Tanzania Integrated Water, Sanitation and Hygiene (iWASH) Program

MINDU DAM BATHYMETRIC SURVEY REPORT

NEEDS PHOTO

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BATHYMETRY SURVEY CARRIED OUT MAY 2014

REPORT FINALIZED JANUARY 2016

SUMMARY

Mindu Dam is an earth embankment dam, designed and built between 1978 and 1985, and opened officially on 9 May 1985. The dam embankment is ~1.5km long and 11m high at the dam crest. The dam captures surface runoff of several perennial and seasonal streams during the rainy season, making water available during the dry season. There are several small rivers in the upper Ngerengere catchment that feed this reservoir including; Mzinga, Mlali, Mkurunge, and Lukulunge Rivers. Mindu Dam is one of the Morogoro Municipal's main sources of water for domestic and industrial use, serving approximately 65% of the Municipals' total population. As the population and water demand increases, it is important that the storage volume be known for efficient water management and reservoir planning. The dam design was originally envisaged in two phases, Phase I to raise the dam spill level to an elevation of 507m (AMSL) was implemented, and Phase II to raise the dam level a further 2m was not implemented, but is being currently being re-examined as an option by the utility, MORUWASA.

The purpose of this study is to establish the current capacity of the Dam, and the percent of effective storage capacity that sediments have occupied. At the same time the study establishes the 'elevation - area – volume' relationship based on a bathymetric survey carried out in May 2014. The bathymetric survey was done using a transducer mounted on a boat providing location (x,y) and depth readings (z) every second. The transducer was assembled and programmed at IWASH offices by WRBWO Staff with guidance from iWASH consultant, Chris Dutton. The bathymetry unit cost was ~ US$405.

The depths obtained were deducted to obtain altitudes of Dam bottom using datum at the Dam gauge. Dam interpolated elevation ranged from (498 - 507m) with maximum volume of 11,407,511 m^3 (eleven million cubic meters) extending a total area of 22,211,207 m^2 (~2.2km^2) at an altitude of 507 AMSL. At the lowest elevation of 498 AMSL the volume is calculated at 39,648 m^3 covering a total area of 20,629 m^2.

The study determined the depth of the reservoir, and established a relationship of bottom elevation, volume and area. On the survey date, the Dam was spilling and at full capacity; the total volume computed was 11,407,511m^3 with an area of 2,211,207m^2. Reliable information and data on the original reservoir capacity was not readily available. Design data was obtained from a report on the design aspects[1] indicating a reservoir capacity of 12,623,000m^3 with an area of 3,833,000. This would indicate there is a reduction in the Dam's volume by 1,215,489 m^3 (9.63%) and area by 1,621,793m^2 (42.3%) respectively over the past 29 years.

The reduction in the dam volume is in fact significantly less than anticipated in the design report, where a siltation rate of 0.5% per year over the first 20 years of operation was cited, and would have resulted in a 15.6% reduction in volume over the intervening 29-year period. The apparent reduction in the surface area is difficult to explain, as there little conclusive evidence of such a significant shrinkage. However, in a report dated 1994[2] the dam is described as being 1.5km wide and 3.5 km long, although it is not clear whether these dimension were measured/observed or taken from the original design documentation. The dam today is ~1.5km at the widest point by ~2.4km long. There is no conclusive explanation for this discrepancy.

[1] Contract No 1. The Mindu Dam – Report on Design Aspects, January 1979 by Sir Alexander Gibb & Partners.

[2] Tanzania Urban Sector, Yield estimates for Tanga and Morogoro, August 1994 by Institute of Hydrology, UK

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ABBREVIATIONS

AMSL	Above mean sea level
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GIS	Geographical Information System
GPS	Global Positioning System
GPSU	Global Positioning System Unit
iWASH	Integrated Water Sanitation and Hygiene
MORUWASA	Morogoro Urban Water and Sanitation Authority
WRBWB	Wami Ruvu Basin Water Board
WRBWO	Wami Ruvu Basin Water Office

1. INTRODUCTION

1.1 BACKGROUND

Mindu Dam is an earth embankment dam, designed and built between 1977 and 1985, and officially opened on 9 May 1985. It is ~1.5km long and 11m high. The dam captures surface runoff of perennial and seasonal streams during the rainy season, making water available during the dry season. There are several small rivers in the upper Ngerengere catchment that feed this reservoir including; Mzinga, Mlali, and Mkurunge, Rivers, and the dam discharges into the Ngerengere River. This Dam is one of the Morogoro Municipal’s main sources of water for domestic and industrial use, serving almost 65% of the Municipals’ total population. As the population and water demand increases, it is important that the storage volume be known for efficient water management and reservoir planning.

