EFFECTS OF SEDIMENTATION ON RESERVOIRS IN THE MUSHIBEMBA CATCHMENT, MKUSHI FARM BLOCK, CENTRAL ZAMBIA

by

Goodfellow Mphande

Thesis submitted to the University of Zambia in fulfilment for the award of the Master of Science in Integrated Water Resources Management

UNIVERSITY OF ZAMBIA

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DECLARATION

I, **Goodfellow Mphande,** hereby do declare that all the work done in this study originates from my own work and it has not previously been submitted for a degree or other qualification at this or another University. All secondary sources referred to in this work have been duly acknowledged. Therefore, this thesis is submitted in fulfilment of the award of the degree of Master of Science in Integrated Water Resources Management (IWRM) of The University of Zambia.

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APPROVAL

This thesis of **Goodfellow Mphande** has been approved as fulfilling the requirements for the award of the Master of Science Degree in Integrated Water Resources Management (IWRM) by the University of Zambia.

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ABSTRACT

Sedimentation is one of the problems that affects the storage capacity of most small reservoirs, and if not addressed on time, may lead to the dams being filled up with sediment and failing to meet the intended objective of providing agricultural water for food and economic security. The aim of this study was to assess the effects of sedimentation on the storage capacity losses of Moffat dam and GRZ weir located in the Mushibemba catchment of the Mkushi Farm Block in Central Province, Zambia. The Mushibemba catchment has the highest number of reservoirs that were constructed to meet increased irrigation water demands. However, there is lack of application of the knowledge on appropriate techniques of assessing sedimentation rates on reservoirs in the catchment. Understanding the nature of sedimentation in the Mushibemba river catchment is useful for mitigating against the reservoirs being filled up with sediment. The specific objectives of this study were to (i) determine the storage capacities of two reservoirs; (ii) estimate suspended sediment transport into the streams draining reservoirs and; (iii) determine the rates of sedimentation on the Mushibemba reservoirs. Bathymetric survey using hydrographic boat mounted with a differential GPS was used to collect reservoir depths, water surface elevation and reservoir perimeter. For water quality assessment, water samples were collected at the intake of each reservoir and analysed for concentration of total suspended and total dissolved solids.

The results of the study revealed that the measured volumes of Moffat dam and GRZ weir were 1,180,462 m^3 and 197,218 m^3, respectively. The measured reservoir capacity values were then compared with the originally calculated designed capacity values to determine changes in storage capacity over the years. The storage capacity losses for Moffat reservoir was found to be 223,789 m^3 (16 percent) whereas that of the GRZ Weir was 53,312m^3 (21.3 percent). The estimated rate of sedimentation loss for Moffat reservoir was found to be 13,986.81 m^3 yr^{-1} with a lifespan of 84 years while that of GRZ weir was 1,480.89 m^3 yr^{-1} with a lifespan of 133 years. The sediment concentration inflows inflow into the Moffat reservoir and GRZ weir were in the same low order of magnitude, 0.6 mg/l and 0.4 mg/l respectively. The source of the suspended sediment was mainly attributed to the cleared commercial agricultural land which predominantly consists of clayey to loamy soils in the vegetated catchments. This also accounted for the high turbidity of the reservoir water. It is concluded that sedimentation in the catchment is fairly low but serious given reservoir capacity losses observed due to agricultural activities despite having a good vegetation cover. Soil conservation measures are needed to avoid degradation of the catchment in future.

Keywords: Sedimentation, Bathymetry survey, Reservoir storage capacity, Suspended sediment, Central Zambia

DEDICATION

Dedicated to the rural people of Northern Zambia whom I worked with passionately for over 10 years in managing and developing the water resources in order to realise socio-economic benefits.

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ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
CSO	Central Statistical Office
DGPS	Differential Global Positioning Satellite
DWRD	Department of Water Resources Development
ECM	Elevation Change Method
GRZ	Government of the Republic of Zambia
IWRM	Integrated Water Resources Management
LE	Life Expectancy
MoA	Ministry of Agriculture
MLNR	Ministry of Land and Natural Resources
MWDSEP	Ministry of Water Development Sanitation and Environmental Protection
RSC	Reservoir Storage Capacity
SR	Sedimentation Rate
SST	Suspended Sediment Transport
SV	Sediment Volume
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UNZA	University of Zambia
USGS	United States Geological Survey
WARMA	Water Resources Management Authority
ZNFU	Zambia National Farmers Union

CHAPTER 1: INTRODUCTION

1.1 Background

One of Zambia's commercial farming challenges in the past two decades was her vulnerability and constraints related to water availability and accessibility. Although water demand from different economic sectors had increased due to rapid economic growth, water supply was limited by hydrological variability worsened by floods and droughts, seasonal water shortage, and lack of infrastructure, placing serious constraints on economic development (COWI, 2016).Therefore, in order to increase water availability and accessibility, commercial farmers in the Mushibemba catchment of Mkushi Farm Block in Central Province invested huge sums of money in the construction of new dams for irrigation purposes. The construction of dams was aimed at increasing domestic water access, and providing economic opportunities for irrigated agriculture, livestock, fish-farming, and other water-dependent economic activities. Farming in the Mushibemba catchment is mechanised and mainly practised on a very large scale. However, the construction of dams involved extensive alteration of the river system through diversions and impoundments (Mehta *et al*, 2012). Not much consideration was paid to the effects of sedimentation on the reservoir storage capacity.

In a study conducted by Chao (2004), it was observed that sedimentation problems are a matter of global concern as they include issues arising from erosion, desertification, sediment yield, transport and deposition in reservoirs and lakes.

Sedimentation has been defined by Martinko *et al.* (2006) as particulate matter that can be transported by fluid flow and is eventually deposited as a layer of solid particles on the bed or bottom of a water body such as a reservoir. Johnson and Lewis (1995) argue that in many developing countries, sustainable land management and water resources management are threatened by soil erosion and sediment-related problems. Sedimentation is one of the problems that affects the storage capacity of most small reservoirs and if not addressed on time, it could lead to the reservoirs being filled up with sediment and failing to meet the intended objectives of providing agricultural water for food and economic security. Chao (2004), observed that about one (1) percent of the storage capacity of the world's reservoirs is annually lost due to river-related sedimentation with more floods and droughts induced and leading to deteriorated ecosystems. The progressive loss of water-storage capacity resulting from sedimentation in reservoirs, coupled with increasing societal water demand, negatively affect environmental, social and economic benefits of small dams (Chomba and Sichingabula, 2015). If sedimentation increase is ignored, it results in the reservoir being completely filled up thereby defeating the purpose for which it was constructed. Therefore, assessment and prevention of sedimentation impacts in reservoirs is very important for the sustainable management and operations of the reservoirs. The Mushibemba river catchment of the Mkushi Farm Block has the highest number of reservoirs that were constructed in the last two decades due to increased irrigation water demand. According to the Water Resources Management Authority (WARMA, 2016), Mushibemba catchment has a total of 58 reservoirs. The storage capacities of these reservoirs were estimated by a private consultant, Imagen Consulting who were engaged in the year 2015 by the farmers in the catchment to assess the available water resources against irrigation water demands (Imagen Consulting, 2016). The researcher did not come across any reservoir sedimentation assessments in Central Province despite an extensive literature search.

1.2 Statement of the Study problem

Reservoirs in the Mushibemba catchment have never had detailed bathymetric surveys to determine their storage capacities. The only attempts made were those done by Imagen Consulting (2016) who used reconnaissance RADAR remote sensing to estimate the capacities of most reservoirs in the catchment. Unfortunately, the method used could not be relied upon in terms of appropriateness and accuracy because it only focused on estimating reservoir storage capacity by remote sensing without carrying out actual field measurements to determine reservoir sedimentation. The advantage of bathymetry survey method over RADAR remote sensing is that it can illustrate the spatial distribution of accumulated sediments within the reservoir (Zarris *et al*, 2002). Consequently, the need to employ bathymetric surveys with appropriate modern equipment to accurately determine reservoir storage capacities. The only known appropriate assessments that were conducted in Zambia to measure the effects of sedimentation on reservoir storage capacity were those done on small dams in Lusaka province by Chomba and Sichingabula (2015) while Sichingabula (1997) using regression approach reported that many dams had lost considerable storage capacity due to sedimentation.

In order to increase water availability and accessibility, commercial farmers in Mushibemba catchment invested huge sums of money in the construction of new reservoirs for irrigation purposes. Increase in storage capacity of reservoirs was significant in the expansion of economic opportunities for irrigated agriculture, livestock, fish-farming, and other water-dependent economic activities. However, the construction of dams involved extensive alteration of the river system thereby leading to an increase in soil erosion and consequently, the production and transportation of sediment into reservoirs. According to Brandan *et al.* (2006), reservoir sedimentation is a big problem as it affects the water storage capacity if adequate sediment management policies are not available and applied. This called for detailed investigation on the effects of sedimentation in Mushibemba catchment. It was on this basis that this study was embarked upon.

1.3 Aim

The aim of this study was to examine effects of sedimentation on reservoir storage capacity in the Mushibemba river catchment of the Mkushi Farm Block.

1.4 Specific Objectives

The specific objectives of the study were as follows:

i. To determine the storage capacity of two reservoirs in the Mushibemba catchment
ii. To estimate suspended sediment transport of the streams draining reservoirs in the Mushibemba catchment
iii. To determine rates of sedimentation on two Mushibemba reservoirs

1.5 Research Questions

To adequately address the aim and specific objectives of the study, the following research questions were formulated:

i. What is the current reservoir storage capacity of each of the two Mushibemba reservoirs?

ii. What is the rate of suspended sediment transport of the streams draining reservoirs in the Mushibemba catchment?

iii. What are the rates of sedimentation on the reservoirs of Mushibemba catchment?

1.6 Justification of the study

The application of the bathymetric surveys will improve the estimation of loss of storage capacity in reservoirs in the Mushibemba catchment. This study also enhances understanding of sedimentation problems in the reservoirs of central Zambia. Chomba and Sichingabula (2015) assert that many dams constructed in Zambia in the 1950s and 1960s are silted up and need to be dredged. Therefore, to determine the useful lifetime of a reservoir, it is essential to periodically assess the sedimentation rate in a reservoir. The findings of this study will further help WARMA to regularly assess the levels of sedimentation in reservoirs and ensure that water permit holders pay for the correct amount of water abstracted and stored in reservoirs. In addition, the study will provide invaluable information which may be used in the formulation of sustainable sediment monitoring and management system for dams in Zambia. One of the key achievements of this research study is that, it will provide knowledge to the reservoir owners on the advanced techniques of assessing sedimentation rate on reservoirs in the Mushibemba catchment.

1.7. Limitation of the Study

There was lack of baseline data on reservoir sedimentation in the Mushibemba catchment. As such, a study of this nature was being conducted for the first time in the Mkushi Farm Block. Similarly, there was no baseline data on bathymetry surveys that had been conducted using the hydrographic boat with high accuracy and efficiency in terms of time. Therefore, the lack of adequate baseline data on the reservoirs was a problem in estimating deposited sediment. Selection of study reservoirs was limited to two reservoirs that had design information on their storage capacities.

There were three other reservoirs that had adequate information on the design storage capacities, however, they could not be selected for bathymetry surveys because they were too big for the size of small reservoirs in the district. The choice of study reservoirs was further limited by the presence of many dead tree stumps in some reservoirs thereby posing a danger to the free navigation of the hydrographic survey boat. The only option on the sites with tree stamps was to conduct physical measurements of the reservoir depths and simultaneously record geographic location of each point, this exercise would have taken many months to complete. However, the above stated challenges did not affect the scope of the study because the two reservoirs selected for the bathymetry surveys were successfully surveyed.

1.8 Organisation of the Thesis

This thesis is composed of six chapters. Chapter One consists of the background, problem statement, the aim, specific objectives, research questions and significance of the study. The second Chapter covers the literature review. Chapter Three provides a detailed geographical description of the study area, Mushibemba catchment. Chapter Four presents the methodology in terms of data collection and analysis, and ends with limitations of the study. The study findings and discussion of results are outlined in Chapter Five. Finally, Chapter Six presents the conclusion and recommendations. The thesis ends with References and Appendices.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature on effects of reservoir sedimentation in Zambia and elsewhere. The main focus is on the effect of sedimentation of reservoirs in general and how suspended sediment transport affects the reservoir storage capacity.

The term "sedimentation" can simply be defined as the settling of a suspended material due to gravity (Sahu, 1990). Martinko *et al.* (2006) define sedimentation as particulate matter that can be transported by fluid flow and eventually is deposited as a layer of solid particles on the bed or bottom of a water body such as a reservoir. The process by which sediment settles in reservoirs is essentially the same as the sedimentation process that occurs in any body of fluid. As water enters the reservoir the velocity decreases, turbulence is dampened and particles or aggregates begin to settle out (Sahu, 1990).

A dam is defined as any structure capable of diverting or holding back water (PEM Consult, 1999). Dams are classified based on either height or reservoir storage capacity. The International Committee on Large dams (ICOLD, 2011) has defined small dams as reservoirs with a height of more than 2.5 metres above the river bed to maximum crest level and not above 15 metres with a storage capacity of less than 3 million m^3. This research study focused on two small dams.

2.2 Causes of Reservoir Sedimentation

Reservoir sedimentation is basically a process that has been going on since the first dams were build and is a consequence of creating a calm reservoir lake where there used to be a fast flowing river (Bronsvoot, 2013). When sediment laden water flows into a reservoir, the coarser particles begin to deposit the upper reach of the reservoir due to decrease in flow velocity. Subsequently, the first material are deposited further into and along the reservoir bed (Mehta *et al*, 2012). Suspended sediment transported by a river eventually starts to influence the reservoir capacity and the river morphology. Sedimentation of the reservoir is therefore a natural process and a universal problem. Halcrow (2001) stated that river erosion is the most uncertain of the sediment sources in terms of river budget modeling. Furthermore, Halcrow (2001) points out that, degradation of riparian vegetation and other impacts on the rivers have resulted in increased rates of riverbank erosion, to the extent that this erosion process cannot be ignored as a sediment source in regional assessment.

Ainstworth (2005) asserts that, sediment is produced by the erosion of the land surface and subsequently transported downstream by rivers and eventually deposited in reservoirs. Furthermore, Ainstworth (2005) points out that, the rate of erosion depends on complex interaction of the following processes:

- Climate: Precipitation and runoff, temperature, wind speed and direction;
- Geotechnics: Geology, volcanic, tectonic activity soils;
- Topography: Slope, Catchment orientation, drainage basin area, drainage density;
- Vegetation cover: Land use and human impact.

Queensland Government (2006) observed that, over clearing of catchments and stream bank vegetation, poorly managed sand and gravel extraction and stream straightening works significantly contributed to soil erosion and consequently led to reservoir sedimentation. Sediment delivered to reservoirs originates from a number of upstream primary and secondary sediment sources, including cultivated fields and stream bank erosion (Collins *et al.*, 1997). However, it is important to note that, though erosion is a natural process, it is speeded up by human activities.

To determine the useful lifespan of a reservoir, it is essential to periodically assess the sedimentation rate in a reservoir. Human actions can considerably hasten the natural process and increase the rate of sedimentation. Mehta *et al.* (2012) identified major detrimental effects of sediment deposit in reservoirs as being loss of storage capacity; damage or impairment of hydro-equipment; bank erosion and instabilities; upstream aggradation; effect on water quality; and effect on eutrophication

Chao (2004) study findings showed that about one percent of the precious storage capacity of the world's reservoirs is annually lost due to river-related sedimentation with more floods and droughts induced and leading to deteriorated ecosystems. Halcrow (2001), states that, in many cases the rates of sedimentation calculated are dependent upon the accuracy not only of a recent survey but also of the original survey at the time of dam construction and on comparability of the two surveys.

Suspended sediment transported by rivers has fundamental environmental and economic consequences. An excess of sediment leads, for instance, to an increase in water turbidity, eutrophication, alteration of river habitats and reservoir siltation (Packman and Mackay, 2003). The suspended load comprises all the particles with a diameter smaller than 2mm (i.e. sand-sized or less). The finer particle fraction transports a significant part of biogeochemical fluxes conveyed by rivers, and its transfer needs to be better understood (Packman and Mackay, 2003). By transporting the nutrients required by all the living organisms, fine sediment plays an essential role in the productivity of riverine, estuarine and marine ecosystems (Collins *et al.*, 2005).

The impoundment of water behind a dam causes the velocity of the water to drop. Sediment carried by the river is dropped in the still water at the head of the dam (Fradkin, 1996). Below the dam, the river water flows from the clear water directly behind the dam. Because the river no longer carries any sediment, the erosive potential of the river is increased. Erosion of the channel and banks of the river below the dam will ensue. Even further downstream, sediment deprivation affects river bank processes and biological productivity. Fradkin (1996) gives an illustration of the problem that occurred within the Grand Canyon below Glen Canyon dam after its construction was completed in 1963, erosion of the sediment along the beaches began because of the lack of incoming sediment. By the early 1990's, many beaches were in danger of disappearing. In the spring of 1996, an experimental controlled flood of the river below Glen Canyon Dam was undertaken to attempt to redistribute existing sediments along the sides of the channel. While many of the beaches were temporarily rebuilt, this redistribution of sediments was short lived. Research on this issue is continuing, however, the fundamental problem of the lack of input sediment for the river downstream of the dam remains unresolved.

Dam constructions and river diversions have proven to be primary destroyers of aquatic habitat, contributing substantially to the destruction of fisheries, the extinction of species, and the overall loss of the ecosystem services on which the human economy depends (Postel, 1998). Their social and economic costs have also risen markedly over the past two decades (Postel, 1998). The environmental changes described above create a new environment in which native species may or may not be able to survive. New species frequently invade such localities, further disrupting the system. Early photographs of rivers in the southwest desert illustrate the dramatic modern invasion of non-native plants (Reisner, 1993). Entire lengths of these rivers and streams have been transformed from native desert plants to a dense riparian environment. Native species that formerly lived in this zone have been replaced as a result of the changes in river flow patterns (Reisner, 1993).

