capacity (m^3) (Sediment Quantity + Water Quantity at current Capacity)	458, 928.43	732, 970.69	1, 338, 736.46
Estimated Storage Loss	17%	15%	17%

(Field Data, April 2022)

Based on field observations and lived experiences of the local people, various drivers of sedimentation were documented especially those which were human-induced. For example, deforestation accounted for 18%, brick making for 12%, sand mining accounted for 6% whereas gardening, especially in buffer zones, accounted for 36% (Figure 11). One of the respondents at Mulabalaba reservoir mentioned that: Despite the local council coming to this community to sensitize us on how to manage the reservoirs sustainably, people keep cutting trees and making gardens around the reservoir and in all parts of the catchment. In a separate interview, another respondent at Musokotwane was of the view that: The river does not flow always and it is difficult to do gardening throughout the year and we tend to do the gardening near dams that have water all year round. The scenario presented here means that people needed just more than geophysical engineering of reservoirs, but also adequate water and environmental literacy around water resources management.

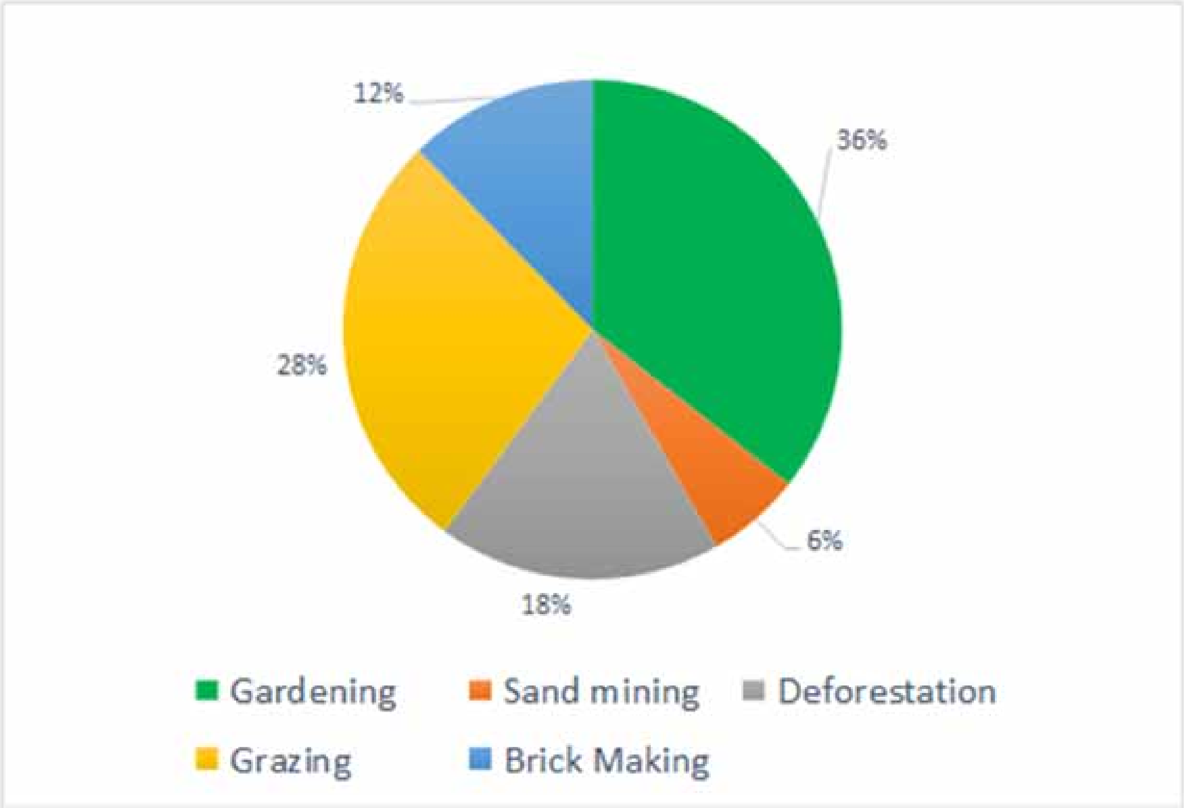


Figure 11. Major Anthropogenic drivers of Siltation in Reservoirs within the Zambezi River (Field data, 2022)