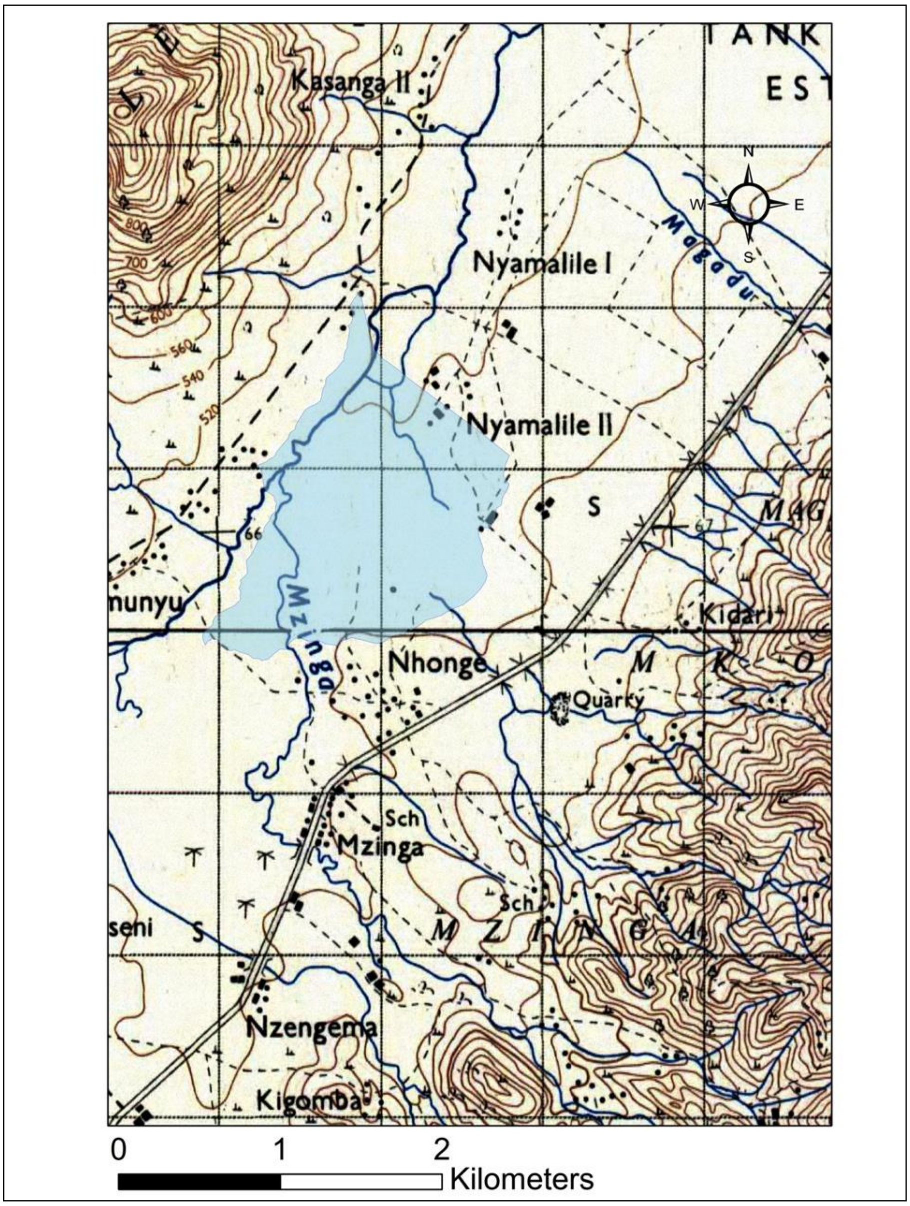

Figure 1: The Mindu Dam – Government of Republic of Tanzania 1972 Topographical Map

1.2 OBJECTIVES

The main objective of this bathymetric survey was to establish water and sediment volume of the Dam. Other objectives include; capacity building to the WRBWB staff on determining the water volume of the Dam, the surface area of the Dam and water depths of the Dam using low cost instrumentation.

2.0 FIELD BATHYMETRIC SURVEY

2.1 GENERAL

The Mindu Dam Bathymetric survey process involved deskwork prior to the field survey using Google Earth Digitization of the Dam. Following successful deskwork planning, the fieldwork comprised a site verification of key assumptions used during the planning, and execution of the bathymetry survey.

2.2 DESCRIPTION OF DAM ENVIRONMENTS

2.2.1 Mindu Dam dimensions

The first step was to roughly obtain dimensions of Dam that could assist with planning of the fieldwork. Mindu Dam shape was established from Google Earth imagery, which gave the shape of a rough pentagon lake wider on the Dam wall side and the thinner end representing one of the Rivers that fills the Dam.