2.3 Methods for assessment of sedimentation in reservoirs

A large number of approaches and models are available for estimation of reservoir sedimentation. However, approaches and models differ greatly in terms of their complexity, inputs and other requirements (Yang and Lu, 2014). Pawal *et al*. (2015) suggests the following methods: conventional bathymetric survey; inflow-outflow method; remote sensing method; empirical methods comprising of area reduction method and mathematical models.

According to Pawal *et al*. (2015) the empirical method and mathematical models are the methods for prediction of reservoir sedimentation and are normally used during planning stage, whereas, the remaining three methods (bathymetric survey, inflow-outflow and remote sensing) are used for monitoring of sedimentation during operation stage. According to Yang and Lu (2014), they argue that in simple ways at a small scale, the fraction of sediment deposited in an individual reservoir can be determined through the knowledge of its trap efficiency, but this method is usually confined to individuals or to a small scale. In a more sophisticated way, reservoir sedimentation in a multi-reservoir system can be estimated through basin trap efficiency (Vorosmarty et al, 2003) or

Geographical Information system (GIS) models on the basis of land use and hydrological data at a large scale. However, the application of existing reservoir sedimentation models at a large scale are limited by two important factors: the effect of upstream traps and excessive dependence on hydrological data (Yang and Lu, 2014).The construction of upstream reservoirs significantly reduces sediment yield to downstream reservoirs with perennial river inflows. Yang and Lu (2014) furthermore point out that, reliable hydrological records accompanying reservoir construction history are important to predict sediment trapped in reservoirs. However, this information is usually not available at reservoirs of interest. In instances where there has been consistent collection of reservoir sediment data, it is possible to develop and use a model based on basin scale trapping efficiency to predict decreased sediment load at the catchment outlet. Sometimes, the amount of reservoir sedimentation is not directly equivalent to the reduction in sediment load at its outlet and the interaction of different drivers (Walling, 2006). Therefore, to develop a model to estimate reservoir sedimentation in a catchment, there is need for consistent recording of annual water discharge and sediment load. Collins and Walling (2004) noted that information on sedimentation is an important data requirement for restructuring historical catchment erosion pattern and assist in the interpretation of sediment load in small reservoirs.

2.4 Methods of Estimating Dam Capacities

Estimating of the storage capacity of existing reservoirs is very important in order to understand their rate of sedimentation. There are several approaches used to determine and estimate storage capacities of dams. Sawunyama (2005), identifies direct and indirect methods of estimating reservoir capacities. The direct method basically involve hydrographic surveys and quick survey methods whereas, the indirect method involve the use of topographic maps and satellite images to calculate the reservoir storage capacity. An example of a direct method of estimating the rate of reservoir sedimentation was the study done on two reservoirs by Aynekulu *et al* (2006) in Ethiopia. The study was done after two years of construction of the two reservoirs and during the time when both reservoirs were dry. Estimation of sediment deposits was done by digging pits in the form of grids to measure the thickness of the sediment deposits and the entire reservoir was surveyed using a theodolite (Aynekulu *et al*, 2006). Finally, a contour map was developed using the sediment depth pits and calculation of area was done with the use of a digital coordinator (planimeter). The volume of sediment was computed by multiplying depth of pits by the area while sediment deposition and average silt density were analysed in the laboratory. A number of these methods are outlined below.

2.4.1 Hydrographic survey

Hydrographic survey is basically the survey of physical features present underwater. Furnans and Barney (2007) define Hydrographic survey as the science of measuring all factors beneath water that affect all the marine activities like dredging, marine constructions and offshore drilling. According to Zarris *et al.* (2002), the hydrographic survey of a reservoir is a very satisfactory procedure for reconstructing sediment yield records of a drainage basin. This survey method basically involves mapping of the reservoir topography underneath. The strongest merit of this method is that it can illustrate the spatial distribution of accumulated sediments within the reservoir. However, its weakness lies in the fact that it can only give one year average of the sediment yield but not its temporal evolution (Zarris *et al.* 2002). It is therefore very important to conduct repeated hydrographic surveys of reservoirs, for example every five years so that sediment yields can be computed in finer scales.

2.4.2 DGPS Bathymetric Survey

Bathymetry is the foundation of the science of hydrography, which measures the physical features of a water body (Ajith, 2016). Bathymetric survey is a direct method for the assessment of sedimentation distribution and its bed profile in the reservoir of dams (Ajith, 2016). This method is mainly used to estimate the capacity of reservoir and the amount of sedimentation. The bathymetric approach is based on a simple comparison of reservoirs morphology at two different time periods, first at the time of the construction of the reservoir and second, at the time of the survey, which should be at least ten years later to detect significant changes (United States Army Corp of Engineers (USACE), 2015). Present day bathymetric surveys are conducted with modern hi-tech survey systems consisting of Differential Global Positioning System (DGPS) and depth measuring units such as echo sounders. The use of DGPS based bathymetric survey is much faster, more accurate and requires lesser time than the conventional hydrographic survey (U.S. Geological Survey, 2016).

Bathymetric survey approach provides reservoir sedimentation details and much needed information such as reservoir depth, capacity and bottom topography with great accuracy to optimize reservoir operations. This method is mainly used to estimate the capacity of reservoir and consequently, the amount of sedimentation over time (Curtarelli *et al.*, 2015). It is important to note that bathymetry surveys can be done by both DGPS and

Acoustic Doppler Current Profiler (ADCP). However, DGPS based bathymetric survey has advantages over ADCP because all target points are measured without difficulties. In the case of the ADCP, reservoir bottom vegetation greatly interferes with normal operations, thereby making it impossible to record correct water depths (U.S. Geological Survey, 2016). In addition, the bottom layer motion greatly affects the measurements recorded by the ADCP. The DGPS has improved location accuracy than the ADCP. The DGPS uses fixed known portions to adjust real time GPS signals to eliminate pseudo range errors, thereby improving on the accuracy of position data. The ADCP is very ideal in measuring river discharge.

To calculate reservoir volumes, this study used Coden hydrographic survey remote controlled boat RC-S2 equipped with a Differential Global Positioning System (DGPS) and a digital eco-sounder (Appendix 1). The XYZ data collected from bathymetry surveys was analysed using Surfer 15 software.

2.5. Calculating Reservoir Volume using Surfer 15

Surfer is a very ample informatics product of Golden Software specialised in computer graphics. It is a full-function 3D visualisation, contouring and surface modeling package that runs under Microsoft Windows. Surfer is used extensively for terrain modeling, bathymetric modeling, landscape visualisation, surface analysis, contour mapping, watershed and 3D surface mapping, gridding and volumetric calculations (Ajith, 2016). Surfer is also used in image geo-referencing, digitising the scanned image and exporting into various file formats (Golden Software, 2017). Surfer's sophisticated interpolation engine transforms XYZ data into publication of good quality maps. Furthermore, Surfer provides more gridding methods and more control over gridding parameters, including customised variograms, than any other software package on the market (Ajith, 2016). Surfer also uses grid files obtained from other sources, such as USGS DEM files or ESRI grid files. It displays grids as outstanding contour, 3D wireframe, watershed, vector, image, shaded relief, and post maps. To create the most informative display possible, it is advisable to add base maps and combine map types. Virtually all aspects of a maps can be customized to produce exactly the presentation that is needed. Generating publication quality maps has never been quicker or easier.

The most advanced and latest Golden software product is called Surfer 15 and is very ideal for calculating reservoir volumes. When calculating the volume or surface area inside a polygon in Surfer 15, all you need are the grid file and a polygon (either drawn in a base layer, or in a vector file format (Golden Software, 2017). The following are the steps to use provided by Golder Software (2017): First, grid the data over the entire rectangular bounding box. You can choose to create a map from the grid file, if desired; Define the polygon for the area(s) you want to calculate the volume within. You can either:

- Add an empty base layer to the map, edit the base layer, draw the polygon(s) you want, and stop editing the base layer or
- Obtain a vector file of the polygon in a BLN format. You can choose to add this to the map as a base layer, if desired.
- Create a vector file containing the polygon.

To calculate the reservoir volume, click on **Grids | Calculate | Volume**. In the Grid Volume dialogue, the following are the steps to take: In the *Upper Surface* section, choose a grid-based map from the dropdown list, or click *Browse* to navigate to and select your grid file; Since volume is calculated between two surfaces, in the *Lower Surface* section, either choose a different map layer or browse to a grid file for the lower surface, or set a constant Z value.; If your z units are not the same as your x and y units, enter the appropriate *Z Scale Factor* to convert from the z units to the x and y units; In the *Polygon Boundary* section, choose a base map containing your polygon from the dropdown list, or click *Browse* to navigate to and select your vector file; Toggle *Volume Inside*, and choose whether to calculate for all polygons on the map layer or just the selected polygon(s). Click *OK* and a **Grid Volume Computations** report is generated (Golden software, 2017).

2.6 Sediment Volume Calculation

Sediment Volume in a reservoir is calculated by subtracting the current reservoir storage capacity value from the originally calculated designed capacity values (Adwubi *et.al*. (2009). The changes in the storage capacity of the reservoir are attributed to the accumulation of sediment over the years.

In order to have a better understanding of the Sediment Volume computed using bathymetric data in Surfer 15, the Elevation Change Method (ECM) of differencing bed elevation at construction is helpful. The first step involves collecting Surface water elevation and downstream elevation of each reservoir. The elevation data is useful in determining maximum depth near the reservoir crest. The study made use of the formula devised by Muchanga (2017) adapted from Sawunyama (2005) study. The method has proved useful in the quick analysis of sedimentation volume in the reservoirs.

$$SV = A\left[\frac{(W_e - D_{se}) - M_{wd})}{3}\right]$$

SV	Sediment Volume (m^3)	M_{wd}	Maximum Water Depth near the Crest (m)
W_e	Water Surface Elevation (m)	3	Constant
D_{se}	Downstream Elevation (m)	A	Total Surface Area of the bed (m^2)

It is important to note that the constants differ for the equation because of different study areas and climatic conditions and methods used to estimate surface areas, that is, from topographical maps and/or field survey (Sawunyama, 2005).

2.7. Remote Sensing

Remote Sensing is basically a method of obtaining information about an object or area without coming in direct contact with it. According to Campbell (1996) Remote Sensing imagery is acquired with a sensor such as electronic scanning, using radiations outside the normal visual range of the film and camera-microwave, radar, thermal, infra-red, ultraviolet, as well as multispectral. Special techniques are applied to process and interpret remote sensing imagery for the purpose of producing conventional maps, thematic maps and resource surveys. The advantage of using Remote Sensing is that the approach is cost effective, time saving and requires less manpower. This method does not require field work and normally more reservoirs are covered in a single scene.

In this study, multi-date satellite images were used to understand land use of the reservoir catchments before and after construction. Remote sensing based reservoir sediment assessment surveys are essentially based on mapping of water-spread areas at the time of satellite over pass (Kalvit and Kulkarni, 2010). It uses the fact that water-spread area of the reservoir reduces with the sedimentation at different levels. The water-spread area and the elevation information are used to calculate the volume of water stored between different levels (Kalvit and Kulkarni, 2010). These capacity values are then compared with the previously calculated capacity values to find out change in capacity between different levels.

In a similar study carried out in Italy by Brandan *et al*, (2006) QuickBird an earth observation satellite which collects image data to 0.65m pixel resolution degree of detail was used to evaluate the bathymetry of La Penna reservoir. The results of this study which assessed the depth of penetration zone showed that the method is well established for bathymetric mapping in shallow coastal waters (Brandan *et al*, 2006). This method seemed to be able to assess the spatial extension of the deposited sediment in a reservoir. Remote sensed data is processed using GIS. GIS is basically a computer based information system which attaches a variety of qualities and characteristics to geographical location and helps in planning and decision making (Campbell, 1996). Therefore, the use of Remote Sensing and GIS are integral to each other in the assessment of sedimentation effects in reservoirs. Remote Sensing has the capability of frequently providing large amount of data of the river catchment, whereas GIS has the abilities of analysing a large amount of data within no time.

2.8. Summary of Literature Review

The review of literature has revealed that not too many studies have been conducted on reservoir sedimentation in Zambia as compared to other countries in Africa. In Zambia, the recent and notable studies on reservoir sedimentation were those conducted by Chomba and Sichingabula (2015) on four small dams in Lusaka Province and by

Muchanga (2017) in Southern province of Zambia. This study was therefore conducted in order to bring out more information on the effects of sedimentation in a highly impacted river system in Zambia. The study area is unique in that it has the biggest number of reservoirs that are used for commercial farming. The consulted literature has also revealed that hi-tech equipment and methods are now being used in assessing reservoir sedimentation.

CHAPTER 3: DESCRIPTION OF THE STUDY AREA

3.1 Location

This research project was undertaken in the Mushibemba river catchment, a sub-catchment of the Lunsemfwa river located in the Mkushi Farm Block of Mkushi district in Central Province of Zambia (Figure 3.1). The Lunsemfwa river catchment is itself a sub-catchment of the Luangwa a tributary of the Zambezi river system. Mkushi district is situated about 293 kilometers away from Lusaka, Zambia's capital city. Digital Elevation Models (DEM) covering the Lunsemfwa catchment were used in QGIS to calculate the catchment areas. The calculated total surface area for Mushibemba catchment was found

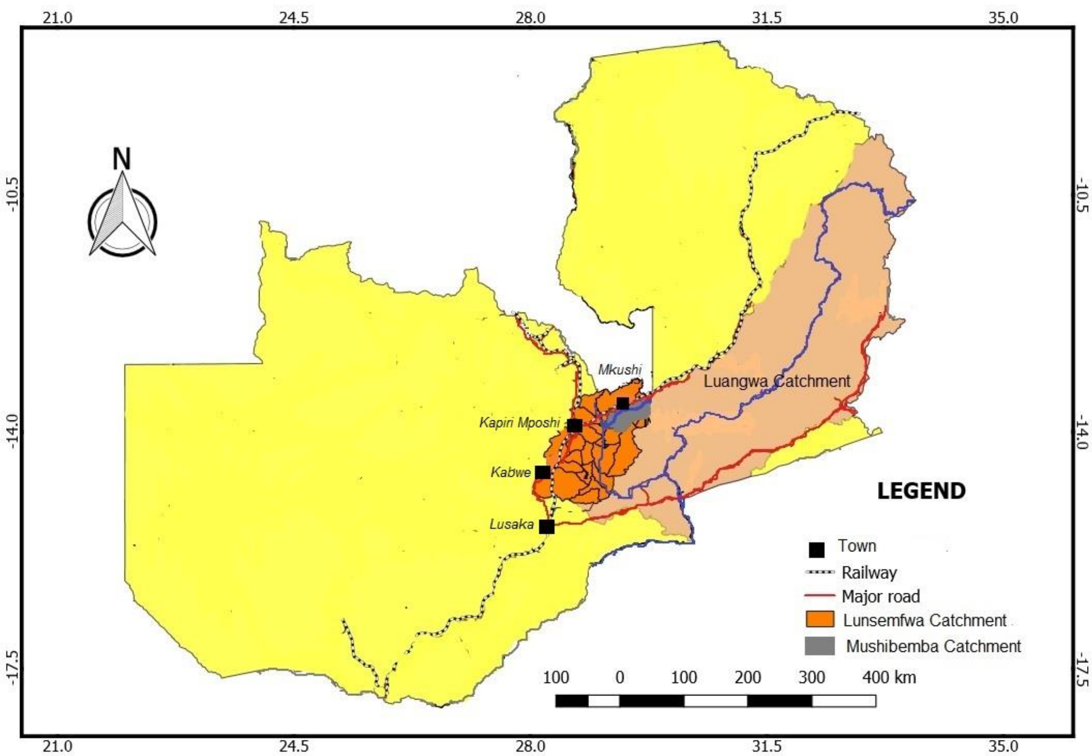


Figure 3.1: Location of Mushibemba river catchment in Mkushi Farm Block, Central Zambia *(Source: Drawn by Author)*

to be 995 km^2 while the reservoir catchment areas for Moffat dam and GRZ weir were 42.5 km^2 and 25.4 km^2, respectively.

The study reservoirs are both classified as small dams or reservoirs because they have crest heights of more than 2.5 metres but less than 15 metres and their storage capacities are less than 3 million m^3 (ICOLD, 2011). In this study, the smallest reservoir is referred to as GRZ weir because that is the common name used by the Ministry of Agriculture who built it with funding from the Government of the Republic of Zambia (GRZ). The commercial farmers and WARMA have also adopted the same name.

The Mushibemba is a perennial river which is partially subterranean from the source up to near the entry point of Moffat reservoir, the same situation exists as the river flows into the GRZ weir. This explains the differences in terms of catchment sizes of the reservoirs. In some sections along the river course, the Mushibemba is not clearly seen flowing.

In terms of location, Moffat dam is entirely located in Andrew Moffat's farm and its catchment had a large vegetation cover. In contrast, GRZ weir was surrounded by 5 commercial farms with vast cleared agricultural land (Figure 3.2).