4. Discussion

For some reservoirs, sedimentation is a developing problem, but it is already occurring and is a cause for concern for others. The findings in the Zambezi Basin gave the general impression that reservoir siltation and capacity losses were within the same range as those found in other geographic contexts (Rooseboom & Lotriet, 1992) at the Welbeck reservoir in South Africa, (Haregeweny *et al.*, 2006) at a number of reservoirs in Ethiopia, (Onwuegbunam *et al.,* 2009) at the Afaka reservoir in Nigeria, (Majumdar, 2015) at Khodiyar Reservoir in Gujarat, India, and; (Rahmani *et al*., 2018) at selected reservoirs in central USA with an average storage loss of 17%. This demonstrates how geographically dispersed the siltation issue is. The first sign of silting in the Musokotwane, Mulabalaba, and Sianankanga reservoirs was the insufficiency to meet the water demands per person by the selected reservoirs. According to the criteria of typical water requirements per person per year (Chisanga *et al.,* 2022), the combined full storage for the three reservoirs could only sustainably support less than 1000 people per year, but there were more than 200,000 people who required water from the three reservoirs, meaning over 198,000 would be affected. The study findings suggest that the measured water could not meet the water demand. Both measured and anticipated storage capacity suggested a critical water shortage due to the high-water demand (40 litres per day or 0.04 m^3) for animals like cattle. Actually, if the total available water was to be equally shared among over 200,000 people, each will only have less than 5.6 m^3, signifying a critically stressing situation with regard to water demands.

In the target catchments, the issue of water stress and shortage was an unsettling reality. According to the hydrological regimes, smaller reservoirs in the Zambezi basin are far more likely to be prone than bigger ones to endure extended water stress periods and water scarcity, this observation was earlier made in another study (Muchanga, 2020). From July to November, both stress and a lack of water were common, with October being the most stressful month for a lack of water. The Musokotwane Reservoir Catchment saw the worst case of water stress, which by hydrological regimes, was longer than for the other two reservoirs. In smaller reservoirs compared to bigger ones, hydrograph analysis showed persistent low flows rather than peak flows. The study showed that reservoirs' basins were most water-secure from December to April, which corresponded to about 40% of the year. This means that for the remaining 60% of the year, strategic water conservation measures such as recycling and rationing must be implemented if the already limited water supply is to meet water demands.

The analysis also found that, in contrast to the period from 2016 to 2019, there were very strong rising and lowering limbs for the Sianankanga and Mulabalaba reservoirs from 2019 to 2021. According to previous research by Muchanga *et al.,* 2019), anytime such a situation happens, it may be indicative of a siltation issue that encroaches on the reservoir's available area, causing a single rain event to quickly fill it up. On the other hand, the water quantities rapidly decrease following a storm event because of fast evaporation compared to reservoir depth. While other factors may impact the quantity and quality of water in reservoirs, siltation continues to be the main cause of storage capacity loss (Muchanga, 2020). Under the influence of human activity, siltation continues to be a very significant challenge for the sampled reservoirs as well as in most parts of the Zambezi Basin. According to the Ministry of Water Development and Sanitation (MWDS, 2021), reservoir siltation in the Zambezi Basin is still a problem, affecting up to 88% of the reservoirs, particularly the medium-sized and small ones, with their storage capacity losses ranging from 8% to 57%. If the accumulation continued at the same rate as earlier illustrated in Table 1 and Figure 1, the reservoirs may on average, silt up significantly and lose part of their storage capacity. Table 5 summarises some other findings on the state of sedimentation in some parts of the Zambezi Basin (MWDS, 2021). The evidence shows that some reservoirs lost closer to half of their storage capacities, which negatively impacted water-linked sectors such as pastoral farming. The regional sediment prediction model is shown in Figure 12. The regional regression model in Figure 12 could potentially help predict siltation in reservoirs when maximum sediment depth is known.