Figure 2: Mindu Dam from Google Earth

2.2.2 Topography

Mindu Dam lies at the base of the Uluguru Mountains (south east), and Mindu mountains (on the west), both being part of the Eastern Arc Mountain range, where the numerous streams that fill it originate. There are several small rivers in the upper Ngerengere catchment that feed this reservoir including; Mzinga, Mlali, Mkurunge, and Lukulunge Rivers. The discharge from Mindu Dam spills into Ngerengere River and flows around the eastern side of Mt. Uluguru.

2.2.3 Accessibility

Figure 3: Mindu Dam South of the Iringa Road Mindu Dam south of the Iringa Road

2.2.4 Climate and weather

The Mindu Dam is located in Morogoro Municipality, which experiences average daily temperature of 30ºC with a daily range of about +/-5ºC. The highest temperature occurs in November and December, during which the mean maximum temperatures are about 33ºC. The minimum temperatures are in June and August when the temperatures drops to about 16ºC. The total average annual rainfall ranges between 821mm to 1,505mm. Long rains occur between March and May, and short rains occur between October and December each year.

2.3 DEFINING SURVEY TRANSECTS

2.3.1 Criteria

In order to capture dam bottom elevations accurately, it is important to measure depths from the dam surface at closely spaced intervals. The boat was used to cruise zigzagging the lake for depth sounding in order to get as many representative depth readings as possible.

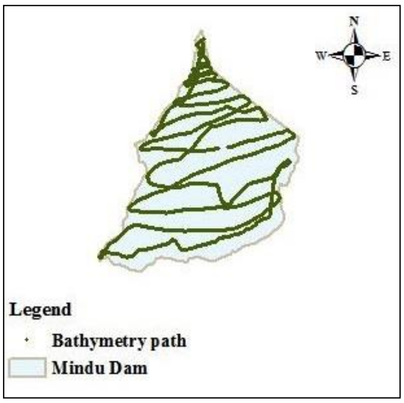

Figure 4. Bathymetric path

2.4 CARRYING OUT THE BATHYMETRIC SURVEY

2.4.1 Surveying

The bathymetric survey was carried out using an eco-sounder (with internal GPS) mounted at the side of the boat near the rear. This location was selected to minimize periods in which the sounder would be out of water due to waves lifting the boat. The sounder comprises of a high capacity transducer transmitting and receiving ultrasonic waves every second. For real-time data visualization, the assembly was connected to a mobile phone that displays depth measurements as the boat cruises over water surface.

The bathymetric survey for each transect was carried out using the following procedure:

i) The start and end locations of the transect were recorded in the GPS before the start of measurements

ii) The eco-sounder was mounted on a wooden stand lowered onto water and reset ready for measurements

iii) The boat was driven from the nearest transect end towards the opposite bank while a directional navigator carrying the GPS providing guidance to boat coxswain to steer the boat on the line of the transect

iv) Real-time verification of reading was carried out by slowing the boat, checking the depth readings and accelerating it while checking changes of depths readings

2.4.2 Data storage

Depth measurements were stored automatic on a memory card embedded into the eco-sounder. Each depth sounding was associated with location readings (latitude, longitude in degree decimal minutes). Each evening the data were downloaded from the memory card into a laptop for security, although the memory cards had large storage capacity.

3. MINDU DAM CHARACTERISTIC RELATIONSHIPS

3.1 GENERAL

The fundamental aim of carrying out bathymetric survey was to obtain the topography of areas of the lake below its surface, not normally captured on land surface topographical maps (topo sheets, DEM, DTM, etc). Once the survey is completed, the shape of Dam bottom /floor can be established by processing survey data, and the lake extent (area) and volume can be computed for each elevation. Following the completion of bathymetric survey, the Dam characteristic relationships were established through:

i) Quality checks of data to remove erroneous readings

ii) Reducing good quality recorded water depth to altitudes

iii) Interpolation of depths and altitudes to obtain the Dam shape

iv) Estimation of lake surface area and volume for different water depth

3.2 DATA QUALITY PROCESSING

3.2.1 Quality checks of measured depths

The automatic eco-sounder recorded water depths every second thus giving a huge number of depth readings. However, during the fieldwork survey, several problems were experienced relating to periods when relatively amplified waves or a higher boat cruising speed caused the eco-sounder to lift out of the water giving erroneous readings. During those particular periods, rapid checks of records at the visual interface were affected to provide control of depth measurements. These erroneous depth measurements had to be removed during data processing and visual plots of depth data along transects were constructed to effect depth variations checks to identify outlying data (**Figure 4**).