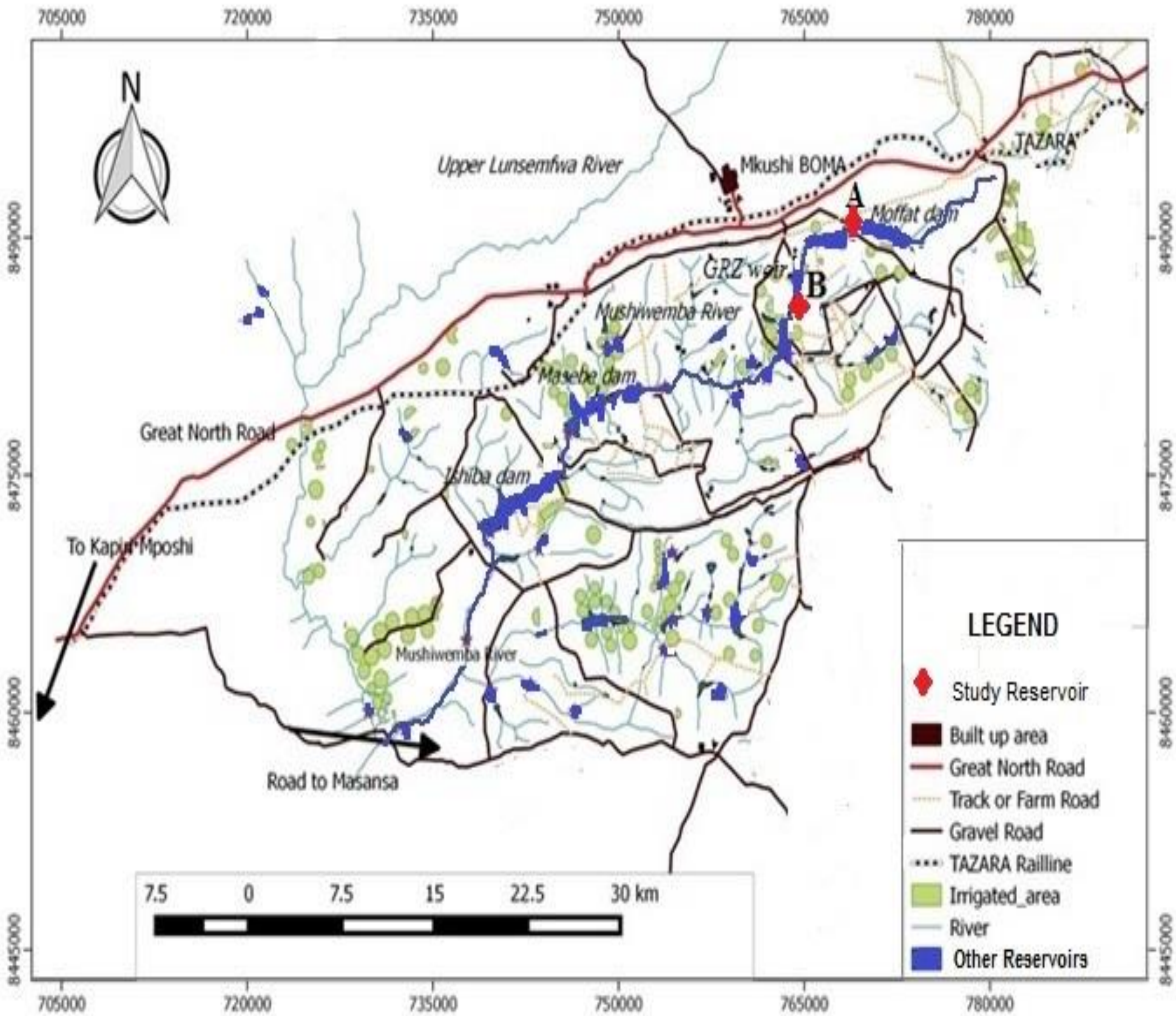


Figure 3.2: Location of Moffat dam and GRZ weir in the Mushibemba catchment, Mkushi District *(Source: Drawn by Author).*

3.2 Physical Characteristics

The physical characteristics of the study area focus on details of the climate (temperature and rainfall), hydrology, wind, geology, topography, soils and vegetation.

3.2.1 Climate

Climate of the study area is described in terms of temperature and rainfall in Mushibemba catchment. The climatic data was obtained from Zambia Meteorological Department and a commercial farm with a rain gauge in the catchment.

3.2.1.1 Temperature

The temperature of Mushibemba catchment does not deviate significantly from the national average. The minimum temperature is 7.5ºC experienced in the month of July and maximum being 30.3ºC in October (Zambia Meteorological Department, 2016). Annual evapotranspiration is estimated at 818 mm in comparison to the potential of 1538 mm. Considering annual rainfall received in this area, potential evapotranspiration is high (JICA, 1995).

The Zambia Meteorological Department (2016) observed data indicates that, over the last 30 years, the average summer temperatures had increased at a rate of about 0.6°C per decade (a total increase of 1.8°C). Summer temperatures exhibited the highest increase during the main cropping period, from November to December, across the Mushibemba catchment. Increased temperatures led to higher water demand due to high evapotranspiration. Plans of constructing reservoirs in Mkushi district came about as a result of decreased water availability.

3.2.1.2 Rainfall

Rainfall is the biggest driver of runoff which leads to increased suspended sediment transport into reservoirs. Historical rainfall data was obtained from a farm in the Tembwe river, a sub-catchment of Mushibemba. This rainfall data is one of the most reliable daily long-term rainfall records in the area. Based on this data the mean annual rainfall for the area was calculated as 970 mm. Rainfall since 1996 had generally been higher than average with the exception of the 2004/2005 and 2013/2014 rain seasons which were below average (Figure 3.3). This coincided with the time when irrigation development of the Mkushi area began expanding. Historical rainfall data of Mushibemba catchment reveals that the recent 15 years have been exceptionally wet and that future rainfall cycles could possibly fall below average gain, resulting in consecutive years of failure (Imagen Consulting, 2016). According to JICA (1995) study report, the Lunsemfwa river catchment which also includes Mushibemba catchment receives 1100 mm as annual rainfall which slightly exceeds the range for Agro Ecological Region II (Figure 3.4). This amount is received over an average period of 103 days. Jain (2007) suggested that, since the late 1980s, rainfall patterns in the Mushibemba catchment changed significantly, with a tendency of late onset and earlier end of rainy seasons in many areas.

When climate change was taken into consideration in this study, it is possible that the recent spell of wet years is indicative of what is to come and that the average rainfall of the area is set to rise with time. A study of the 3-year moving average does suggest a general increase in wetness over the 36 years of data available (Imagen Consulting, 2016). This can be seen on a linear trend line of the data (Figure 3.3)

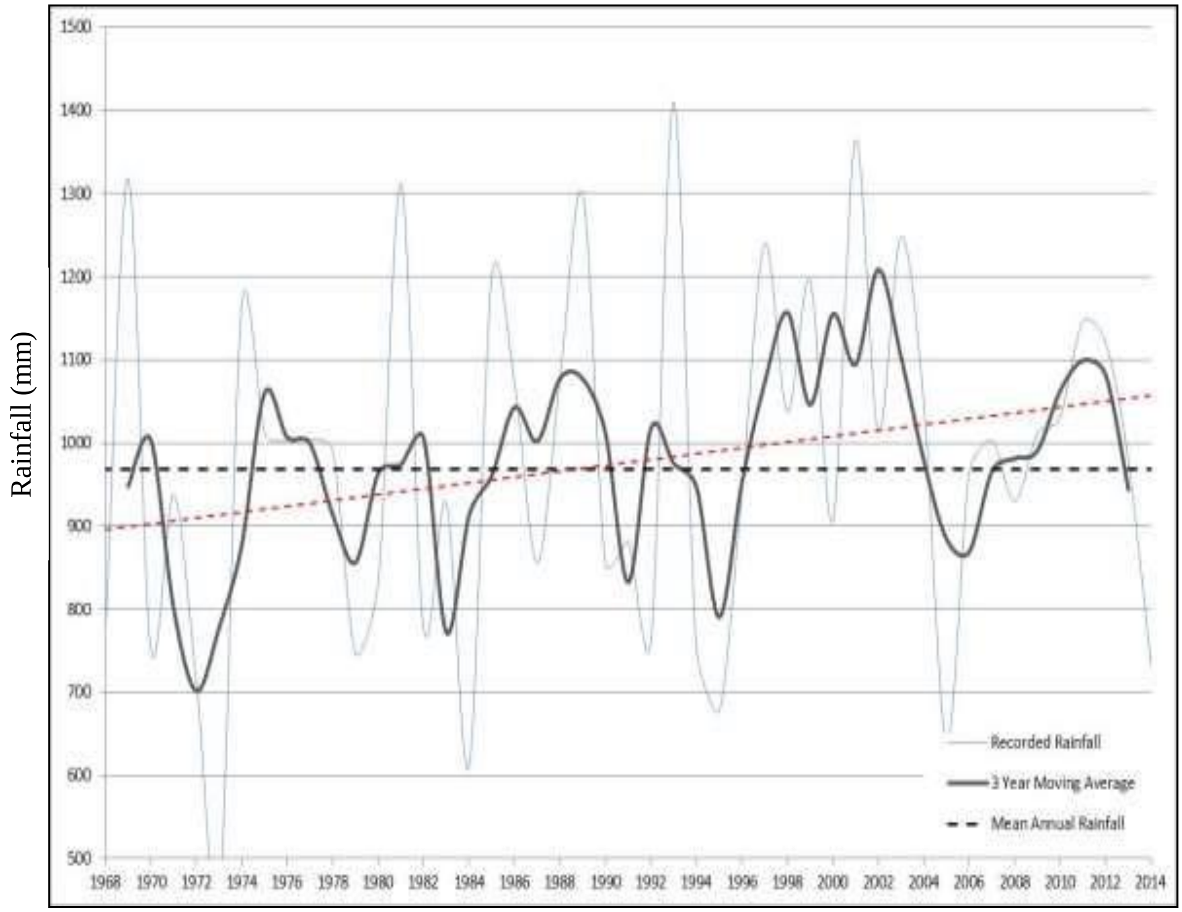


Figure 3.3: Historical Rainfall Trends of Mushibemba catchment

(Source: Imagen Consulting, 2016)

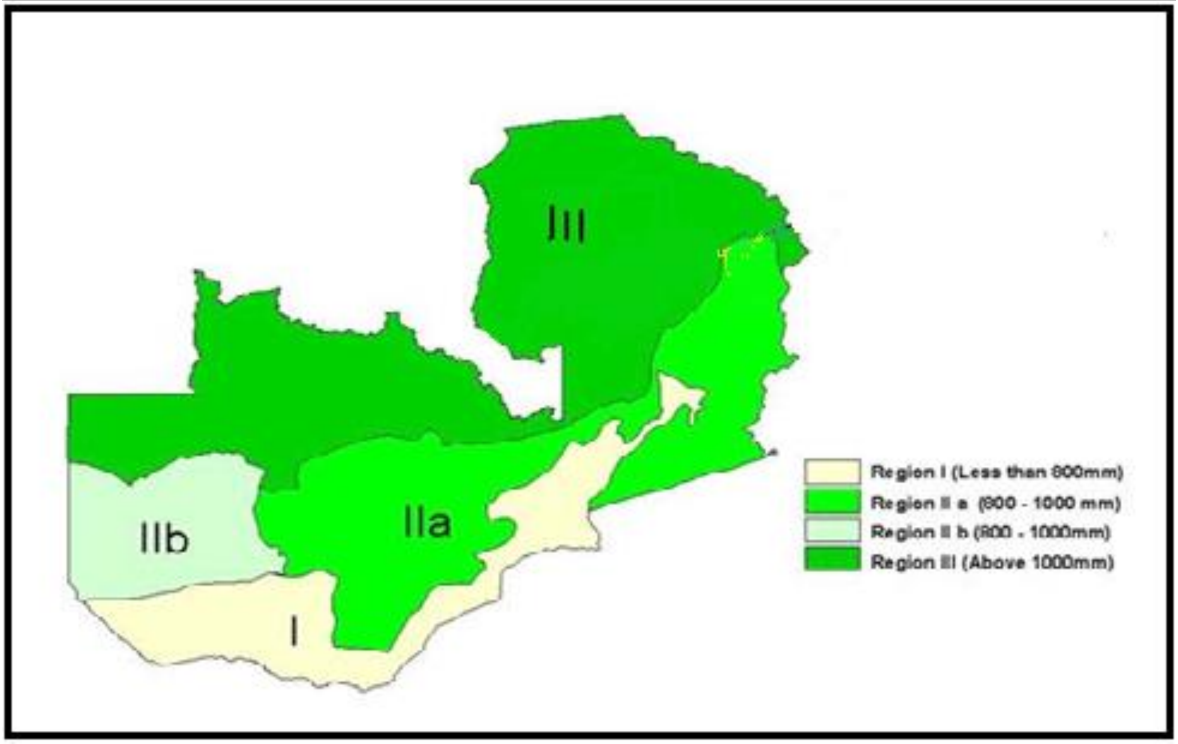


Figure 3.4: Agro-ecological regions of Zambia *(modified from Zambia Meteorological Department,2004).*

3.2.2 Hydrology

The drainage system of the Mushibemba catchment is composed of narrow main rivers with small tributaries and numerous extensive valley bottom wetlands (dambos). The prominent river located in the study area is the Mushibemba, a perennial tributary of the Lunsemfwa River (WARMA, 2016).

The study area is also considered to be a stressed river in the sense that more than 75 percent but less than 100 percent of its allocable water is utilised (WARMA, 2016). Allocable water means the total sustainable volume of water available for use after allowing for inter-basin transfers and statutory minimum flows (FAO, 2019). In terms of groundwater, the Water Resources Master Plan (JICA, 1995) estimates the annual groundwater potential at 8 percent of the annual rainfall for the entire Mkushi district.

Groundwater recharge is therefore 73 mm per annum. Furthermore, annual base flow in the rainy season is equivalent to 0.294 x 10^6 m^3 (JICA, 1995). Overall, the Mushibemba catchment has a reasonably high potential for groundwater which contributes to the overall potential of surface water.

A physical assessment of the topographic map of Mkushi district revealed that, the Mushibemba river flows through a gentle slope from the source at an elevation of 1,380 m to the confluence of the Lunsemfwa river at an elevation of about 1,280 m above sea level. The Mushibemba river catchment has the highest number of reservoirs in the Luangwa catchment (WARMA, 2016). Flow records on Mushibemba are not available because the river is not gauged.

3.2.3 Geology and Soil formation

The geology of Mkushi Farming Block is dominated by a sequence of granite gneiss and highly metamorphosed schist's and quartzite of the pre–Katanga formation (Stillman, 1965). The predominant rock type of the study area is gabbro, white gneisses and granites. In terms of Agriculture, the gneisses and granites are important because the light sandy soils derived from them are ideal for commercial farming (Stillman, 1965). Most of the agricultural activities are done along the Mushibemba river and its tributary streams. The soils are fertile, especially that they are alluvial deposited annually during flood periods. Mushibemba river on the hill ranges comprises of shallow soils derived from acidic rock. More than three quarters of the river catchment is composed of moderately leached reddish to brownish clayey to loamy soils (GRZ, 1969). The banks of Moffat dam and GRZ weir comprise of highland areas with loam soil and a lot of tall trees. The loam soil which is a mixture of clay, sand and silt supports large agriculture activities. Tall trees have been cut down and large tracts of land have been cleared specifically for commercial farming.

The grasslands that surround the river and reservoirs mainly consist of clay soil which normally holds water. The soil on the river and reservoir banks mainly consist of top layer of clay soil of about 5-10 cm thickness, followed by silt of 8-10 cm thickness then fine sand of about 8- 10 cm thickness (GRZ, 1969). Physical examination conducted on the soil samples from upstream of Moffat's dam revealed that the soil was composed of about 45 percent clay soil, 30 percent silt and 25 percent sand. In contrast, the soil samples examined from upstream of the GRZ weir consisted of 40 percent clay, 35 percent and 35 percent sand.

3.2.4 Vegetation

The vegetation type of the Mushibemba river catchment can best be described as *Miombo* woodland with some grasslands in areas that get flooded during the rainy season. The term *Miombo* is derived from "Muombo" a Bemba name for *Brachystegia boehmii* and *Brachystegia longifolia* (Storrs, 1995). *Miombo* is a two-storeyed woodland with an open or partially closed canopy of semi-evergreen trees 15 to 21m high, characterized by species of *Brachystegia*, *Julbernardia*, *Parinari*, and *Uappaca* as frequent associates. The *Miombo* woodland is known to be secondary re-growth resulting from extensive disturbance in the past. The source of Moffat dam mainly comprises moderate forest with a mixture of closed and open grassland along the river course. Areas without vegetation were mainly cleared for crop cultivation by the commercial farmers.

3.2.5 Population

According to CSO (2014) projections, the population of Mkushi district in 2018 was estimated at 165,989. Mkushi district recorded the highest annual population growth rate in Central province of 3.5 percent. The majority of the population (76%) in Mkushi district lives in rural areas whereas the urban areas have the remaining 24 percent (CSO, 2014).

3.2.6 Land use and Economic activities

The main land use in the area under consideration is agriculture. The main crops cultivated are wheat, maize and soya beans. Livestock being kept include cattle, goats, chickens, pigs and sheep. Much of the land in Mkushi is arable land. There are many commercial farmers that have cleared huge tracks of land specifically for farming. The Mushibemba river catchment is the most heavily and intensively utilised area in the Lunsemfwa catchment, most commercial farmers use Centre pivots for irrigation (Figure 3.2). The economy of Mkushi district is largely dependent on farming.

An assessment of the 2016 landuse land cover map of Mushibemba catchment revealed that the highest landuse category for Moffat dam was moderate forest estimated at 56 percent of the total reservoir catchment, this was followed by croplands 33 percent, wetlands 8 percent and open shrubland 3 percent (Figure 3.5). In contrast, the GRZ weir catchment had cropland with the highest landuse category of 71 percent followed by moderate forest at 20 percent, shrubland 7 percent and wetland 2 percent (Table 3.1).

One of the biggest problem identified that potentially poses threats to reservoir storage capacity reduction was that of anthropogenic activities associated with commercial agriculture practices. On the GRZ weir catchment, clearing of vast vegetation cover and tiling of the land for agriculture purposes encouraged soil erosion and increased the generation and transportation of suspended sediment arising from rainfall-runoff mainly during the wet season.