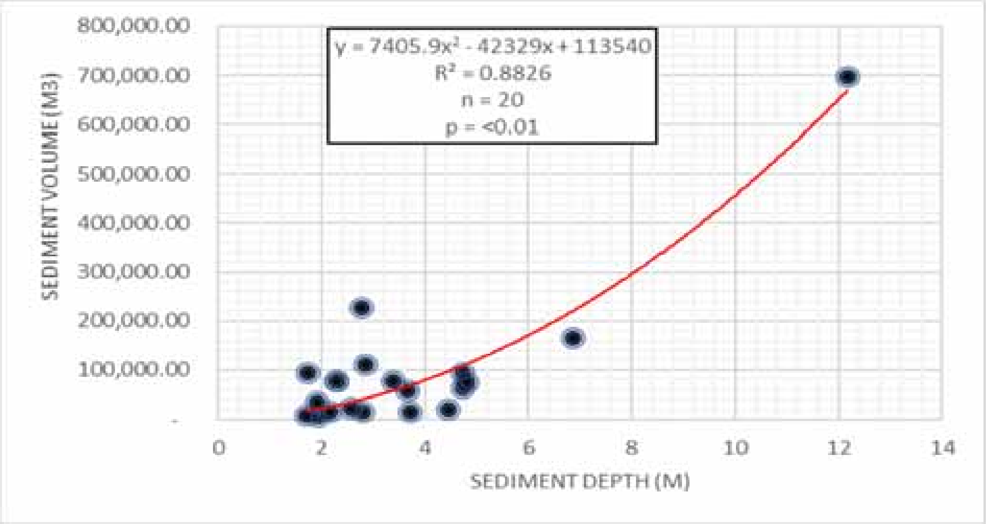


Figure 12. Regional Predictive Model for Sediment Depth-Volume Relationship
(based on field data and secondary data)

Table 5. Storage capacities, water availability, sedimentation, and storage losses for selected reservoirs within selected areas in the Zambezi Basin (MWDS, 2021)

No.	Name of Reservoir	UTM Location		OSC (m^3)	Max Sediment Depth (m)	Measured Water Volume (m^3)	Estimated sedimentation (m^3)	Storage Capacity Loss
		X	Y					
1	Mainza A	578457.95	8212009.5	330,777.02	3.71	315,134.48	15,642.54	5%
2	Nankenya 1	602494.72	8214607.9	264,634.05	4.45	243,039.28	21,594.77	8%
3	Magoye Weir	565800.31	8230545.9	372,055.73	6.86	206,513.55	165,542.18	44%
4	Simwendengwe	547608.32	8176170.1	168,276.09	2.8	151,797.58	16,478.51	10%
5	Hachanga	560196.29	8201840.6	5,387,679.37	12.16	4,689,547.30	698,132.12	13%
6	Mainza C	576710	8208596	155,254.78	2.56	131,233.00	24,021.78	15%
7	Hanchobezyi	556940.25	8178815.1	42,015.67	1.92	34,277.92	7,737.75	18%
8	Kanyemba	561431.12	8185561.8	82,331.26	2.14	66,846.30	15,484.96	19%
9	Lweeta	565992.52	8197852.4	245,251.93	3.64	186,836.78	58,415.15	24%
10	Singonya	561622.15	8180555.5	374,049.27	4.73	277,976.63	96,072.64	26%
11	Hambweka 1	552499	8170164	33,581.25	1.7	24,313.40	9,267.86	28%
12	Rusangu	555441.96	8189420.5	229,950.38	4.73	164,885.60	65,064.78	28%
13	Chipongwe	564295.44	8187533.6	219,536.01	3.37	141,419.89	78,116.12	36%
14	Chipembele	563871.75	8191105.3	81,019.16	1.9	45,456.40	35,562.76	44%
15	Makoye	574725.57	8204106.3	167,031.15	1.71	72,650.40	94,380.75	57%
16	Gwembe	563630.77	8175871.3	155,472.75	2.29	76,076.58	79,396.17	51%
17	Hakwangala	546882.97	8169478.3	308,807.41	4.79	233,688.66	75,118.75	24%
18	Musokotwane*	382361.82	8050897.6	458,928.43	2.29	380,264.80	78,663.63	17%
19	Sianankanga*	411713.09	8088504	1,338,736.46	2.76	1,111,497.00	227,239.46	17%
20	Mulabalaba*	397757.28	8069512.2	732,970.74	2.85	621,737.16	111,233.58	15%
OSC = Original Storage Capacity CSC = Current Storage Capacity, 2021 *Specific study sites				Total: 8,617,723.28	Mean: 3.67	Total: 7,061,693.7	Total: 1,973,166.26 Mean: 98,658.31	Mean: 26%

Source: MWDS (2022)