To facilitate plotting for spatial display, open source software **GPSU File Converter** was used to change recorded coordinates degree decimal minutes to decimal degrees and plot on the lake map.

3.2.2 Reducing measured depths to altitudes

The whole bathymetric survey was carried out in ~2 hours on a sunny day, providing confidence that there were minimal surface elevation variation. This is important as a key assumption is that the lake surface is a horizontal area. The lake surface was considered to be constant as at the stage reading on 10^{th} May 2014 at 11:04 AM using a lake datum altitude of 507.26m. All transect depths were subtracted from this altitude to estimate Dam bottom altitudes.

3.3 DATA INTERPOLATION

3.3.1 Establishment of Lake Shoreline

A recent (2014) Google Earth image was traced to provide the Dam surface shape. This shape was then converted to a polyline shape file for the most recent lake shape, which was then converted to a point's layer, the boundary layer. Since the lake water surface was assumed as horizontal, water depths at boundary layer points were assumed to be zero. This depth corresponds to an altitude of 507.26 m.

3.3.2 Interpolation of lake depths

These boundary points layer were then merged into the lake depth layer to obtain a new combined layer. A spatial interpolation by the Spline Method was used to interpolate the depth of the lake. This method was chosen because it produces data with acceptable results and smooth transitions between points. The resulting surface (**Figure 5**) indicates that lake depth ranges predominantly between 1m and 9 m.

3.3.3 Interpolation of lake bottom altitudes

Spline Method was similarly used to interpolate altitudes of the dam bottom resulting into a similar picture to depth with values representing elevation above mean sea level (**Figure 6**). Consequently, the deepest part of the lake in the south basin is at an altitude of 497.76 m.

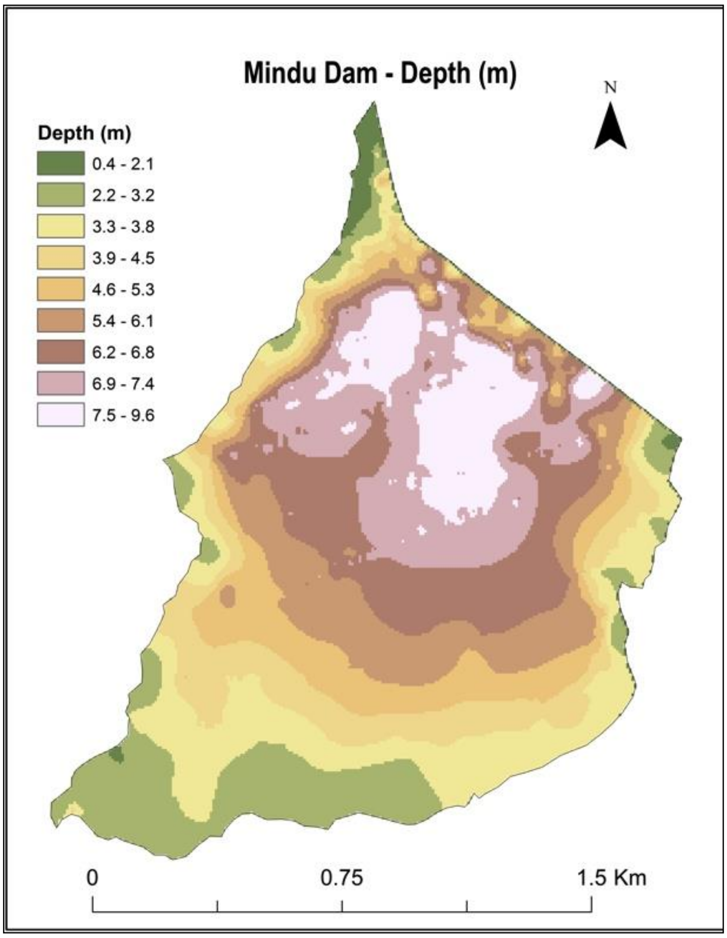

Figure 5. Depth variations of the Mindu Dam as of 10 May 2014 at 11:00 AM.