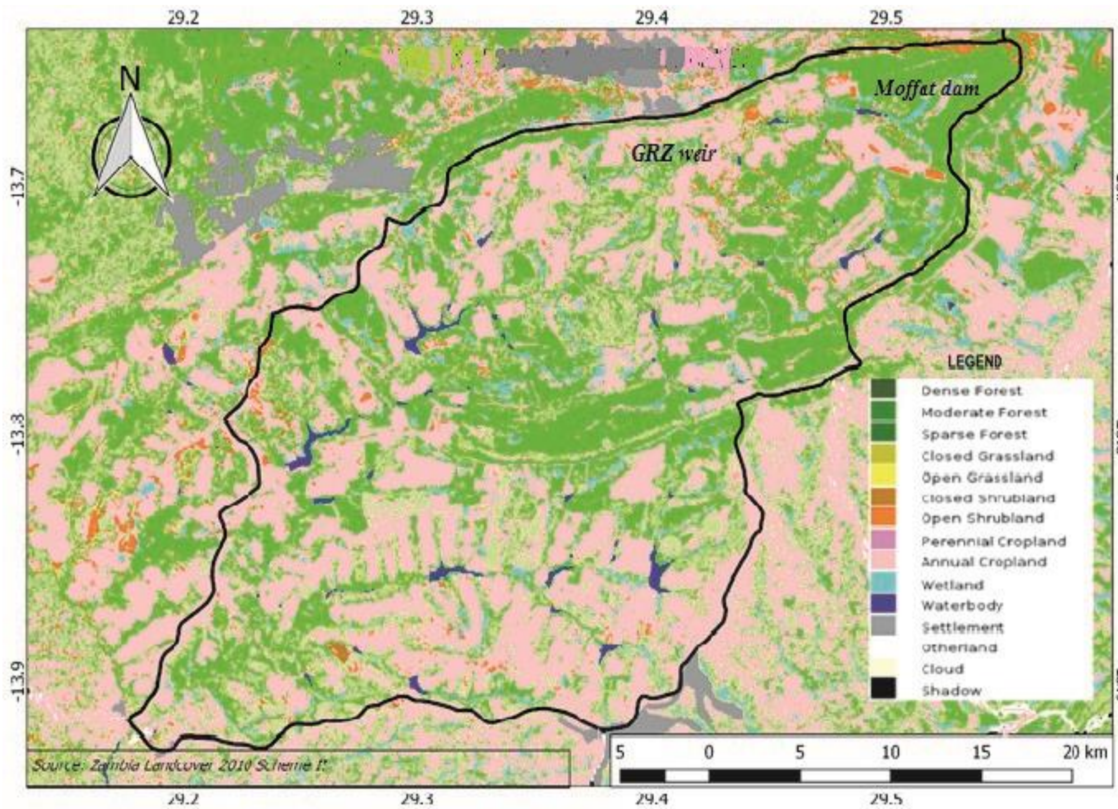


Figure 3.5: Land Classification of Mushibemba catchment (Source: Zambia Land cover, 2016)

Table: 3.1: Landuse categories for Moffat dam and GRZ weir

Land cover	Moffat dam Coverage		GRZ weir Coverage	
	Km²	%	Km²	%
Moderate Forest	23.8	56	5.08	20
Cropland	14.03	33	18.03	71
Wetland	3.4	8	0.51	2
Shrubland	1.28	3	1.8	7
Total	**42.5**	**100**	**25.4**	**100**

Source: 2016 Land use land cover map of Zambia

The geographical location and size of farms also had an impact on land management practices. For instance, Moffat dam had a very big catchment of 42.5 km^2, meanwhile GRZ Weir catchment was 25.4 km^2. Moffat dam is located at the bottom of a low lying mountain consisting of moderate and sparse forests. Moffat dam is located on Andrew Moffat's farm with an estimated area of 2,000 hectares, therefore it was easy for the dam owner to properly plan for management of the land. To begin with, there is controlled grazing. The farm has a number of wire fences to control animal grazing. There is a larger portion comprising 56 percent of the land that has been left entirely under moderate forest. In contrast, the GRZ weir is surrounded by 5 different farms that also depend on its water for irrigation and livestock. The catchment of GRZ weir has been heavily cleared for agricultural farm expansion with cropland use of about 71 percent followed by moderate forest covering 20 percent.

When the Mushibemba catchment was compared with the Makoye Catchment where reservoir sedimentation studies have been conducted, it was found that both catchments practiced agricultural farming. However, in the Makoye Catchment sedentary subsistence type of agriculture was practiced while in the Mushibemba catchment commercial agriculture faming was predominant (Muchanga, 2017). The Makoye reservoir has been referred to in this study because it is one of the reservoirs that experiences huge problem of sedimentation in Zambia, and it is also a major source of domestic and livestock water during most parts of the year (Muchanga, 2017).

It is important to note that land tenure systems differ in the areas where sedimentation studies have been conducted. Land tenure system will also have an impact on soil erosion and sedimentation. In the Mushibemba catchment the land tenure system is mainly state leasehold, meaning that, the land is given out with title deeds by the state and has a longer security of tenure that is 99 years. In the Makoye catchment the land tenure system is traditional or customary. Under customary land, the traditional rulers have authority over the land. According to Walling *et.al* (2001) land tenure in the communal area of the Kaleya Catchment is a mixture of traditional and state leasehold system.

CHAPTER 4: METHODOLOGY

This Chapter describes the procedure used in collecting and analysing data for the study.

4.1 Research Design

A case study research design technique was used. Two (2) reservoirs located in the Mushibemba river catchment, namely, Moffat dam and GRZ weir with known storage capacities of 1,404,251 m^3 and 250,530 m^3 respectively and more than five years old were used. Information on the original reservoir capacity was required for estimating the storage capacity loss.

4.2 Data Collection

This section highlights the types of data and the methods used in collection of data for the study. The types of data collected were grouped into primary and secondary data.

4.2.1 Primary data

Primary data involved actual field observations and measurements such as bathymetry surveys, water and sediment sampling.

Interviews were conducted with staff from the Department of Water Resources Development (DWRD) and Water Resources Management Authority (WARMA) who provided key information on the hydrological details of the reservoirs. Ministry of Agriculture (MoA), Zambia National Farmers Union (ZNFU) and the dam owners in the Farm Block were also interviewed in order to obtain information on the nature and type of soil erosion/ sedimentation. Photographs of the reservoirs were also taken at different periods to observe changes in terms of the river bank erosion and deposition of sediment.

4.2.1.1 Bathymetry Survey

In order to determine the reservoir storage capacity, Bathymetry surveys were conducted during the period of high water flows when the reservoirs were at Full Supply Level (FSL) (Figure 4.1). Bathymetry surveys were conducted using a hydrographic survey boat mounted with a Differential Global Positioning System (DGPS and a digital eco-sounder (Appendix 1). Field measurements also included the collection of elevation for the dam crests, spillway level, water surface elevation and downstream elevation at the time of measurements (Appendix 2).

(a) **(b)**

Figure 4.1: (a) Hydrographic Survey boat before being launched (b) Bathymentry Survey of Moffat Dam, 2nd July, 2018 *(Source: Author, 2018)*

4.2.1.2 Water Sampling

The water samples were collected during the period of high discharge (high water flow) in the month of March, 2018. Having noticed that the intakes to the two reservoirs were narrow with shallow depths of less than 50 cm, depth-integrating sampling method was used. This technique requires that the sediment sampler is lowered and raised at a uniform transit rate through the range in depth of the sampling vertical (Yuquian, 1989). The method of depth-integrating is based on the assumptions that the sampler is designed to admit the water-sediment mixture at a rate proportional to the velocity of the approaching flow and that it traverses the depth of a stream at a uniform speed (International Organisation for Standardisation, ISO, 1993). The sampler therefore receives at every point in the vertical a small instantaneous specimen whose volume is proportional to the local stream velocity. In this way, the collected sample was representative of the mean concentration and particle size distribution in the vertical.

4.2.1.3 Discharge measurement

Discharge measurements were carried out using a current meter on the streams at the intake of each study reservoir during the period of high flows in order to estimate suspended sediment transport (Figure 4.2). The reason for conducting discharge measurements was to facilitate the calculation of suspended sediment load transport per day in tonnes. In some rivers there is a moderately good relationship between suspended sediment concentration and discharge, that is, the higher the discharge the higher the suspended sediment concentration (Bartram and Ballace, 1996). It is possible, therefore, to develop a rating curve which is a regression of suspended sediment concentration Y as a function of discharge X. When used carefully, and the rating curve is checked frequently for stability, this method is useful in the measurement of discharge to estimate suspended sediment concentration for the purpose of calculating suspended sediment transport in tonnes per day (Bartram and Ballace, 1996).

Discharge measurements were also carried out at the intake in order to know the amount of water entering the reservoir (Appendix 3). Water samples were collected at the point of discharge measurement and were tested for Total Dissolved Solids (TDS) and Total Suspended Solids (TSS). The water was tested for TDS using a multi parameter meter in

(a)

(b)

Figure 4.2: Discharge measurements (a) at intakes of Moffat dam and (b) at GRZ weir, 16th March, 2018 *(Source: Author, 2018)*

order to understand the amounts of dissolved solids present in the water samples. In order to find out the rate of suspended sediment transport of the streams draining the two reservoirs, the collected water samples were tested in the laboratory for TSS. Water sampling was done twice, the first sampling conducted in March 2017 during research design period and later in March 2018 during the actual data collection (Appendix 4).

4.2 Secondary Data

Secondary data on storage capacities and other reservoir design details was obtained from the Department of Water Resources Development (DWRD) and Water Resources Management Authority (WARMA). Historical data of the reservoirs was used to account for long-term storage capacity loss trends. Satellite remote sensing data and topographic maps were used to estimate the water spread area of the reservoirs.

4.3 Data Analysis

4.3.1 Estimation of Current Reservoir Storage Capacity

To determine the current reservoir storage capacities, the data collected from the Bathymetry surveys of the reservoirs was analysed using Surfer 15 which is a powerful contouring, gridding and surface mapping software. Surfer was instrumental in the interpolation of the XYZ data to a grid suitable for the calculation of volume, area and depth (Appendix 5). The other data that was taken into consideration was elevation, and geographical location of the reservoir's spillway, crest and downstream. The spillway height of the reservoirs was set as zero.

Surfer was instrumental in screening the bathymetry data by removing repeated points and adding points (Appendix 6). In cases where the echo-sounder did not receive strong signal, but the software still registered points, this resulted in a series of points with the same z-values. Surfer was then used to create contours of the water surface area. Arc GIS 10.3 developed by ESRI in the year 2015 was used to create a polygon for each study reservoir. The reservoir polygon was drawn from a LANDSAT 5 image and saved in a BLN vector file format. The maximum reservoir surface water area was determined by using LANDSAT 5 images that were taken when the reservoirs were completely full. The

LANDSAT 5 images consisted of 7 bands with different wavelengths. The used band combination was 432. This combination gave a clear view of the land-water boundaries. The created BLN vector file containing the reservoir polygon was then added to the grids. To calculate the reservoir volume the **Grids| Calculate |Volume** button was clicked on. Since volume is calculated between two surfaces, in the Lower Surface section, the XYZ data for a particular reservoir was browsed from its saved location and then added.

The maximum surface water area extracted from the field measurements and LANDSAT 5 images was used as breakline. This meant that a polygon was added with the Z-values of 0. When the gridding algorithm saw a breakline, it calculated the Z-value of the nearest point along the breakline, and used that value in combination with nearby data points to calculate the grid node value. To eliminate the irrelevant values outside the maximum area, a blank grid was created using Surfer's blank function.

In the Polygon Boundary section, a base map containing the polygon for a particular reservoir was selected from the dropdown list, or, use the other option of clicking Browse to navigate and select a vector file. When the volume button was clicked on, a grid Volume Computation report was generated for the reservoir and it contained detailed reservoir volume calculations (Appendix 7).

The calculated capacity values were then compared with the originally calculated designed capacity values to find out changes in reservoir storage capacity. Then an estimation of capacity (volume) loss due to sedimentation was made using Adwubi *et.al*. (2009) formula in Equation 1.

$$SV = RSC\ initial - RSC\ initial + n \ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where: **SV**= Sedimentation Volume (m^3); **RSC initial** = Reservoir Storage Capacity at Initial year, **i** (m^3). The initial **(i)** year is the reservoir storage capacity at construction of the dam and the storage capacity **n** years after the initial **(i)** year is the study measured storage capacity.

4.3.2 Estimation of Suspended Sediment Load Transport

To estimate suspended sediment load transport in the reservoirs, the water samples collected at the intake of the reservoir were analysed for Total Suspended Solids (TSS) and Total Dissolved Solids (TDS). The collected water samples were tested and analysed both in the field and at the Environmental Laboratory of the School of Engineering at the University of Zambia. The water from the sediment samples was filtered, and the sediment was dried and then weighed to get sediment concentration (mg/l). Discharge measurements conducted at the intake of each study reservoir were analysed alongside the calculated sediment amount. The annual rate of suspended sediment transport into the reservoir was estimated by measuring the actual amount of suspended sediment contained in the water which entered the reservoir at the intake. To estimate suspended sediment load transport, TSS concentration (mg/l) was multiplied by discharge (m^3/s) and then multiplied by 0.0864, a conversion factor to obtain tonnes per day (Equation 2).

$$TSS\ Load\ per\ day = Concentration\ (mg/l) * discharge\ (m^3/s) * 0.0864 \ldots\ldots\ (2)$$

0.0864 is a conversion factor (number of seconds in 24hrs, divided by number of grams in a metric tonne).

4.3.3 Estimation of Current Rate of Sedimentation

The rate of sedimentation per year was estimated by dividing the number of years the reservoir has been in operation into the volume of deposited sediment. Below is equation 3 provided by Aynekulu *et al.* (2006) to calculate the rate of sedimentation:

$$SR = SV/Y \quad \text{………………………..} \quad (3)$$

Where: **SR** is rate of sedimentation (m^3y^{-1}); **SV** is Sediment Volume (m^3) and **Y** is age of reservoir (year)

The sediment volume determined in part (i) above was accumulated from the period the reservoir was constructed and became operational and as such the sediment volume was divided by the number of years.

4.3.4 Estimation of Life Expectancy of Reservoir

The future rate of reservoir sedimentation is also referred to as the Life Expectancy (L.E) of the reservoir. Therefore, life expectancy is used to estimate the time the reservoir will survive from the time operations started to the day it will completely be filled with sediments and thereby rendering it ineffective for water storage. As such, using the current rate of sedimentation that was determined above and using equation 4, the expected reservoir life was determined by dividing the designed reservoir capacity by rate of sedimentation (Aynekulu *et al.*, 2006).

$$LE = RSC/SR \quad \text{………………………..} \quad (4)$$

LE is the life expectancy of the reservoir (years); **SR** is rate of sedimentation ($m^3 y^{-1}$), **RSC** is the reservoir storage capacity (dead) (m^3).

CHAPTER 5: FINDINGS AND DISCUSSION

This Chapter presents the findings of the sedimentation studies conducted on Moffat dam and GRZ weir in Mushibemba catchment of Mkushi Farm Block. These include a discussion of the study findings on the current reservoir storage capacities, reservoir storage loss, sediment volumes and rate of sedimentation.

5.1 Findings

The findings of this study focus on the measured reservoir storage capacity, rate of suspended sediment transport into the reservoirs, loss of storage capacity and the current and future sedimentation rates.

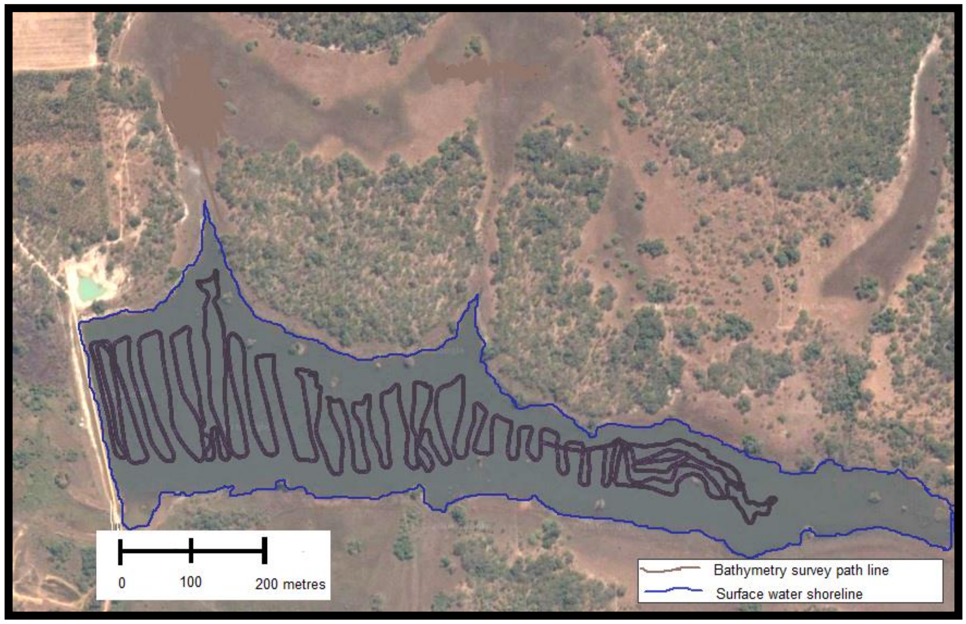
5.1.1 Reservoir Storage Capacity

The details of the measurements of the storage capacity of each reservoir and other vital information are presented in this section.

5.1.1.1 Moffat Dam

Information on Moffat dam was obtained from WARMA and it stated that, the earth dam was constructed sixteen (16) years ago in the year 2002 and had a designed storage capacity of 1,404,251 m^3. The reservoir has a catchment area of 42.5 km^2. At the time of the bathymetry survey, the water surface elevation was at 1337.73 m above sea level. Figure 5.1(a) (b) show bathymetry survey path line results recorded during the survey.