Crop farming was one of the main causes of siltation, and previous research (Muchanga & Sichingabula, 2021; Simweene and Muchanga, 2021) (Sichingabula, 2018) (Alemaw *et al.,* 2013) (Sichingabula, 1997) (Walling, & Webb, 1996) (Rooseboom & Lotriet, 1992) also suggest that it is responsible for siltation of most reservoirs and riverine habitats. Moreover, (Kamtukule & Kaseke, 2012) and (Mavima *et al.,* 2015) have previously observed that human activities like crop growing posed a serious risk to the reservoirs in Malawi and Zimbabwe's usable economic life spans. Beyond crop farming, other mixed landuse such as sand mining, charcoal burning, and brick moulding, continue to be some of the main causes of reservoir sedimentation and, eventually, the issue of water shortage. Due to climate changes, problems with water scarcity are projected to arise often during the next 50 years (Global Water Forum, 2007). Environmental issues surrounding reservoirs in the Zambezi Basin in general and the three target locations, in particular, are societal issues that have been greatly exacerbated by people, who ultimately became their victims. The decrease in reservoir storage capacities was generally due to human-induced siltation (MWDS, 2021).

The reservoirs could no longer store adequate water for approximately 60% of the year, domestic fishing was impacted by the shrinking water supplies, according to some field voices which suggested drying of rivers and reservoirs. Livestock was generally the most negatively impacted sector and, this could trigger a high risk of food insecurity. According to a study (Muchanga, 2020) conducted in a remote small sub-catchment within the

Zambezi Basin, protracted water shortages caused by silted reservoirs negatively impacted cattle health because there was insufficient water to operate dip tanks, leading to animal illnesses and deaths.

Governments throughout the Zambezi Basin have also been confronted with significant financial costs related to the management and control of reservoir siltation (Sichingabula, 2018). Findings from earlier studies (Mwiinde, 2017) (Saruchera & Lautze, 2019) revealed that governments will have to spend a lot of funds (>ZMW 500,000) to address dwindling water scarcity through desilting and rehabilitation of reservoirs and other water sources. As evidenced by a case study from the Magoye sub-catchment, Zambian governments as well as their local and international cooperating partners may incur significant costs (ZMW 1,462,786,060 (US$ 73,139,303) in order to restore degraded water resources infrastructure, such as reservoirs and riverine environments, and desilting (MWDS, 2021). Further proof demonstrates that sedimentation reduces the intended environmental and socioeconomic advantages of reservoirs in terms of money, as demonstrated by Reduced Net Present Value (NPV) (Mwiinde, 2017). Furthermore, (Saruchera & Lautze, 2019) reported that reservoirs in the Zambezi Basin offered declining returns as a result of reduced storage capacity brought on by siltation in the context of the expense of sedimentation in reservoirs. Only Mboole (built in 2002) and Mulabalaba, according to (Saruchera & Lautze, 2019), had moderate sedimentation issues, therefore even the people who relied on these water facilities failed to report siltation as a concern. The results for the latter reservoir are consistent with the present results, despite the fact that the hydrological regimes appeared to point to an impending siltation problem. On the other hand, siltation resulted in Chuuka, Milangu, and Nteme losing more than half of their storage capacity (Saruchera & Lautze, 2019).

In general, the study's findings indicate that reservoirs' declining water storage capacities pose a serious threat to the water security and long-term socioeconomic and cultural development of several rural communities in the Zambezi Basin, particularly the reservoirs that were the subject of the study. Yet, the same silt that adversely affects the bathymetries of nearly all reservoirs within the Zambezi Basin might be useful if clear economic models are created around them, according to (Mwiinde, 2017), (Saruchera & Lautze, 2019), and (Muchanga, 2020). For instance, (Mwiinde, 2017) demonstrates that dredging each small to medium reservoir would cost the government around >ZMW 500,000, but the earnings that might be realized from the sale or use of dredged fertile material for agricultural uses may be up to three times the amounts spent on dredging. This further demonstrates the need to examine various possibilities and problems related to water resources and siltation management in order to realize the advantages and lower the expenses.