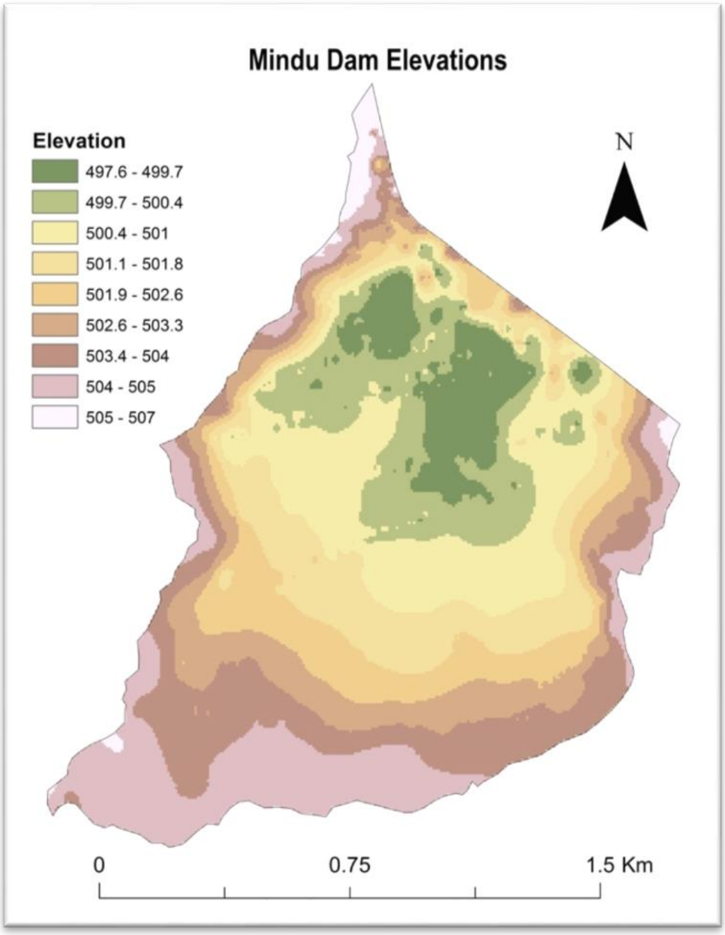

Figure 6. Mindu Bathymetry elevations as of 10th May 2014 at 11:00 am

3.3.4 Lake Elevation-Area-Volume Calculations

The next step, after establishing the Lake bathymetry, was to calculate the elevation area volume relationship. A GIS tool called Spatial Analyst was applied and data from Spline method were used in the calculations of the area and volume of the lake.

The Lake water depths were first converted into elevations (AMSL). The lowest (deepest) point (9.5m deep) had an elevation of 497.76 (AMSL) and the water level (zero depth). Then, using the GIS Spatial Analyst tool, firstly, under the raster creation function, a constant raster layer for different depths were created and followed by use of cut/fill function to calculate volume change between the created constant depths and the interpolated depths and altitudes. The interval of the calculations (from the lowest elevation to the highest) was 0.5m. The calculations started at the elevation of 490m AMSL where the corresponding area and volume were zero. At 497.76m AMSL, the lake started occupying some area and volume. At 507.26m AMSL (water level of the day of survey), the Mindu Dam surface area was 2,211,207m^2 and the volume was 11,407,511 m^3. **Appendix 1** has the details of the data used in the calculations.

Plotting of the three parameters in excel was a useful method in establishing the relationship for easy use by the managing authorities. Three plots were prepared, the first one (**figure 7**) is the relationship between elevation and the surface area of the lake. It was noted that, there is a very small increase in area of lake at elevation between 500.26 and 497.76 m AMSL because the deepest parts of the lake is not predominate. Also there was an abrupt increasing of area from elevation of 501.76 to 507.76m

AMSL. This is due to the fact that, the full reservoir height is 507 m AMSL and the lowest drawdown level is 501.1m AMSL.