(a)



(b)

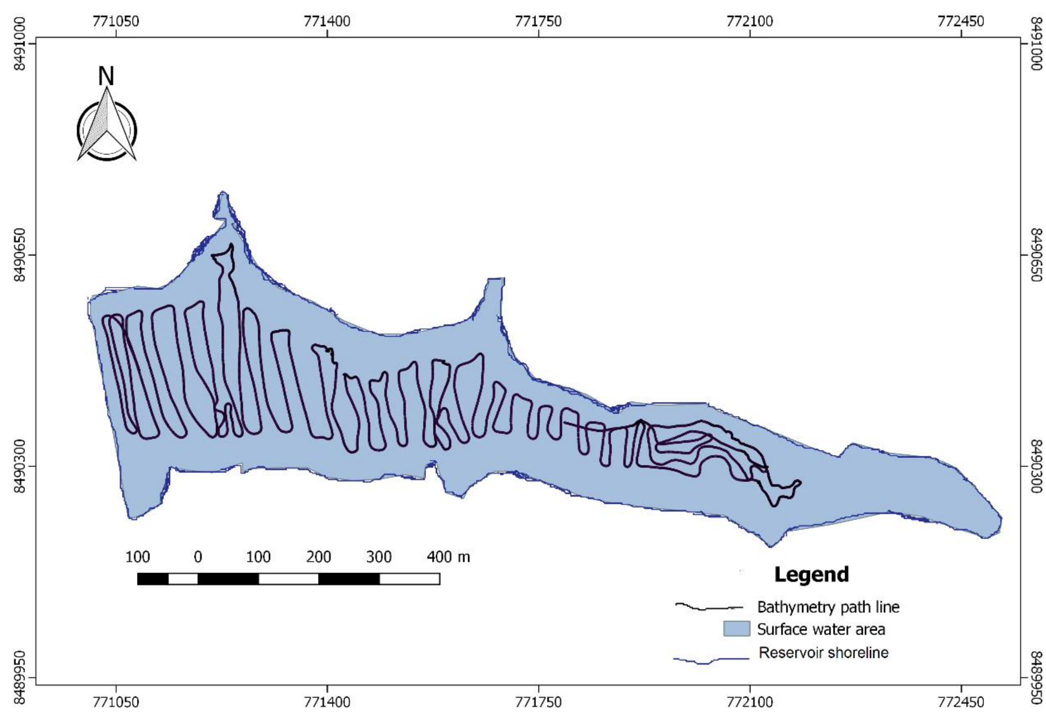


Figure 5.1: Moffat dam bathymetric Survey maps, (a) Moffat dam survey path line overlay on satellite image (b) Surveyed reservoir water surface area, 2nd July, 2018

Based on the bathymetric map (Figure 5.2), the water depth of Moffat reservoir ranged from -0.38 m to -5.74 m with half of the reservoir depth occurring at –1.59 m. The deepest portion of the reservoir was -5.8 m, situated about 20 metres from the middle of the crest. The shallowest waters were situated on the shores of the reservoir with a depth of about -0.2 m.

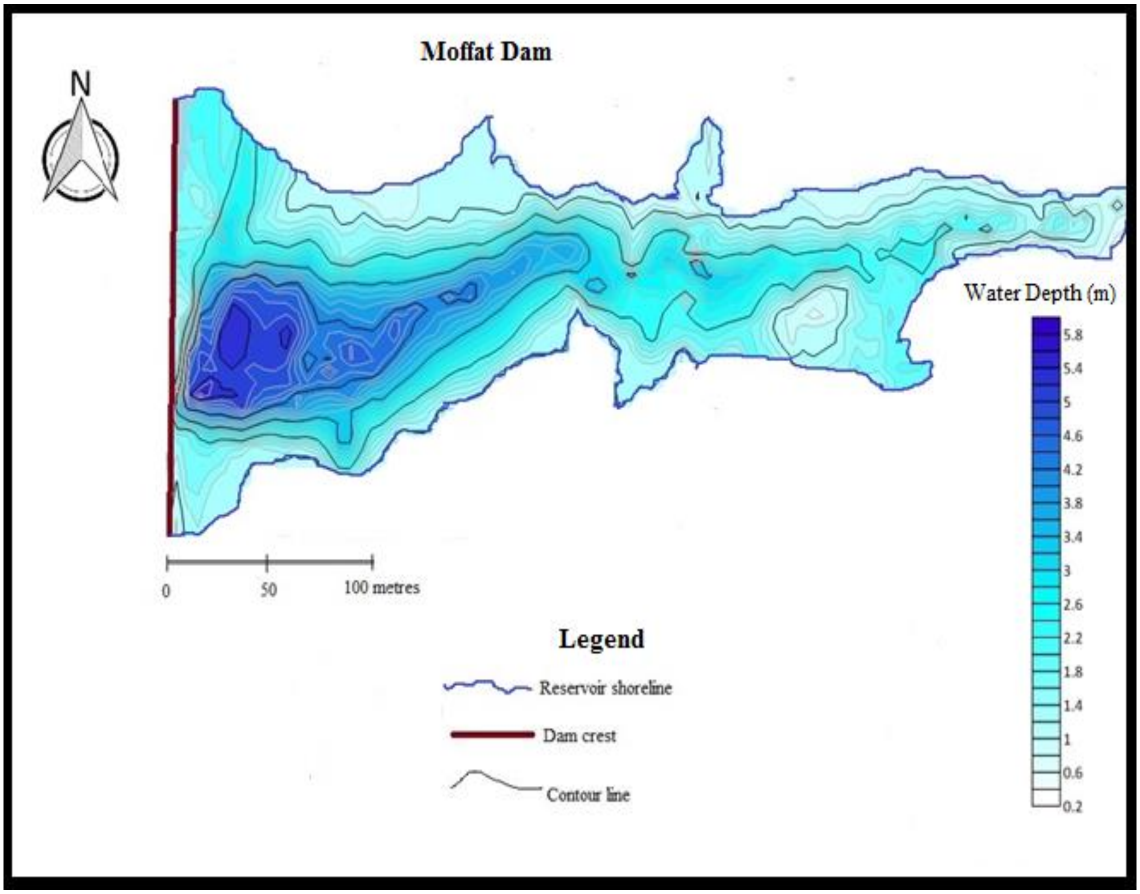


Figure 5.2: Bathymetry Map of Moffat dam, 2ndJuly, 2018.

The reservoir's current storage capacity was found to be 1,180,462 m^3 which was slightly lower than 1,404,251 m^3 the storage capacity at construction in the year 2002 (Table 5.1) This indicates that sediment deposition between 2002 and 2018 in Moffat dam has resulted in a loss of approximately 223,789 m^3 (16%) of the initial storage capacity of 1,404,251 m^3.

Table 5.1: Summary of Storage Capacity Statistics for Moffat dam and GRZ weir

S/N	**Reservoir Name**	**Year Constructed**	**Measured Water Surface Area (km^2)**	**Storage Capacity at Construction (m^3)**	**Measured Reservoir Storage Capacity (m^3)**
1	Moffat	2002	435,865	1,404,251	1,180,462
2	GRZ Weir	1982	88,661.5	250,530	197,218

The water surface area for Moffat dam was found to be 435,865 m^2 with a water volume of 1,180,462 m^3 (Table 5.1). The generated hypsometric curves between water depth and reservoir volume (Figures 5.3 a) and between depth and surface area (Figure 5.3.b) show a very close relationship that exist between depth and reservoir surface area, and depth and reservoir volume. There is also a close relationship between water surface area and reservoir volume (Figure 5.3.c). In other words, the R squared is a statistical calculation that measures the relationship between variables. In this case, there is a strong degree of

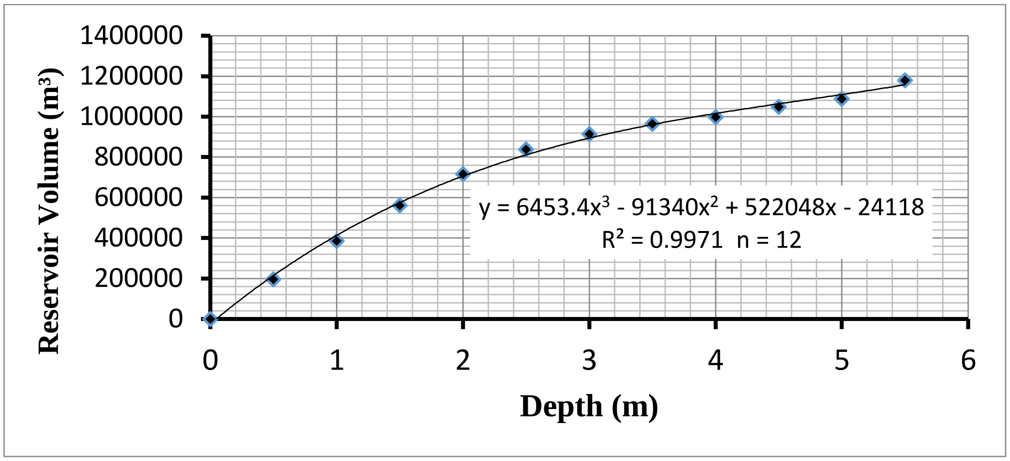
Table 5.2: Reservoir Surface Area and Volume at different depths of Moffat dam, 2nd July 2018

Depth (m)	Surface Area (m^2)	Volume (m^3)
0	0	0
0.5	109,478	196,732
1	194,147	386,920
1.5	255,740	562,036
2	298,814	717,182
2.5	333,575	838,333
3	349,692	914,220
3.5	368,395	965,220
4	383,869	998,046
4.5	397,071	1,049,021
5	411,308	1,089,321
5.5	435,865	1,180,462

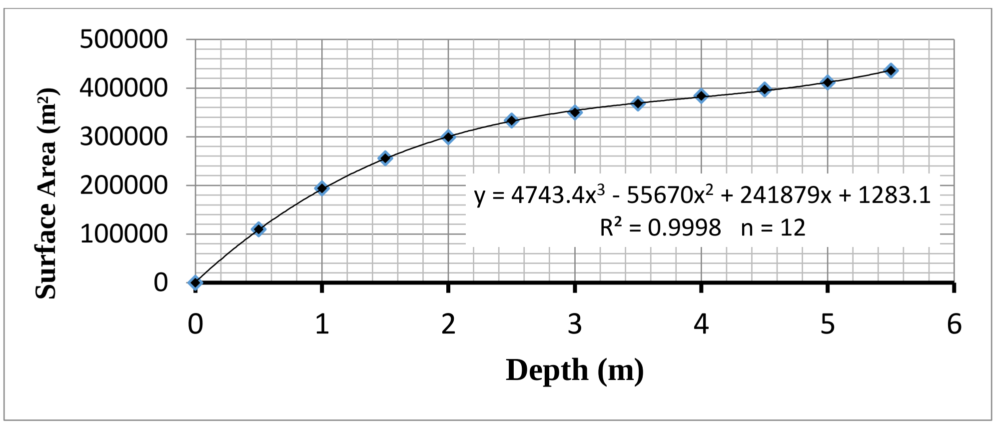
Source: Field data statistics report generated by Surfer 15

Interrelation and dependence between two variables stated above in Figure 5.3 (a) (b) and (c). A measure of 0.99% for each hypsometric curve means that the behavior of the dependent variable is highly explained by the behavior of the independent variable being studied.

(a)



(b)



(c)

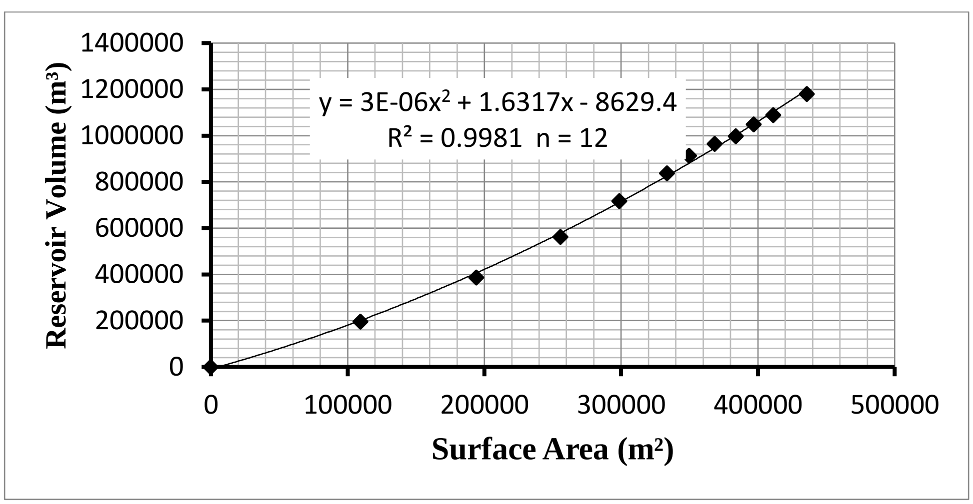
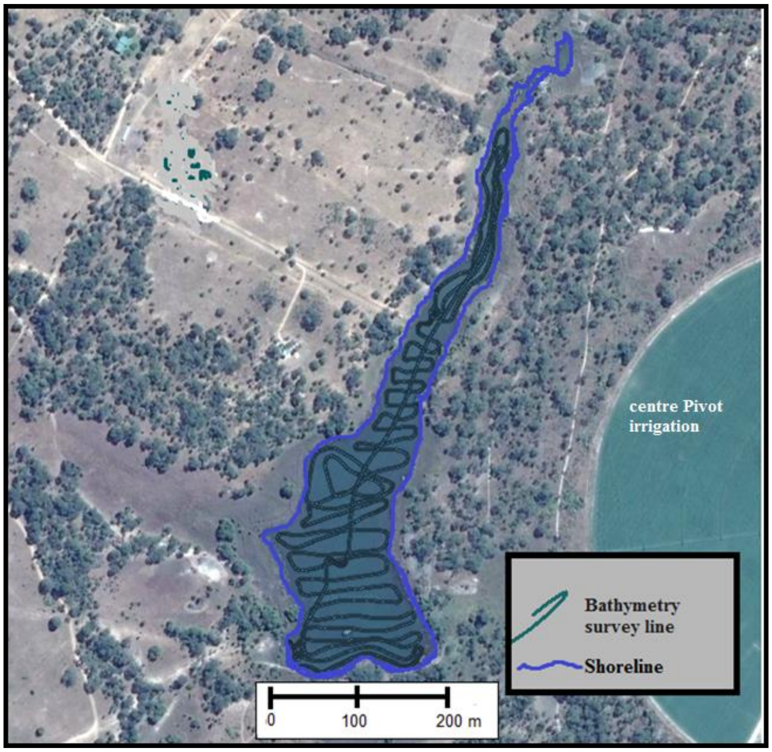


Figure 5.3: Hypsometric graphs showing (a) Depth-Volume (b) Depth-Area and (c) Surface Area-Volume relationships for Moffat dam, 2nd July, 2018.

5.1.1.2 GRZ weir

Information on the GRZ weir was obtained from the Water Resources Management Authority (WARMA) and Ministry of Agriculture offices. The information collected stated that the GRZ weir was constructed thirty-six (36) years ago in the year 1982 with funding from Ministry of Agriculture and had a designed storage capacity of 250,530 m^3. The reservoir has a catchment area of 25.4 km^2. At the time of the bathymetry survey its water surface elevation was at 1305.2 m above sea level. Figure 5.4 (a) (b) shows bathymetry survey path line results and reservoir water surface area surveyed on 4th July, 2018. Based on the bathymetric map (Figure 5.5), the water depth of the GRZ weir ranged from -0.63 m to -5.2 m with half of the reservoir depth occurring at –1.49 m. The water surface area for GRZ weir was found to be 88,661.46 m^2 with a water volume of 197,218 m^3 (Table 5.3). The generated hypsometric curves between water depth and reservoir volume (Figures 5.6 a) and between depth and surface area (Figure 5.6 b) show a very close relationship that exists between depth and reservoir surface area, and depth and reservoir volume. There is also a close relationship between water surface area and reservoir volume (Figure 5.6 c). In this case, there is a strong degree of interrelation and dependence between two variables stated above in Figure 5.6 (a) (b) and (c). A measure of 0.99% for each hypsometric curve means that the behavior of the dependent variable is highly explained by the behavior of the independent variable being studied. The reservoir's current storage capacity found to be 197,218 m^3 was slightly lower than 250,530 m^3 the storage capacity at construction in the year 2002. This indicates that sediment deposition between 1982 and 2018 in the GRZ weir had resulted in a loss of approximately 53,312 m^3 (21.3%) of the initial storage capacity of 250,530 m^3.

(a)



(b)

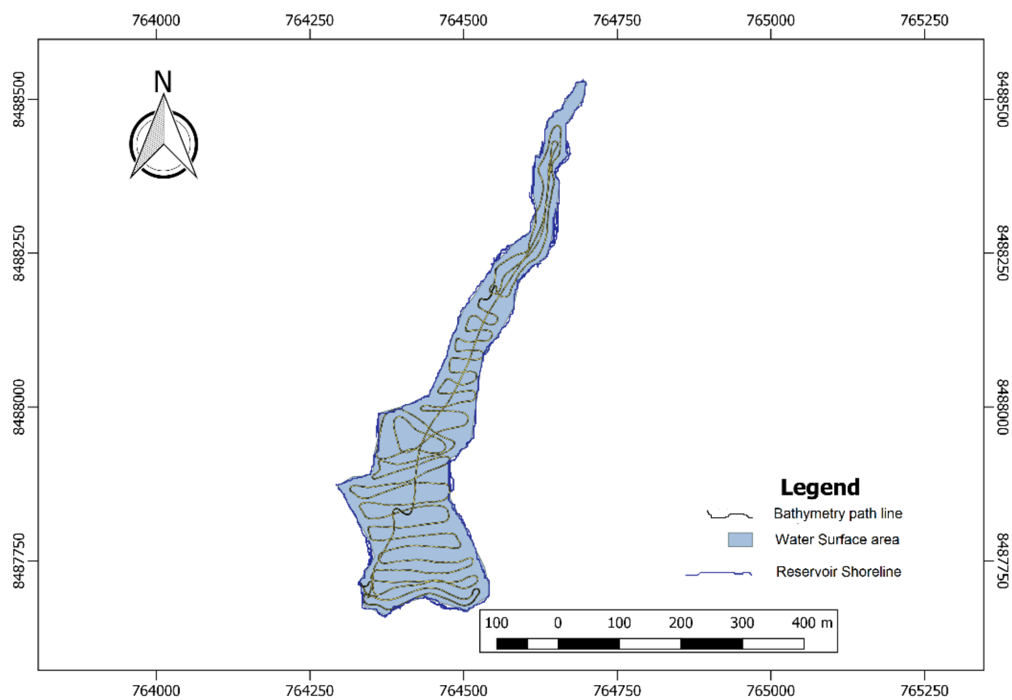


Figure 5.4: GRZ weir bathymetric Survey maps, (a) Survey path line overlay on satellite image (b) Surveyed reservoir water surface area, 4th July, 2018.