The local communities used both constructive and harmful strategies to deal with the problems of water shortage and siltation, which should be carefully evaluated in future planning for sustainable water resource management and silt control. Data from the research (Sichingabula, 2018) (Mavima *et al.*, 2015) (Global Water Forum, 2007) (Rooseboom, & Lotriet, 1992) sampled reveals intra-basin variability in how communities respond to various issues of water shortage and siltation. Furthermore, (Saruchera, & Lautze, 2019) noted that 25% of African communities experience high levels of chronic water stress and 40% experience drought stress every 30 years, arguing that a well-engineered increase in use may be helpful in reducing water-related development and pollution constraints, which also give rise to a variety of social science and engineering issues (Vörösmarty *et al.*, 2005). They contend that a larger multidisciplinary approach is necessary for a more thorough knowledge of human-water interactions and the creation of effective policy measures to relieve water stress. To address the many difficulties encountered in managing water resources, a framework based on scientific principles and including social sciences is needed. As a result, proactive planning is required to incorporate contextually relevant measures for a sustainable water resource supply for everyone, as stated in SDG 6. The study suggests a conceptual framework that may enable sustainable sediment control in reservoirs, which would ultimately assure sustainable water resources management (Figure 13).

The conceptual model represents concepts that call for an interdisciplinary and transdisciplinary strategy to solve the issues of water shortage brought on by surface water body siltation. It would be easier to reduce the causes or drivers of changes in water availability if hydraulic engineering technologies, nature-based approaches, and effective transboundary water governance and regulations were all combined. The majority of intervention options embrace education and awareness only very minimally, and in many cases, they stop at awareness, which cannot result in the needed behavioral change for long-term, community-based catchment management (Hamatuli & Muchanga, 2021). Just increasing awareness does not necessarily bring about the needed change that would prompt local communities to take decisive action for sustainable water resource management in order to realize long-term benefits. Many of the study's findings are in line with the SADC Water Policy, which recognizes low urban and rural water supplies as well as high rates of water-borne diseases, rapidly urbanizing populations as a cause of water scarcity and pollution, very low irrigation water use efficiency, degraded watersheds, declining water quality, and significant economic strain in the region (SADC, 2005). Because of the large reductions in storage capacity caused by siltation in reservoirs and rivers, policymakers need to reconsider their intervention strategies from both the country and basin perspectives. If this is not addressed with the urgency it requires, major difficulties with water scarcity and perhaps water disputes should be anticipated in the near future, which will have a variety of socioeconomic repercussions. The majority of water-related industries, particularly agriculture, and energy, are anticipated to be the most severely impacted (Vörösmarty *et al.,* 2005). Given the importance of these and other industries, there may be a number of cascading repercussions if the gap between water availability and demand continues to grow.