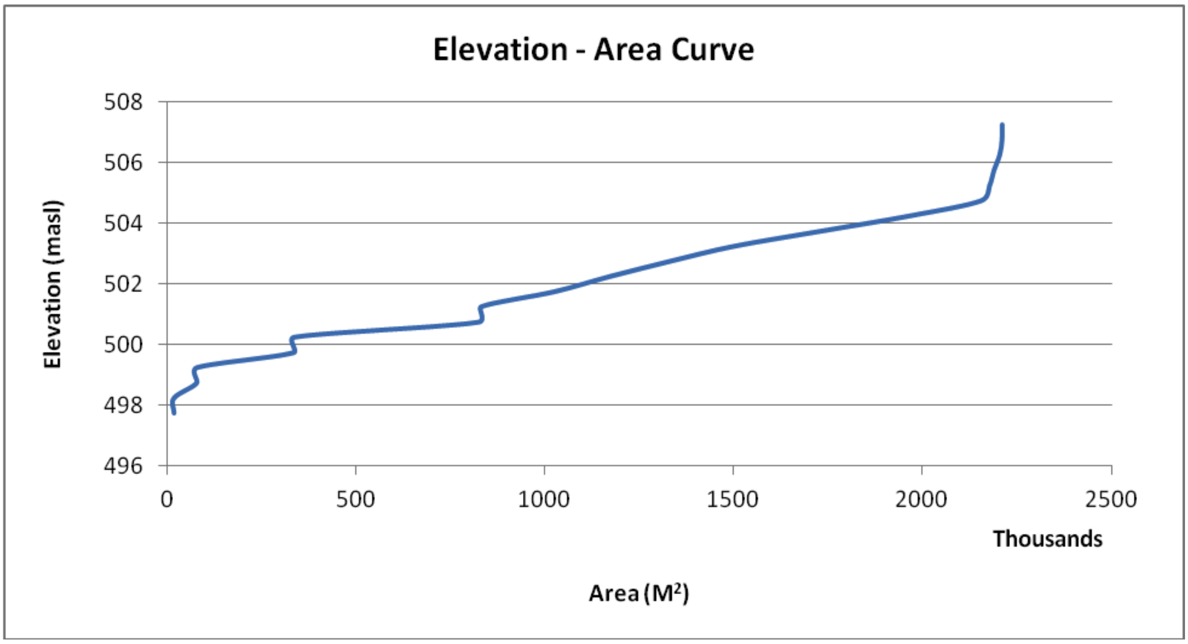

Figure 7. Relationship between Elevation and Area

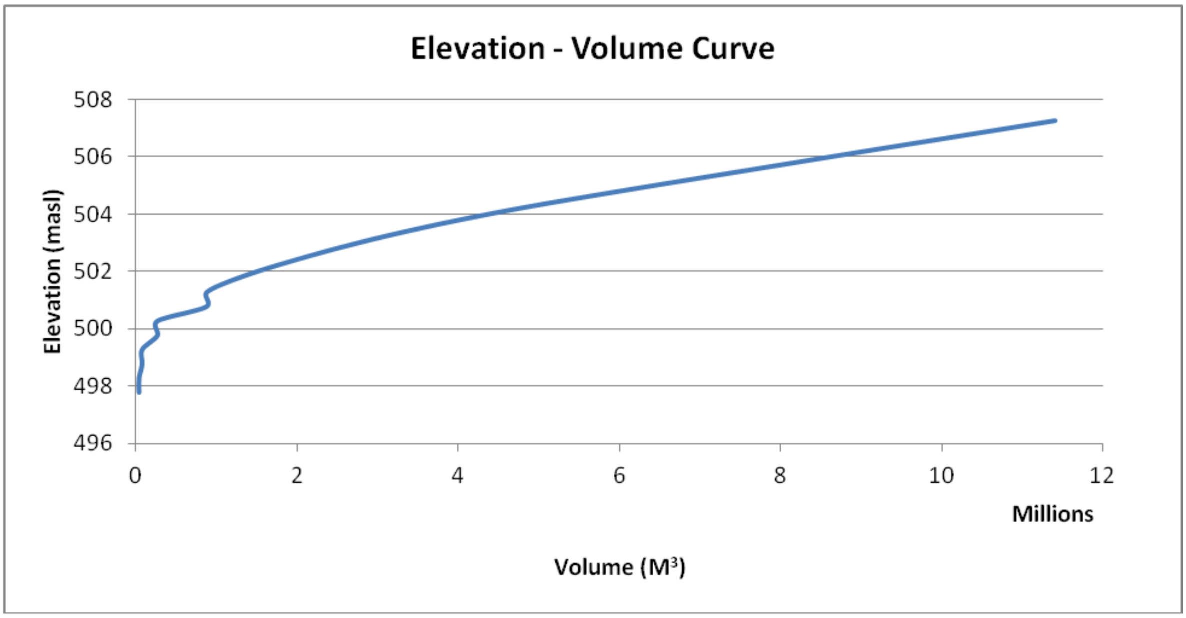

Figure 8. Relationship between Elevation and Volume

by The second plot is the relationship between elevation and volume of the lake. Figure 8 shows how the surface area of the lake responds to increase in the water level. However from the bottom elevation which is below 497.76 up to 1831.6 MAMSL the volume is zero. This is due to the fact that, there was a small depression whose volume was not significant to be detected GIS computation. The rest of data shows that, the volume of the lake increases as elevation increase due to increased surface area of the lake hence increasing lake storage capacity.

The third plotting (Figure 9) illustrates a relationship between elevation, area and volume of the lake. Generally the volume and area of the lake increases as elevation increase. This is due to increasing surface area and storage capacity of the lake from the bottom to the surface.