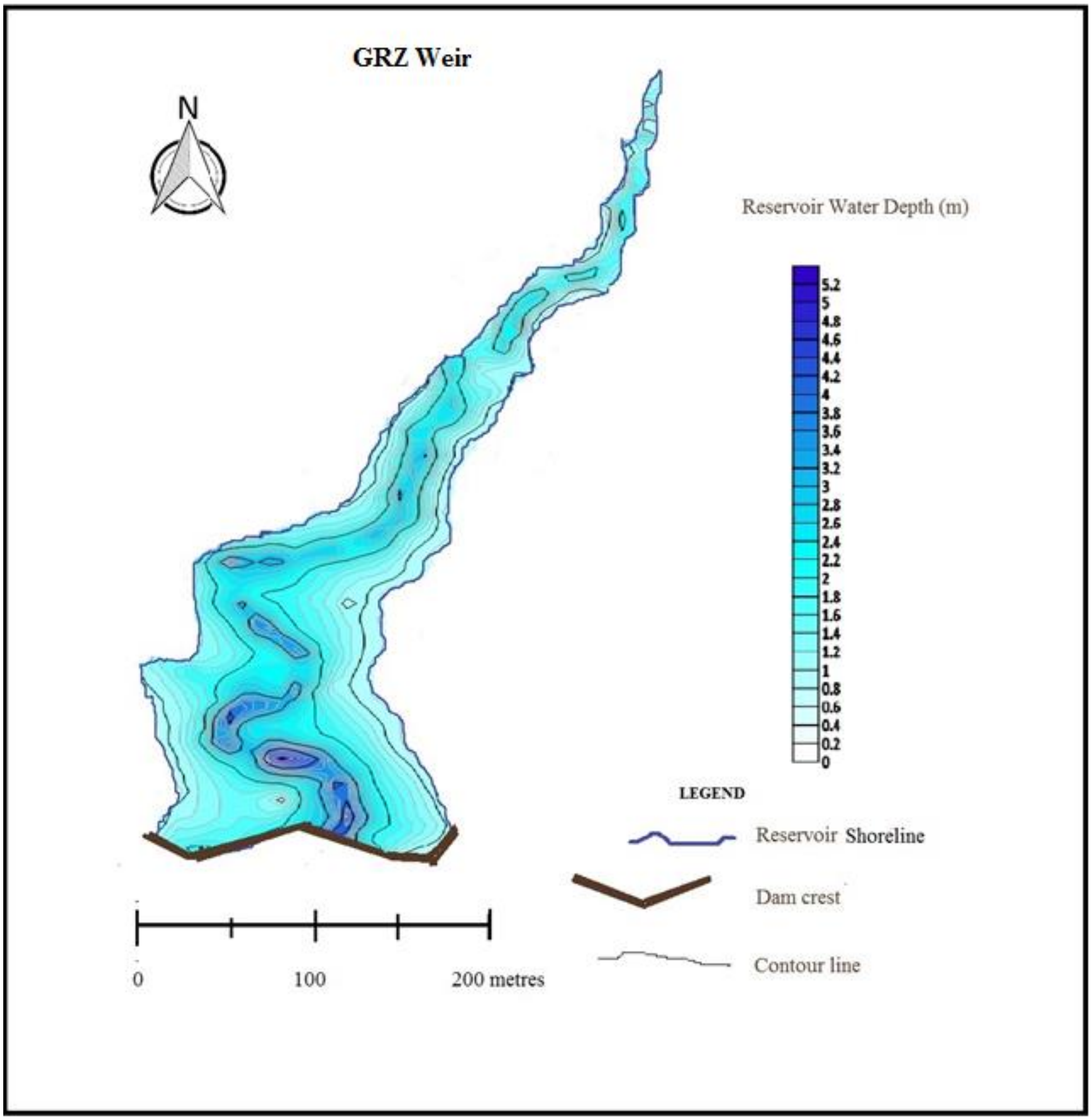


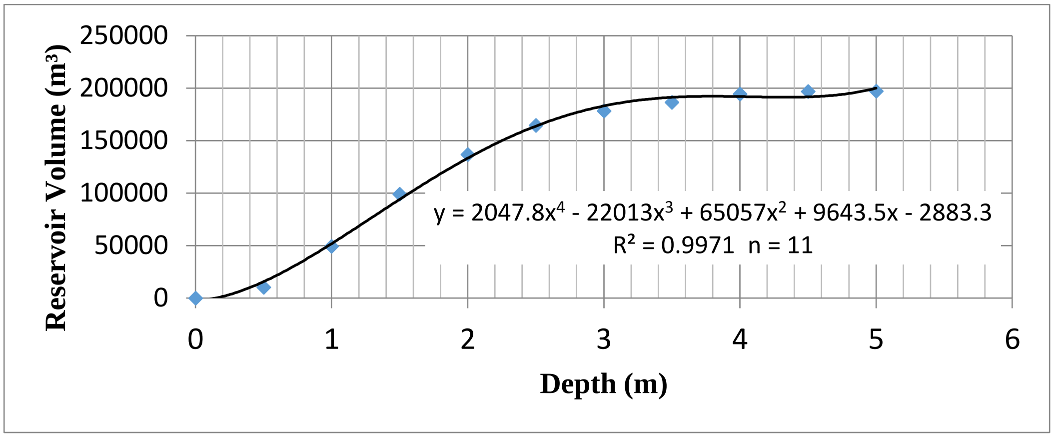
Figure 5.5: Bathymetry map of GRZ weir, 4th July, 2018

Table 5.3: Reservoir Surface Area and Volume at different depths of GRZ weir, 4th July 2018.

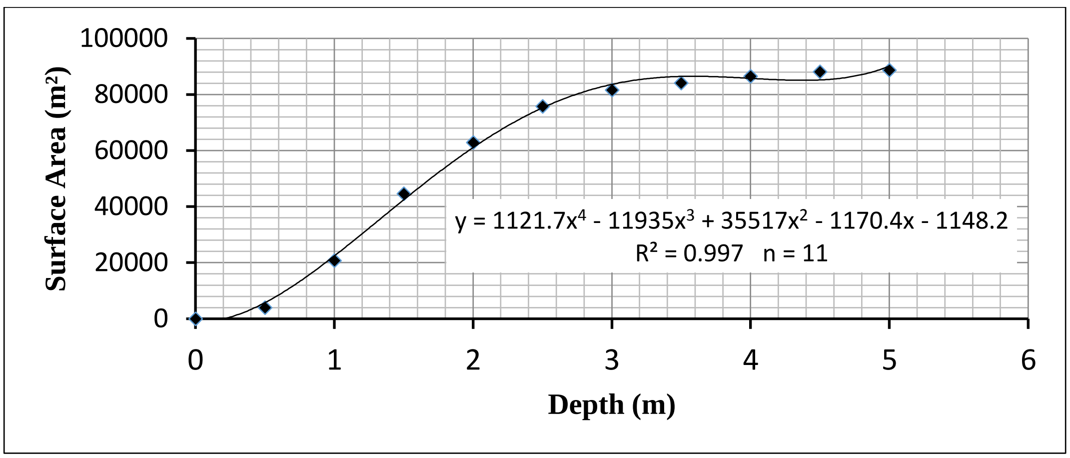
Depth (m)	Surface Area (m^2)	Volume (m^3)
0	0	0
0.5	3,900	10,263
1	20,715	49,441
1.5	44,629	99,216
2	62,857	136,799
2.5	75,795	164,689
3	81,567	178,239
3.5	84,076	186,733
4	86,523	194,512
4.5	88,049	196,849
5	88,661	197,218

Source: Field data statistics report generated by Surfer 15

(a)



(b)



(c)

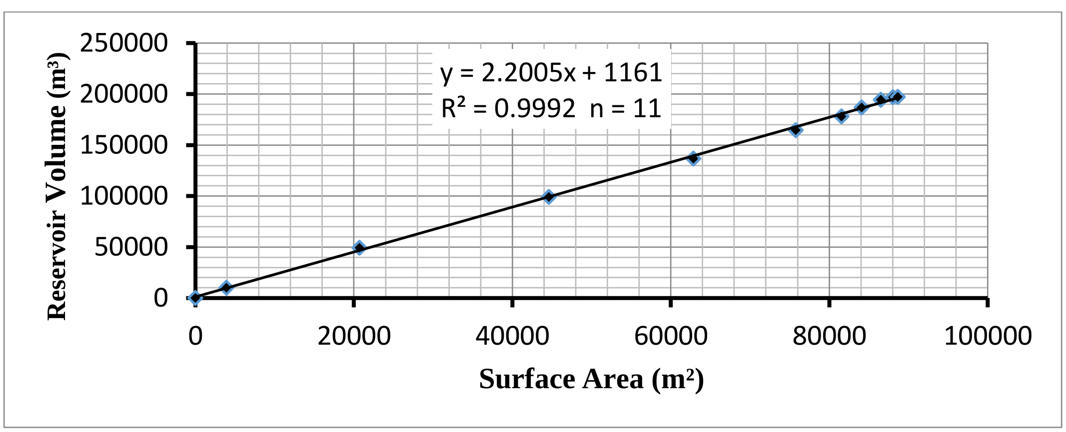


Figure 5.6: Hypsometric graphs showing (a) Depth-Volume (b) Depth-Area relationships and (c) Surface Area-Volume Relationship for GRZ weir, 4th July, 2018.

5.1.2 Suspended sediment transport

Suspended sediment transport into Moffat dam and GRZ weir were calculated using the results from Total Suspended Solids (TSS) and discharge measurements obtained at the intake. Moffat dam and GRZ weir intake discharge results were 0.024 m^3/s and 0.090 m^3/s respectively. TSS mean concentration results revealed that, Moffat dam transported 0.4 mg/l while GRZ weir had 0.6 mg/l. The annual TSS transported into Moffat dam was estimated at 0.303 tonnes while that for the GRZ weir was at 1.702 tonnes in 2018 (Table 5.4).

Table 5.4: Total Suspended Sediment Transport into Moffat dam and GRZ weir, 2018

S/N	Name of Reservoir	Discharge (m^3/s)	TSS (mg/l)	TSS Load (tyr^{-1})
16/03/2018	Moffat dam	0.024	0.4	0.303
16/03/2018	GRZ weir	0.090	0.6	1.702

5.1.3 Current and future rate of sedimentation

The life expectancy of the reservoir is the estimated time for the reservoir to survive from the time reservoir operations started to the day it will completely be filled with sediments and thereby rendering it ineffective for water storage.

The reservoir storage capacity loss for Moffat dam in 16 years was estimated at 223,789 m^3. The estimated rate of sedimentation loss for the reservoir was found to be 13,986.81 m^3yr^{-1} with a lifespan of 84 years. The reservoir storage capacity loss of GRZ weir in 36 years was found to be 53,312 m^3. The estimated rate of sedimentation loss for the reservoir was 1,480.89 m^3yr^{-1} with a lifespan of 133 years (Table 5.5).

Table: 5.5: Estimated Lifespan for Moffat dam and GRZ weir

S/N	Reservoir Name	Estimated Sediment Volume (m^3)	Estimated mean Sediment Depth (m)	Estimated Annual Rate of Sedimentation (m^3yr^{-1})	Estimated Reservoir Lifespan (Years)
1	Moffat dam	223,789	2.01	13,986.81	84
2	GRZ Weir	53,312	1.71	1,480.89	133

5.2 Discussion

This section discusses study findings on the current reservoir storage capacities, reservoir storage loss, sediment volumes and rate of sedimentation. A comparison is then made between the findings of the two study reservoirs and those of other reservoirs studied in Lusaka and Southern Provinces of Zambia including other parts of Africa.

5.2.1 Reservoir Storage Capacity

The studied reservoirs on the Mushibemba catchment have lost a small amount of storage capacity to sedimentation. The reservoir storage capacity losses observed in Moffat dam and the GRZ Weir were 16 percent and 21.3 percent, respectively, agreeing with Chao (2004) findings that showed that one (1) percent of the precious storage capacity of the world's reservoirs is annually lost due to river related sedimentation. When the study findings were compared with the results of the small dams studied by Chomba and Sichingabula (2015), it was noted that the reservoirs had lost a substantial amount of storage capacity ranging from 49 percent and 50 percent, which is much higher than what was found in this study. Meanwhile, when the study findings were further compared with the results of the sedimentation study of Makoye reservoir in Southern province of Zambia by Muchanga (2017), it was found that there was a reservoir storage capacity loss of 53.5 percent. The results of the storage capacity loss for the Makoye reservoir which was constructed in 1940 were much higher especially that the reservoir had been dredged in 1988.

The 16 percent reservoir storage capacity loss for Moffat dam is of great concern especially that it is comparatively low despite it being located upstream of the Mushibemba river catchment. Some satellite images that were not very clear observed from Google images indicated that, before the year 2002 there existed a very small reservoir at the intake of Moffat dam whose walls were later razed down to make one reservoir with the newly constructed dam. The designed storage capacity for Moffat dam was therefore, highly affected by alteration of the reservoir structure. There is also a high probability that that suspended sediment transported into the reservoir could have been deposited before the intake of the small reservoirs due to backflows.

Secondly, Moffat dam is located at the bottom of a gentle slope where the inflow into the reservoir drops in the velocity and turbulence of the water thereby reducing the potential to erode the river channel. Physical assessment of Moffat dam revealed that the catchment and banks had a very good vegetation cover comprising of tall trees upstream followed by grassland and wetland areas on the banks of the river and reservoir thereby impeding the fast erosion and transportation of sediment. This was attributed to the low storage capacity loss of the reservoir, found by the study.

5.2.2 Rate of Sedimentation

The two studied reservoirs had low amounts of deposited sediment. Moffat dam had the highest amount of deposited sediment of 223,789 m^3, followed by GRZ weir with 53,312 m^3. However, the rate of sedimentation for Moffat dam (13,986.81 m^3yr^{-1}) was higher than that of GRZ Weir (1,480.89 $m^3 yr^{-1}$).

The results of the rate of sedimentation obtained for the GRZ weir were in the same order of magnitude as those observed by Aynekulu *et al*, (2007) in the study conducted in Tigray, northern Ethiopia, where the annual rate of sedimentation of Filiglig and Grashito reservoirs were found to be 6,928 $m^3 yr^{-1}$ and 11,987 $m^3 yr^{-1}$, respectively. However, the sedimentation rate for Moffat dam was slightly higher than that of the Ethiopian study mentioned above. When the study findings were further compared with the results of the four dams studied by Chomba and Sichingabula (2015), it was found that two dams, namely, Katondwe (283.9 m^3yr^{-1}) and Morester (251 m^3yr^{-1}) had annual rates of sedimentation that were lower than that of GRZ weir ((1,480.89 m^3yr^{-1}). Meanwhile

Moffat dam had an annual rate of sedimentation that was slightly lower than Silverest dam with 14,595.4 $m^3 yr^{-1}$ (Table 5.6). On the other hand, findings by Muchanga (2017) study found the annual rate of sedimentation to be 3,112.969 $m^3 yr^{-1}$ a figure which is lower than the results for Moffat dam and higher than the results for GRZ weir.

Table 5.6: Comparison of Annual Rate of Sedimentation of studied reservoirs in Zambia.

Parameter of Comparison	**Moffat Dam[1]**	**GRZ Weir[1]**	**Morester Dam[2]**	**Katondwe Dam[2]**	**Silverest Dam[2]**	**Lwimba Dam[2]**	**Makoye Dam[3]**
Annual Rate of Sedimentation (m^3yr^{-1})	13,986.80	1,481	251	283.9	14,595.40	2,200.90	3,113
Year Built	2002	1982	1989	1980	1960	1970	1940, Dredged 1988
Catchment Area (km^2)	42.5	25.4	6.3	2.2	28.2	11.8	5
Reservoir Storage Capacity when built (m^3)	1,404,251	250,530	28,530	20,652	747,812	200,096	162,917
Reservoir Capacity loss (%)	16	21.3	51.6	51.9	49.3	50.5	53.5

Sources: [1]Mphande and Sichingabula (2019), [2]Chomba and Sichingabula (2015) and [3]Muchanga (2017)

The differences in annual sedimentation rates among the studied dams can be attributed to the differences in catchment characteristics, especially human activities. Moffat dam had a higher annual rate of sedimentation than GRZ weir because of its huge surface area and catchment. However, in terms of the amount of sediment transported, GRZ weir had more sediment conveyed than Moffat dam because it was surrounded by a vast cleared agricultural land and had been in existence much longer than Moffat dam. Moffat dam had a well-managed forest with abundant trees and grassland. According to Queensland Government (2006), over clearing of catchments and stream bank vegetation; poorly managed sand and gravel extraction; and stream straightening works are some of the examples of poor land management practices which result in accelerated rates of bank erosion which eventually leads to reservoir sedimentation when the eroded material is deposited in the reservoirs. In the case of the commercial farmers in the Moffat dam and GRZ weir catchments, it was observed that they have huge tracts of land, therefore it was very easy for them to develop good land management practices which reduced the rate of sedimentation. However, GRZ weir had a very different scenario from Moffat reservoir because it was surrounded by 5 commercial farms with diverse water demands. Even the land use land cover map (Figure 3.4) clearly showed that the GRZ weir catchment had been heavily cleared for agricultural production. Bathymetry survey and sedimentation assessment of the Mushibemba reservoirs were important because they helped to provide information on the suspended sediment transport and sedimentation related problems in the catchment. The results of the study will help the farmers around the GRZ weir to come up with appropriate land management practices that will prevent the generation, transportation and deposition of more sediment into the reservoir.

5.2.3 Suspended Sediment Load Transport

When the TSS concentration results for Moffat's dam (0.4 mg/l) and GRZ weir (0.6 mg/l) were compared with Chomba and Sichingabula (2015) findings estimated at 1 mg/l for each of the four reservoirs, it was noted that the rate of suspended sediment transport for this study was generally low compared to other studies in Zambia. Muchanga (2017) sedimentation study on Makoye reservoir found TSS concentration of 3,100 mg/l which was by far very high. When we focus on the annual rate of suspended sediment load transport into Moffat dam (0.303 tonnes) and GRZ weir (1.702 tonnes) and relate with that of Muchanga (2017) study, it was observed that Makoye reservoir with 6,146 tonnes had by far more sediment transported into the reservoir (Table 5.7). When the above results were compared with similar studies conducted by Walling *et al*. (2001) in the Upper Kaleya River of Southern Province, it was estimated that the mean daily suspended sediment load in the catchment was 3.15 tonnes and annual sediment input of 6,245 tonnes. Most of this sediment load was transported during flood events, which occurred during the rainy season. Sediment delivered to reservoirs originates from a number of upstream primary and secondary sediment sources, including cultivated fields and stream bank erosion (Collins *et al.,* 1997).