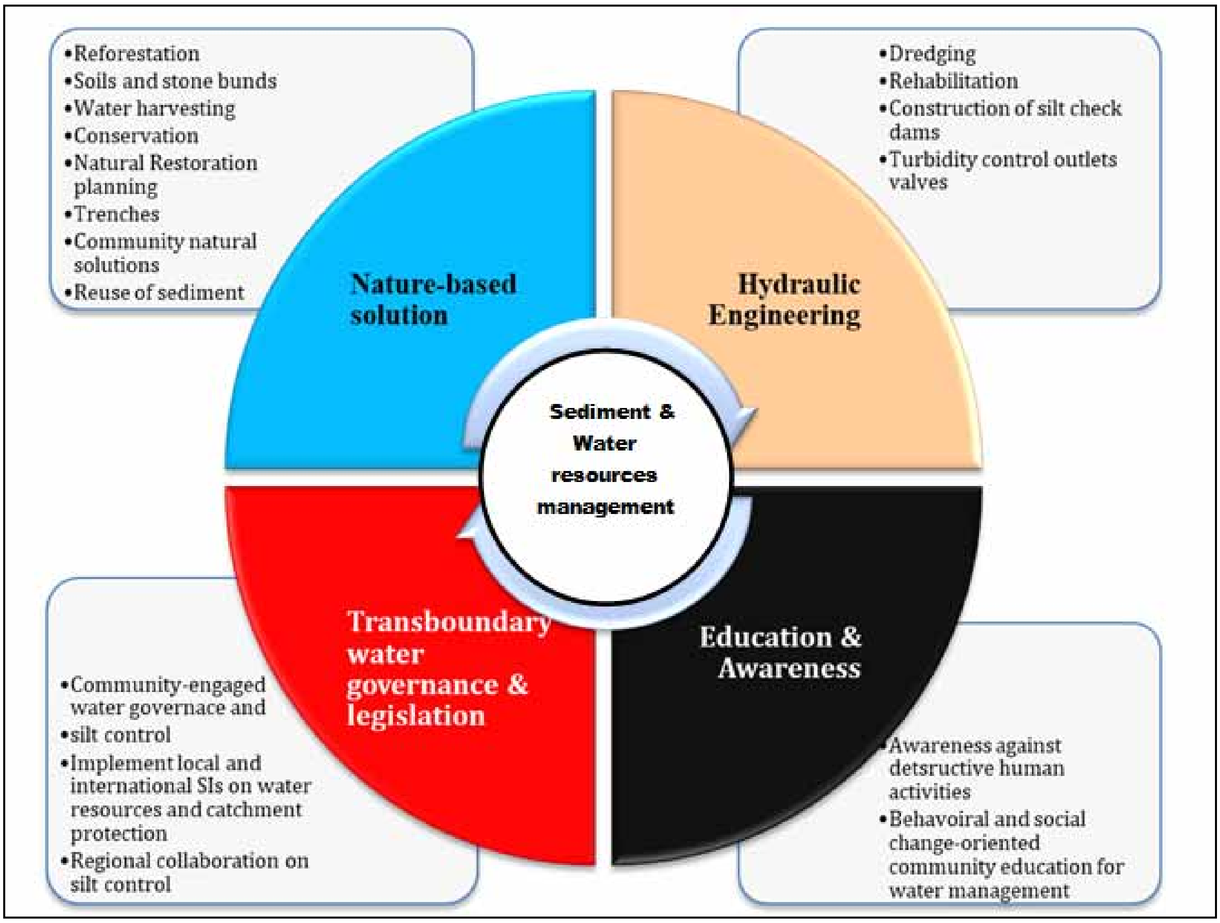


Figure 13. Conceptual Model for sustainable management of water resources and siltation control in reservoirs in the Zambezi River Basin and beyond

Governments must reaffirm current national and even regional regulations that are intended to safeguard water resources in order to address the issue at its source. For instance, Zambia's SI 1 of 2000 and Water Resources Management Act of 2012, which has specific rules for the protection of catchments and buffer zones around all water bodies, have not been properly enforced, resulting in unprecedented deterioration of some river sections and reservoir buffer zones (MWDS, 2021). While this disregard may seem regional, it has various intra-and-inter-spatial consequences. For instance, sediment may be eroded, transported for long distances, and then deposited in a region that does not produce much sediment. As a result, policymakers in different national settings and at the basin scale should work together to draft and execute laws and policies that would help address water problems in an integrated way. This scenario is extrapolatable to all nations within the Zambezi Basin. It is hardly an overstatement to say that human activities are the principal drivers of sedimentation and water insecurity. To address the issues and prevent behaviours that aggravate siltation, water shortage, and stress, non-formal water educational programs, and policies should be implemented. Governments in the Zambezi Basin should think about creating a new research agenda that addresses the current difficult terrain in terms of water security and siltation issues in order to strengthen the scientific database that guides policy decisions. Increased siltation levels and watershed degradations are widely anticipated given the projected climate changes within the two catchments (Chisanga *et al.*, 2022), it is therefore important to continuously include the research agenda for future water security, otherwise, it may not be possible to achieve SDG 6 and other water-dependent SDGs within the of the wider catchment context.

5. Conclusion

Based on a synthesis of all findings, the study concludes all the target small reservoirs were at a high risk of losing storage capacities, and, catchments, where such small reservoirs were located, could also be prone to severe water scarcity and stress, especially between July and early November. This situation would affect crop and animal productivity, and fishing activities, among others. The study also noted that human activities such as agriculture are the main drivers of siltation and loss of storage capacity for most reservoirs. The cost of addressing sedimentation in reservoirs bears a heavy toll on the government planning process; but at the same time, the very propellant of reservoirs' loss of storage capacities could be transformatively utilized to build profitable business models and be reused for fertilization of crops. This remains a poorly utilized coping strategy and opportunity for most countries within the Zambezi Basin. The coping strategies such as alternative livelihoods, water harvesting, and water shedding recorded in various parts of the basin suggest a spatially distributed nature of the problem of water scarcity due to siltation and climatic changes. The study proposed a conceptual model that inherently suggests an integrated and transdisciplinary approach to addressing the challenges of reservoirs' storage losses and siltation challenges for sustainable water resource management by 2030 and beyond.

Competing Interest

There are no competing interests concerning this paper.

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Contributions to the Paper

MM, HS & RW: Conceptualization, methodology and formal analysis, writing - original draft; HS and KB: Funding acquisition, Project administration, technical insights for further improvement of the paper. CBC & KM: Proofreading and suggestion of insights to improve the thoughts.

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