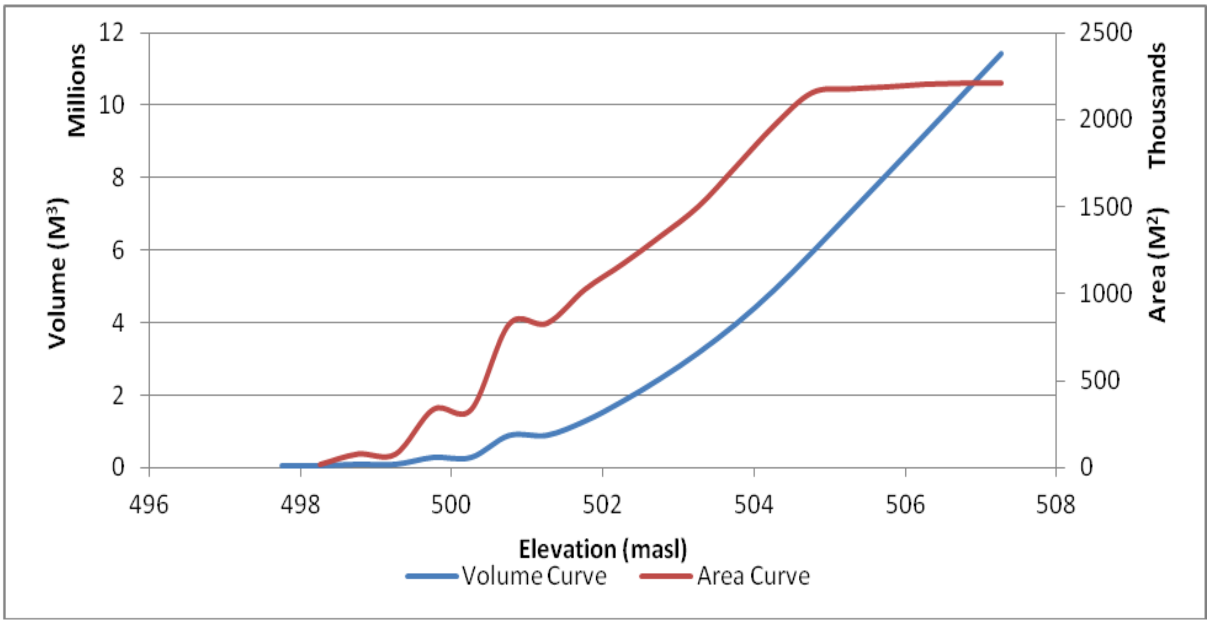

Figure 9. Relationship between Elevation - Volume - Area

The authorities that manage the Dam were unable to provide the Dam design information, such as the design capacity, the full reservoir height, or the allowable dead storage. Thus it has not been possible to assess how the Dam's effective storage capacity has been affected by sediment over years. However, Mr. Ernest Lema, a retired Principal Hydrological Technician, shared a 1979 report on the design of Mindu Dam and various reports on routine monitoring for Mindu Dam siltation.

According to the information available, the design plan was for the reservoir to impound 11 million cubic meters. A detailed survey of the reservoir area was carried out in December 1977. The survey was plotted at a scale of 1 in 5000 with contours at 1.0m vertical intervals. The reservoir characteristics shown in Table 1 were derived from that survey by planimetering at each contour level. The survey does not extend above level 507.0m. It is likely that this methodology, and lack of modern equipment for measuring elevation gave rise to an over estimate in the anticipated water surface area of the dam.

Table 1. Mindu Reservoir Characteristics – During design

Level (m) Altitude	Reservoir Volume (m3)	Surface Area (m2)	Live volume above design lowest drawdown level. (m3)
507	12,623,000	3,833,000	11,280,000
506	9,224,000	2,965,000	7,880,000
505	6,644,000	2,195,000	5,300,000
504	4,687,000	1,720,000	3,340,000
503	3,124,000	1,407,000	1,780,000
502	1,844,000	1,152,000	500,000
501	847,000	841,000	-
500	223,000	406,000	-
499	10,000	20,000	-

According to the design data it was estimated that, the Dam yield would be 57500m3/day, and expected to decrease to 43,000m3/day after 20 years, based on the assumption that the dam siltation would be 0.5%per annum. Once the dam was built, ongoing monitoring appeared to indicate a higher rate of siltation than originally estimated.

On the bathymetry survey date, the Dam was spilling and therefore at full capacity. The total volume computed was 11,407,511 m^3 and total area of 2,211,207m^2. When compared to the original design capacity of 12,623,000 m^3 over an area of 3,833,000 m^2, this would indicate that the decrease in the Dam's volume over 29 years (1985–2014) was 1,215,489m^3 (9.63%), but the reduction in area was 1,621,793m^2 (42.3%).