Table 5.7: Annual Total Suspended Sediment Load Transport into reservoirs

Objective	Moffat dam (tyr^{-1})	GRZ weir (tyr^{-1})	Four dams in Lusaka Province (average) (tyr^{-1})	Makoye dam in Southern Province (tyr^{-1})	Upper Kaleya Dam (tyr^{-1})
Suspended Sediment Input	0.303	1.702	203	6,146	6,245

5.2.4 Reservoir Sedimentation

When the calculated life expectancy of Moffat dam (84 years) and GRZ weir (133 years) were compared with the results of other reservoir sedimentation studies conducted in Zambia, it was found that the reservoirs of Mushibemba catchment had a much longer lifespan. For instance, Chomba and Sichingabula (2015) found the lifespan of their four studied reservoirs in Lusaka Province (Silverest, Katondwe, Lwimba and Morester dams) to range from 26 to 58 year. Chomba and Sichingabula (2015) revealed that most of the vegetative cover that once was well established in the catchments of the studied dams had been cleared for agriculture, settlements, and for charcoal production. Meanwhile, most recently, Muchanga (2017) estimated the lifespan of Makoye reservoir in Southern Province of Zambia to be 24 years. One of the reasons why Moffat dam and GRZ weir have a longer lifespan is because their catchments have very good land management practices which reduce the rate of sedimentation. The reservoir catchments do not experience river bank cultivation and erosion. There is controlled grazing and no unnecessary cutting down of trees and clearing of grasslands thereby leading to continued good vegetation cover. In Southern Province of Zambia, sedimentation rates are much higher than in Central Zambia largely due to long history of sedentary agriculture and large cattle numbers reared by local communities.

5.2.4.1 Elevation Change Method (ECM)

When a quick sedimentation volume assessment was made using the mean bed elevation measurements of each reservoir by differencing it with downstream elevation taken as the assumed elevation at the time of reservoir construction, the results were found to be closely related to those of the bathymetry survey (Muchanga, 2017). The calculated mean bed depth for Moffat dam was 2.01 m while that of the GRZ weir was 1.71 m. The reservoir storage capacity loss for Moffat dam using the mean bed elevation method was found to be 292,030 m^3 while that of the GRZ weir was calculated as 50,537 m^3. Meanwhile, the bathymetry method using the hydrographic survey boat estimated the storage capacity loss for Moffat dam at 223,789 m^3 in 16 years while that of GRZ weir in 36 years was 53,312 m^3. The results obtained from the above sedimentation assessment shows that the Elevation Change Method results are closely related to the hydrographic survey method which is more reliable. The ECM results were 30.5percent higher than Bathymetry results probably because a portion of Moffat dam was altered after completely erasing the walls of a previous reservoir which was joined to the new one, hence changes in the mean bed elevation. Furthermore, it was observed that the calculated sedimentation rates of 18,252 m^3yr^{-1} and 1,404 m^3yr^{-1} for Moffat dam and GRZ weir, respectively, were closely related to the figures obtained from the bathymetry survey method (Table 5.8). Using bathymetry survey method, the rate of sedimentation for Moffat dam was found to be 13,986.81 m^3yr^{-1} while that of GRZ weir was 1,480.89 m^3 yr^{-1}. ECM results for GRZ weir were 5.2 percent Lower than Bathymetry results.

Table 5.8: Comparison of Bathymetry and Elevation Change Method results

S/N	Reservoir Name	Estimated Sediment Volume using Bathymetry (m^3)	Estimated Sediment Volume using Elevation Change Method (m^3)	Estimated Annual Rate of Sedimentation using Bathymetry data (m^3yr^{-1})	Estimated Annual Rate of Sedimentation using Elevation Change Method (m^3yr^{-1})	Comment on results obtained
1	Moffat dam	223,789	292,030	13,986.81	18,252	ECM results were 30.5% higher than Bathymetry results
2	GRZ weir	53,312	50,537	1,480.89	1,404	ECM results were 5.2% Lower than Bathymetry results
3	Makoye dam	87,163.14	79,749.38	3005.63	2,749.98	ECM results were 8.5% Lower than Bathymetry results

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This chapter presents conclusion and recommendations based on the findings of this study conducted in the Mushibemba catchment of Mkushi district, Zambia.

6.1 Conclusion

The research study found that the reservoir storage capacity for Moffat dam had reduced by 16 percent in 16 years while that of the GRZ weir reduced by 21.3 percent in 36 years. The annual rate of suspended sediment transport into Moffat dam and GRZ weir were estimated at 0.303 tonnes and 1.702 tonnes, respectively. Meanwhile, the rate of deposited sediment for Moffat dam was found to be 13,986.81 m^3 yr^{-1} with a lifespan of 84 years while that of the GRZ weir was 1,480.89 m^3 yr^{-1} with a lifespan of 133 years. This amount of sediment deposition led to reservoir capacity storage losses of 223,789 m^3 and 53,312 m^3 for Moffat dam and GRZ weir, respectively. The major effect of sedimentation on the two study reservoirs of Mushibemba catchment was that it reduced their storage capacities and lifespan. The two reservoirs had reduced water storage capacities during the hot dry season thereby making it difficult for the farmers to meet their irrigation water demand.

Catchment characteristics and activities had a great effect on sedimentation rates on the two study reservoirs. Moffat dam had a higher annual rate of sedimentation than the GRZ weir because of its huge surface area and storage capacity combined with large catchment size. However, in terms of the amount of sediment transported, GRZ weir had more sediment conveyed than Moffat dam because it was surrounded by a vast cleared agricultural land and had been in existence much longer than Moffat dam. GRZ weir catchment was small and had poor land management practices. Its catchment had a large area with over cleared trees and grassland which resulted in accelerated rates of bank erosion which consequently led to the eroded material being deposited in the reservoirs. Land management for the GRZ weir could have proved difficult because the reservoir was surrounded by five commercial farms with diverse expansion programmes that contributed to clearing of more agricultural land. In contrast, Moffat dam which was entirely located within Andrew Moffat's farm practiced controlled grazing and had a well-managed forest with abundant trees and grassland, hence levels of reservoir sedimentation were very low.

Despite observing that the reservoir storage capacity losses and annual sediment transport for Moffat dam and GRZ weir were lower than the results of studies conducted on reservoirs located in other parts of Zambia, the study concluded that sedimentation in the Mushibemba catchment was fairly serious given reservoir capacity losses observed due to expanding agricultural activities despite having very good vegetation cover. It was further concluded that, suspended sediment in the two reservoirs mainly originated from the cleared commercial agricultural land upstream which predominantly consisted of clayey to loamy soils. This also accounted for the high turbidity of the reservoir water. This situation therefore calls for periodic reservoir assessment of sedimentation and dredging of the deposited sediment to increase storage capacity. Dredging needs to be planned and budgeted for by the owners of reservoirs.

6.2 Recommendations

Based on the findings of this study, the following are the recommendations:

i. The Department of Water Resources Development (DWRD) and Water Resources Management Authority (WARMA) working with reservoir owners should jointly put in place programmes that promote regular bathymetry surveys of reservoirs.
ii. There is need for higher learning institutions in Zambia to build the capacity of water resources management professionals on sediment monitoring and analysis for them to be able to deal with sediment related problems.
iii. There is need for the Ministry of Water Development, Sanitation and Environmental Protection (MWDSEP), Ministry of Agriculture (MoA) and Ministry of Land and Natural Resources (MLNR) to jointly sensitise commercial farmers on the importance of promoting good land management practices such as controlled animal grazing and planting of more trees and grass near rivers and reservoirs in order to reduce on erosion of the land and sedimentation.
iv. There is need to extend the research study to other reservoirs in the Mushibemba catchments so that there can be better understanding of sediment related problems.

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APPENDICES

APPENDIX 1: Specifications of the Hydrographic Survey Boat.

Coden Hydrographic Survey
Remote Controlled Boat

RC-S2

GPS, Echo-Sounder equipped

- Safe and Easy Data Collection
- One-Man Operation
- Quick Deployment
- Auto-Pilot
- Auto Returning

CODEN

Coden Hydrographic Survey Remote Controlled Boat RC-S2 Standard equipment

- Remote controlled boat
- Boat antenna
- Coden boat control software
- Wireless LAN modem
- Antenna with work board
- Power supply box
- Boat controller
- Battery for boat x2
- Battery for remote control unit x1
- Battery charger x1

■ Specifications

Boat size	
Length	1,060mm
Width	270mm
Height	250mm (Without antenna)
Weight	9.3kg (13kg with batteries)

Power	
Motor	Brushed DC motor x2
Traction	2.2kg f
Boat Speed	2.8kt (Maximum)
Power Source	Rechargeable nickel hydride battery 10A x2
Battery Life	120 minutes (Auto-pilot)

Geodesy	Transverse Mercator User-settable (UTM-North, UTM-Sounth available)

Auto-Pilot	
Line Survey	Maximum 128 lines (one project)
Target Survey	Maximum 255 points (one project)

Echo Sounder (Single Beam)	
Frequency	200kHz
Depth Range	From 0.5m to 80m
Resolution	0.01m
Gain	Auto or Manual (H/L 20 level each)
Sampling Interval	500ms
Beam	6degrees or 24degrees

GPS (SBAS)	
Resolution	1/10000s

Communication	2.4GHz Wireless LAN
Operating Range	500m

Computer Operating System	Windows XP Professional、Windows 7 (32bit)

Information in this brochure is subject to change without notice.

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APPENDIX 2: Technical Details of Study Reservoirs

i. Moffat Dam Details 2nd July, 2018

Dam Name: AJ Moffat Farm

River: Mushibemba river

District: Mkushi

Location: Mkushi Farm Block

Date Constructed: July 2002

Owner: A.J Moffat

Designed Storage Capacity: 1,404,251 m^3

Measured Storage Capacity: 1,180 462 m^3

Measured Reservoir Surface Area: 435,865 m^2

Location (UTM): Y: 8490567.89 X: 771037.74

Geographical Location: S: 13° 38’27.9471 E: 29° 30’18.9661

Right Crest Elevation: 1340. 647m above sea level

Location: Y: 8490585.87 X: 771002.89

Centre Crest Elevation: 1339. 694

Location: Y: 8490463.26 X: 771027.98

Left Crest Elevation: 1339.629

Location: Y: 8490280.21 X: 771072.83

Water surface Elevation: 1337.730

Spillway Elevation 1339.629

Location: Y: 8490494.79 X: 770991.73

Downstream Elevation 1332.049 m

ii. GRZ Weir Details, 4th July, 2018

Dam Name: GRZ weir

River: Mushibemba river

District: Mkushi

Location: Mkushi Farm Block

Date Constructed: July 1982

Owner: GRZ

Designed Storage Capacity: 250,530 m^3.

Measured Storage Capacity: 197,218 m^3

Measured Reservoir Surface Area: 88,661.46 m^2

Location (UTM): Y: 84877674.00 X: 764343.85

Geographical Location: S: 13° 40’04.2822 E: 29° 26’37.3354

Right Crest Elevation: 1305. 941m above sea level

Location: Y: 8487673.39 X: 764333.02

Centre Crest Elevation: 1306. 157

Location: Y: 8487665. 51 X: 764362.37

Water surface Elevation: 1305.222

Spillway Elevation 1306.157

Location: Y: 8487665 X: 764362.37

Downstream Elevation: 1301.498m

APPENDIX 3: Discharge measurements conducted during fieldwork

(a) Intake Point for Moffat dam.

S/N	Distance (m)	width (m)	Depth (m)	Rev. (No.)	Time (Sec.)	N	Velocity (m/s)	Area (m^2)	Discharge (m^3)
1	0.25	0.1	0.200	14	40	0.35	0.128	0.020	0.0026
2	0.35	0.1	0.180	10	40	0.25	0.097	0.018	0.0018
3	0.45	0.1	0.180	18	40	0.45	0.160	0.018	0.0029
4	0.55	0.1	0.180	20	40	0.50	0.175	0.018	0.0032
5	0.65	0.1	0.200	20	40	0.50	0.175	0.020	0.0035
6	0.75	0.1	0.200	21	40	0.53	0.183	0.020	0.0037
7	0.85	0.1	0.210	18	40	0.45	0.160	0.021	0.0034
8	0.95	0.1	0.210	12	40	0.30	0.113	0.021	0.0024
9	1.05	0.1	0.210	0	40	0.00	0.019	0.021	0.0004
			0.197				**0.134**	**0.177**	**0.0236**

(b) Intake Point for GRZ weir.

S/N	Distance (m)	width (m)	Depth (m)	Rev. (No.)	Time (Sec.)	N	Velocity (m/s)	Area (m^2)	Discharge (m^3)
1	0.3	0.2	0.180	37	40	0.925	0.308	0.036	0.0111
2	0.5	0.2	0.240	32	40	0.800	0.269	0.048	0.0129
3	0.7	0.2	0.380	39	40	0.975	0.323	0.076	0.0246
4	0.9	0.2	0.380	38	40	0.950	0.315	0.076	0.0240
5	1.1	0.2	0.240	40	40	1.000	0.331	0.048	0.0159
			0.280				**0.309**	**0.284**	**0.0884**

APPENDIX 4: Water Quality Results

SCHOOL OF ENGINEERING
CIVIL ENGINEERING DEPARTMENT
ENVIRONMENTAL ENGINEERING LABORATORY

PHYSICAL/CHEMICAL EXAMINATION OF SEDIMENT SAMPLES.

Sampled by : Client
Sampling date : 16.03.2018 Report date : 04.04.2018

Lab No. Sample ID. Parameter	**Chibefwe near confluence**	**Lunsemfwa near the Source**	**Moffat Dam**	**GRZ Weir**	**Chisela River at Tributary**
pH	6.69	6.52	6.56	6.61	6.59
BOD ((as mg O_2/l)	8	8	9	7	8
COD ((as mg O_2/l)	18	14	18	12	15
Total Dissolved Solids (mg/l)	12	14	4	16	17
Total Suspended Solids (mg/l)	0.5	1.3	0.4	0.6	0.8
Bicarbonates (as mg $CaCO_3$/l)	40	48	10	44	40
Calcium (mg/l)	7.2	7.2	1.6	2.4	10.4
Iron (mg/l)	<0.01	02	<0.01	<0.01	0.12
Manganese (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01
Chlorides (mg/l)	12.0	10.0	11.0	14.0	9.0
Phosphorous (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrites (as NO_2 –N mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001
Nitrates (as NO_3 –N mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01
Sulphates (mg/l)	<0.01	<0.01	2.11	6.15	<0.01
Acidity (as mg $CaCO_3$/l)	Nil	Nil	Nil	18	Nil
Potassium (mg/l)	2.61	2.18	2.32	3.12	1.96
Sodium (mg/l)	7.92	6.60	7.02	9.44	5.94
Fluorides (mg/l)	0.04	0.03	0.02	0.03	0.02
Magnesium (mg/l)	5.28	7.20	1.44	9.12	3.36

Tests carried out in conformity with "Standard Methods for the Examination of water and Wastewater APHA, 1998".

APPENDIX 5: Bathymetry Data Statistical Analysis Report for GRZ weir.

Wed Jul 11 22:40:29 2018

Data Source

Source Data File Name:	E:\Desktop\GRZ Bathy_Processed_11th July 2018.csv
X Column:	A
Y Column:	B
Z Column:	C

Filtered Data Counts

Active Data:	4041
Original Data:	4069
Excluded Data:	0
Deleted Duplicates:	28
Retained Duplicates:	28
Artificial Data:	0
Superseded Data:	0

Exclusion Filtering

Exclusion Filter String:	Not In Use

Duplicate Filtering

Duplicate Points to Keep:	First
X Duplicate Tolerance:	9.3E-05
Y Duplicate Tolerance:	4E-05
Deleted Duplicates:	28
Retained Duplicates:	28
Artificial Data:	0

X	Y	Z	ID
8487709.8	764514.2	1.25	663
	Retained		
8487709.8	764514.2	1.15	664
	Deleted		
8487716.2	764418.02	1.74	738
	Retained		
8487716.2	764418.02	1.69	739
	Deleted		
8487734.7	764381.92	1.38	808
	Retained		
8487734.7	764381.92	1.44	809
	Deleted		
8487744.7	764358.03	0.88	4022
	Retained		
8487744.7	764358.03	0.86	4023
	Deleted		
8487750.1	764403.4	1.86	949
	Retained		
8487750.1	764403.4	1.87	950
	Deleted		
8487791.1	764435.03	2.3	1093
	Retained		
8487791.1	764435.03	2.44	1094
	Deleted		
8487818.5	764352.88	1.13	1308
	Retained		
8487818.5	764352.88	1.08	1309
	Deleted		
8487825.4	764406.99	3.61	3877
	Retained		
8487825.4	764406.99	3.61	3878
	Deleted		
8487830	764474.45	0.84	1236
	Retained		
8487830	764474.45	0.81	1237
	Deleted		
8487834.3	764392.74	2.77	3949
	Retained		
8487834.3	764392.74	2.79	3950
	Deleted		
8487842.7	764420.56	2.52	1380
	Retained		
8487842.7	764420.56	2.59	1381

	Deleted		
8487870	764316.76	0.91	1523
	Retained		
8487870	764316.76	1.05	1524
	Deleted		
8487876.7	764423.04	3.1	1451
	Retained		
8487876.7	764423.04	2.8	1452
	Deleted		
8487891.9	764435	2.02	1594
	Retained		
8487891.9	764435	1.88	1595
	Deleted		
8487905.8	764362.8	1.03	1737
	Retained		
8487905.8	764362.8	1.01	1738
	Deleted		
8487907.1	764428.61	1.98	1667
	Retained		
8487907.1	764428.61	1.9	1668
	Deleted		
8487908.5	764432.08	1.75	1665
	Retained		
8487908.5	764432.08	1.78	1666
	Deleted		
8487916	764372.93	1.66	1952
	Retained		
8487916	764372.93	1.71	1953
	Deleted		
8487926	764408.3	2	2095
	Retained		
8487926	764408.3	1.96	2096
	Deleted		
8487927.2	764472.7	1.05	1809
	Retained		
8487927.2	764472.7	1	1810
	Deleted		
8487951.6	764451.04	1.44	2023
	Retained		
8487951.6	764451.04	1.51	2024
	Deleted		
8487992.1	764492.19	1.63	2167
	Retained		
8487992.1	764492.19	1.81	2168
	Deleted		