The reduction in the reservoir volume is in fact significantly less than anticipated in the design report, where a siltation rate of 0.5% per year over the first 20 years of operation was cited, and would have resulted in a 15.6% reduction in volume over the intervening 29-year period. Based on the design data the 'live volume' was the reservoir volume minus 1.344 million m^3, or the water below the elevation of ~502 meters. If the non-live volume remains similar to that of the design data, then the live volume has reduced from 11.28 million m^3 to 10.06 million m^3, which would be a reduction of ~10.8% in useable water reserves. The findings relating to the volume would suggest that the siltation has not been as severe as predicted, or indeed as the sediment monitoring findings suggested.

The apparent reduction in the reservoir area is more difficult to explain, as there little conclusive evidence of such a significant shrinkage. However, in a report dated 1994[3] the dam is described as being 1.5km wide and 3.5 km long, although it is not clear whether these dimension were measured/observed or taken from the original design documentation. The dam today is ~1.5km wide by ~2.4km long. Therefore it is possible that the original design, and perhaps the dam when first built, extended 1km further south/southwest. Although as the volume is not significantly reduced, is it possible that there was settling of the reservoir bottom resulting in greater volume storage over a lesser area? Or possibly the sediment carried into the reservoir has been deposited mainly in the shallows at the southern end causing the reduction in area, but less severe impact on the storage capacity? Or that the original design survey using planimetering at each contour level, was not sufficiently accurate in the fairly level areas around the southern end of the dam, resulting in large area expected to be under shallow water.

[3] Tanzania Urban Sector, Yield estimates for Tanga and Morogoro, August 1994 by Institute of Hydrology, UK

4. CONCLUSIONS AND RECCOMENDATIONS

4.1 CONCLUSIONS

Mindu Dam is a major water source used by the Morogoro Municipality for domestic, irrigation, industrial and recreation activities. The bathymetry study is a crucial exercise for understanding the volume and its fluctuations, in order to develop a proper management plan to ensure sustainable utilization of these water resources.

The study has determined the depth of the lake and established a relationship of bottom elevation, volume and area. It is now possible to understand volume and area of the lake by using a specific water level. Also, it has been established that, assuming the initial design volume was correct, there has been ~9.6% of the reservoir volume, and ~10.8% reduction of the reservoir's effective or live water storage. Whilst this maybe less than anticipated, given the growing population of Morogoro and hence growing demand for secure water supplies, it is still a cause for concern.

4.2 RECOMMENDATIONS

Based on the evidence relating to silting up of the Dam, and reduction of its storage capacity, coupled with the increasing demand; the study recommends the following interventions:-

1. Further information collection, including more detailed bathymetric surveys to get a clearer picture of the reservoir's carrying capacity, monitoring over a period of time to establishing the rate of siltation
2. Use of sedimentation fingerprinting to track and monitor sediment sources to identify the main contributors, and regular water quality monitoring on the inflowing rivers
3. Based on the findings from 1 and 2 above, to plan appropriate interventions to protect critical buffer zones of contributing streams, targeted improvements in land management and farming practices, and catchment afforestation
4. Assessment of more specific management actions, such as dredging, and/or completion of the Phase II to raise the dam and increase the storage volume

REFERENCES

1. Morogoro Water Supply Contract No. 1. The Mindu Dam – Report on Design Aspects January 1979 by Consulting Engineers Sir Alexander Gibb and Partners Ltd
2. Tanzania Urban Sector, Yield estimates for Tanga and Morogoro, August 1994 by Institute of Hydrology, UK
3. Midyear reports on erosion and sediment in Morogoro River Valley and Mindu Dam

APPENDICES

APPENDIX 1. Mindu Reservoir Characteristics as of 10th May 2014

Depth Sounder Reading	Level (m)	Reservoir Volume (m^3)	Surface Area (m^2)	Area (km^2)
0	507.26	11,407,510.8	2,211,207.3	2.21
0.5	506.76	10,301,944.1	2,210,688.7	2.21
1	506.26	9,197,693.7	2,204,350.1	2.20
1.5	505.76	8,100,700.3	2,189,310.2	2.19
2	505.26	7,008,544.7	2,177,958.3	2.18
2.5	504.76	5,923,978.0	2,156,003.5	2.16
3	504.26	4,885,380.0	1,967,515.3	1.97
3.5	503.76	3,958,734.1	1,734,195.5	1.73
4	503.26	3,153,131.0	1,503,065.5	1.50
4.5	502.76	2,444,143.7	1,332,037.3	1.33
5	502.26	1,816,829.2	1,172,476.4	1.17
5.5	501.76	1,267,133.7	1,026,341.8	1.03
6	501.26	878,803.4	832,069.3	0.83
6.5	500.76	873,947.4	827,538.9	0.83
7.5	499.76	267,559.4	338,137.9	0.34
8.5	498.76	77,898.8	81,077.3	0.08
9.5	497.76	39,648.1	20,629.4	0.02