8487995.1	764400.74 Retained	1.09	1881
8487995.1	764400.74 Deleted	0.99	1882
8488006.7	764473.92 Retained	1.69	3734
8488006.7	764473.92 Deleted	1.74	3735
8488185	764545.6 Retained	1.39	2734
8488185	764545.6 Deleted	1.32	2735
8488229.2	764590.56 Retained	1.36	3591
8488229.2	764590.56 Deleted	1.34	3592
8488267	764620.64 Retained	1.46	3376
8488267	764620.64 Deleted	1.42	3377
8488426.3	764638.44 Retained	0.72	3095
8488426.3	764638.44 Deleted	0.68	3096

Data Counts

Active Data: 4041

Univariate Statistics

	X	Y	Z
Count:	**4041**	**4041**	**4041**
1%-tile:	8487677.531	764330.822	0.64
5%-tile:	8487688.72	764342.69	0.73
10%-tile:	8487699.57	764356.311	0.82
25%-tile:	8487751.559	764396.26	1.07
50%-tile:	8487914.92	764465.356	1.49
75%-tile:	8488157.944	764538.824	2.15
90%-tile:	8488300.032	764626.211	2.92
95%-tile:	8488376.7	764639.037	3.56
99%-tile:	8488436.354	764654.451	4.19

Minimum:	8487670.371	764315.171	0.63
Maximum:	8488457.414	764658.52	5.2
Mean:	8487961.10096	764472.90547	1.70526107399
Median:	8487914.92	764465.356	1.49
Geometric Mean:	8487961.09802	764472.899935	1.52615076473
Harmonic Mean:	8487961.09507	764472.8944	1.37440997578
Root Mean Square:	8487961.10391	764472.911005	1.90045082501
Trim Mean (10%):	8487951.44207	764470.972315	1.63897442947
Interquartile Mean:	8487928.0269	764464.374923	1.52604156358
Midrange:	8488063.8925	764486.8455	2.915
Winsorized Mean:	8487954.59537	764472.960041	1.65238554813
TriMean:	8487934.83575	764466.449	1.55
Variance:	50040.2348819	8465.12097543	0.703972215239
Standard Deviation:	223.696747589	92.0060920561	0.839030521042
Interquartile Range:	406.385	142.564	1.08
Range:	787.043000001	343.349	4.57
Mean Difference:	253.472928338	105.146195244	0.906736713534
Median Abs. Deviation:	185.612	70.1560000001	0.49
Average Abs. Deviation:	188.114887652	76.7091088839	0.639834199456
Quartile Dispersion:	2.39389235627e-05	9.32439849748e-05	0.335403726708
Relative Mean Diff.:	2.98626401939e-05	0.000137540774162	0.53172896946
Standard Error:	3.5189674084	1.44734531373	
	0.0131987661422		
Coef. of Variation:	2.63545915124e-05	0.000120352325632	0.492024672256
Skewness:	0.502160008024	0.353597737878	1.12142537336
Kurtosis:	2.05670755349	2.12053192729	3.91161748932
Sum:	34299850809	3089235011	6890.96
Sum Absolute:	34299850809	3089235011	6890.96
Sum Squares:	2.91135799638e+17	2.36163649874e+15	14594.9336
Mean Square:	7.20454837015e+13	584418831660	3.61171333828

Inter-Variable Covariance

	X	**Y**	**Z**
X:	50040.235	17124.088	-40.903534
Y:	17124.088	8465.121	-14.449939
Z:	-40.903534	-14.449939	0.70397222

Inter-Variable Correlation

	X	Y	Z
X:	1.000	0.832	-0.218
Y:	0.832	1.000	-0.187
Z:	-0.218	-0.187	1.000

Inter-Variable Rank Correlation

	X	Y	Z
X:	1.000	0.740	-0.147
Y:	0.740	1.000	-0.151
Z:	-0.147	-0.151	1.000

Principal Component Analysis

	PC1	PC2	PC3
X:	-0.337756850886	-0.337756850886	0.000757992489173
Y:	0.941233393539	0.941233393539	0.000173668066801
Z:	9.2555000258e-05	9.2555000258e-05	0.000173668066801
Lambda:	56185.1622908	2320.22708066	0.670458140864

Planar Regression: Z = AX+BY+C

Fitted Parameters

	A	B	C
Parameter Value:	6568.14912369	-0.000757975012973	-0.000173690180584
Standard Error:	0.000103834926191	0.000252456492347	728.679593542

Inter-Parameter Correlations

	A	B	C
A:	1.000	-0.832	-0.989
B:	-0.832	1.000	0.741
C:	-0.989	0.741	1.000

ANOVA Table

Source	df	Sum of Squares	Mean Square
Regression:	2 100.922119611	135.395222544	67.697611272

Residual:	4038	2708.65252702	0.670790620858
Total:	4040	2844.04774957	

Coefficient of Multiple Determination (R^2): 0.0476065222761

Nearest Neighbor Statistics

	Separation	|Delta Z|
1%-tile:	0.0924391693928	0
5%-tile:	0.200927848219	0
10%-tile:	0.389708865839	0.01
25%-tile:	0.999545896755	0.02
50%-tile:	1.56095387512	0.05
75%-tile:	1.77394081097	0.11
90%-tile:	1.87262516274	0.2
95%-tile:	1.90318154688	0.3
99%-tile:	1.95299487991	0.54
Minimum:	0.00141421371186	0
Maximum:	3.70222055002	1.08
Mean:	1.35013969176	0.0866443949517
Median:	1.56095387512	0.05
Geometric Mean:	1.13940079578	N/A
Harmonic Mean:	0.554974144141	N/A
Root Mean Square:	1.45667017883	0.141032270988
Trim Mean (10%):	1.38279424323	0.0709183392906
Interquartile Mean:	1.50044879326	0.0553043047996
Midrange:	1.85181738187	0.54
Winsorized Mean:	1.36314200019	0.0726775550606
TriMean:	1.47384861449	0.0575
Variance:	0.299084835201	0.0123859153454
Standard Deviation:	0.546886492063	0.111292027322
Interquartile Range:	0.774394914214	0.09
Range:	3.70080633631	1.08
Mean Difference:	0.591202403081	0.0977483198244
Median Abs. Deviation:	0.288989367209	0.04
Average Abs. Deviation:	0.426470740878	0.0647315021034
Quartile Dispersion:	0.279213493996	N/A
Relative Mean Diff.:	0.437882395938	1.12815514355
Standard Error:	0.00860305642529	0.00175073183308
Coef. of Variation:	0.405059191578	1.2844688613

Skewness:	-0.849934732071	3.26148170755
Kurtosis:	2.88796258005	18.7152104806

Sum:	5455.91449442	350.13
Sum Absolute:	5455.91449442	350.13
Sum Squares:	8574.549448	80.3759
Mean Square:	2.1218880099	0.01989010146

Complete Spatial Randomness

Lambda:	0.0149539045057
Clark and Evans:	0.330206792081
Skellam:	805.648829585

APPENDIX 6: Bathymetry Data Statistical Analysis Report for Moffat dam

Sat Jul 7 20:25:36 2018

Data Source

Source Data File Name:	E:\Desktop\Moffat Bathy_processed.csv
X Column:	A
Y Column:	B
Z Column:	C

Filtered Data Counts

Active Data:	6702
Original Data:	6743
Excluded Data:	0
Deleted Duplicates:	82
Retained Duplicates:	0
Artificial Data:	41
Superseded Data:	0

Exclusion Filtering

Exclusion Filter String:	Not In Use

Duplicate Filtering

Duplicate Points to Keep:	Average
X Duplicate Tolerance:	5.1E-05
Y Duplicate Tolerance:	0.00013
Deleted Duplicates:	82
Retained Duplicates:	0
Artificial Data:	41

X	Y	Z	ID
8490242.5	772146.69	0.61	Artificial
	Retained		
8490242.5	772146.69	0.61	5431
	Deleted		
8490242.5	772146.69	0.61	5432
	Deleted		
8490259.4	772172.88	0.38	Artificial
	Retained		
8490259.4	772172.88	0.38	5503
	Deleted		
8490259.4	772172.88	0.38	5504
	Deleted		
8490261.4	772120.71	0.4	Artificial
	Retained		
8490261.4	772120.71	0.4	5359
	Deleted		
8490261.4	772120.71	0.4	5360
	Deleted		
8490270.2	772135.42	0.4	Artificial
	Retained		
8490270.2	772135.42	0.4	5645
	Deleted		
8490270.2	772135.42	0.4	5646
	Deleted		
8490273.4	772113.78	0.68	Artificial
	Retained		
8490273.4	772113.78	0.68	5288
	Deleted		
8490273.4	772113.78	0.68	5289
	Deleted		
8490276.1	772110.91	0.68	Artificial
	Retained		
8490276.1	772110.91	0.68	5216
	Deleted		
8490276.1	772110.91	0.68	5217
	Deleted		
8490299.2	771935.6	0.67	Artificial
	Retained		
8490299.2	771935.6	0.67	5073
	Deleted		
8490299.2	771935.6	0.67	5074
	Deleted		
8490315.9	772120.59	0.485	Artificial
	Retained		

8490315.9	772120.59	0.46	5719	Deleted
8490315.9	772120.59	0.51	5718	Deleted
8490333.3	771449.52	0.95	Artificial	Retained
8490333.3	771449.52	0.95	3220	Deleted
8490333.3	771449.52	0.95	3221	Deleted
8490340.5	772082.4	0.63	Artificial	Retained
8490340.5	772082.4	0.63	5789	Deleted
8490340.5	772082.4	0.63	5790	Deleted
8490346.4	771909.02	1.855	Artificial	Retained
8490346.4	771909.02	1.82	4930	Deleted
8490346.4	771909.02	1.89	4931	Deleted
8490353.7	771815.61	1.855	Artificial	Retained
8490353.7	771815.61	1.85	4717	Deleted
8490353.7	771815.61	1.86	4716	Deleted
8490361.7	771140.28	1.585	Artificial	Retained
8490361.7	771140.28	1.57	792	Deleted
8490361.7	771140.28	1.6	791	Deleted
8490365	772051.78	0.39	Artificial	Retained
8490365	772051.78	0.39	5859	Deleted
8490365	772051.78	0.39	5860	Deleted
8490368.9	772000.57	0.72	Artificial	Retained
8490368.9	772000.57	0.72	5931	Deleted
8490368.9	772000.57	0.72	5932	Deleted

8490369	771640.56 Retained	1.83	Artificial
8490369	771640.56 Deleted	1.83	4363
8490369	771640.56 Deleted	1.83	4364
8490370.5	771225.47 Retained	1.46	Artificial
8490370.5	771225.47 Deleted	1.46	1434
8490370.5	771225.47 Deleted	1.46	1435
8490373	771216.51 Retained	1.505	Artificial
8490373	771216.51 Deleted	1.48	1148
8490373	771216.51 Deleted	1.53	1149
8490375.9	771253.62 Retained	1.82	Artificial
8490375.9	771253.62 Deleted	1.78	1577
8490375.9	771253.62 Deleted	1.86	1578
8490379.2	771288.56 Retained	1.9	Artificial
8490379.2	771288.56 Deleted	1.9	2218
8490379.2	771288.56 Deleted	1.9	2219
8490396.4	771170.02 Retained	3.24	Artificial
8490396.4	771170.02 Deleted	3.22	1079
8490396.4	771170.02 Deleted	3.26	1078
8490399.2	771168.77 Retained	3.255	Artificial
8490399.2	771168.77 Deleted	3.23	1077
8490399.2	771168.77 Deleted	3.28	1076
8490402.1	771239.49 Retained	2.93	Artificial
8490402.1	771239.49 Deleted	2.93	1505

8490402.1	771239.49	2.93	1506	Deleted
8490426.2	771137.09	4.785	Artificial	Retained
8490426.2	771137.09	4.71	864	Deleted
8490426.2	771137.09	4.86	863	Deleted
8490434.4	771075.8	4.145	Artificial	Retained
8490434.4	771075.8	4.09	434	Deleted
8490434.4	771075.8	4.2	433	Deleted
8490438.4	771676.93	1.49	Artificial	Retained
8490438.4	771676.93	1.49	4430	Deleted
8490438.4	771676.93	1.49	4431	Deleted
8490445.2	771601.03	2.11	Artificial	Retained
8490445.2	771601.03	2.11	4002	Deleted
8490445.2	771601.03	2.11	4003	Deleted
8490448.4	771049.73	2.3	Artificial	Retained
8490448.4	771049.73	2.27	147	Deleted
8490448.4	771049.73	2.33	148	Deleted
8490448.9	771090.72	5.28	Artificial	Retained
8490448.9	771090.72	5.25	577	Deleted
8490448.9	771090.72	5.31	578	Deleted
8490458.9	771210.46	4.36	Artificial	Retained
8490458.9	771210.46	4.33	1363	Deleted
8490458.9	771210.46	4.39	1362	Deleted
8490469.1	771104.55	5.24	Artificial	Retained

8490469.1	771104.55 Deleted	5.24	720
8490469.1	771104.55 Deleted	5.24	721
8490481.5	771177.59 Retained	3.99	Artificial
8490481.5	771177.59 Deleted	3.99	1220
8490481.5	771177.59 Deleted	3.99	1221
8490491.3	771227.18 Retained	4.41	Artificial
8490491.3	771227.18 Deleted	4.4	1648
8490491.3	771227.18 Deleted	4.42	1649
8490511.3	771150.92 Retained	4.505	Artificial

Data Counts

Active Data: 6702

Univariate Statistics

	X	Y	Z
Count:	6702	6702	6702
1%-tile:	8490248.199	771041.512	0.4
5%-tile:	8490273.45	771068.211	0.5
10%-tile:	8490299.108	771105.644	0.63
25%-tile:	8490347.355	771229.658	0.94
50%-tile:	8490389.329	771468.184	1.59
75%-tile:	8490470.953	771912.733	2.79
90%-tile:	8490536.576	772100.943	4.2
95%-tile:	8490583.331	772127.167	4.81
99%-tile:	8490653.7	772172.822	5.33
Minimum:	8490233.841	771027.641	0.38
Maximum:	8490668.405	772183.669	5.74
Mean:	8490409.2327	771544.865833	2.00886078782
Median:	8490389.3345	771468.343	1.59
Geometric Mean:	8490409.23219	771544.781145	1.59866603616

Harmonic Mean:	8490409.23169	771544.696466	1.2609934919
Root Mean Square:	8490409.23321	771544.950531	2.41229855261
Trim Mean (10%):	8490404.87971	771538.344977	1.92062510363
Interquartile Mean:	8490397.46352	771494.005121	1.69505669949
Midrange:	8490451.123	771605.655	3.06
Winsorized Mean:	8490406.00714	771545.305521	1.95836019099
TriMean:	8490399.2415	771519.68975	1.7275
Variance:	8622.65121327	130715.107447	1.78392882064
Standard Deviation:	92.8582318013	361.545443129	1.33563798263
Interquartile Range:	123.597999999	683.075	1.85
Range:	434.563999999	1156.028	5.36
Mean Difference:	103.647183372	411.731445507	1.46517263911
Median Abs. Deviation:	58.4675000003	273.6345	0.815
Average Abs. Deviation:	73.643828111	312.969542226	1.05654356908
Quartile Dispersion:	7.27868338012e-06	0.00044265195745	0.495978552279
Relative Mean Diff.:	1.22075603816e-05	0.00053364549975	0.729354989649
Standard Error:	1.13427457623	4.41632148639	
	0.0163149801299		
Coef. of Variation:	1.09368381731e-05	0.000468599376575	0.664873340514
Skewness:	0.636357661954	0.342633295278	0.904055607186
Kurtosis:	3.0386231632	1.71020777324	2.83055478946
Sum:	56902722677.6	5170893690.82	13463.385
Sum Absolute:	56902722677.6	5170893690.82	13463.385
Sum Squares:	4.83127402045e+17	3.98957735484e+15	39000.173225
Mean Square:	7.20870489474e+13	595281610690	5.81918430692

Inter-Variable Covariance

	X	**Y**	**Z**
X:	8622.6512	-24308.98	44.577263
Y:	-24308.98	130715.11	-313.02384
Z:	44.577263	-313.02384	1.7839288

Inter-Variable Correlation

	X	Y	Z
X:	1.000	-0.724	0.359
Y:	-0.724	1.000	-0.648
Z:	0.359	-0.648	1.000

Inter-Variable Rank Correlation

	X	Y	Z
X:	1.000	-0.750	0.520
Y:	-0.750	1.000	-0.689
Z:	0.520	-0.689	1.000

Principal Component Analysis

	PC1	PC2	PC3
X:	0.982096928269	0.982096928269	0.00332507475843
Y:	0.188337280335	0.188337280335	0.00301306290901
Z:	-0.00383305636913	-0.00383305636913	0.00301306290901
Lambda:	135377.823119	3960.73048744	0.988983033579

Planar Regression: Z = AX+BY+C

Fitted Parameters

	A	B	C
Parameter Value:	30550.169401	-0.00332417144421	-0.00301289623215
Standard Error:	0.000189714120939	4.87255977164e-05	1638.17660146

Inter-Parameter Correlations

	A	B	C
A:	1.000	0.724	-1.000
B:	0.724	1.000	-0.735
C:	-1.000	-0.735	1.000

ANOVA Table

Source	df	Sum of Squares	Mean Square
Regression:	2 2692.21061984	5326.798305	2663.3991525
Residual:	6699	6627.30872211	0.989298211989
Total:	6701	11954.1070271	

Coefficient of Multiple Determination (R^2): 0.445604033235

Nearest Neighbor Statistics

	Separation	|Delta Z|
1%-tile:	0.0322490314131	0
5%-tile:	0.194537912926	0
10%-tile:	0.363265743248	0
25%-tile:	0.80989196814	0.02
50%-tile:	1.48274407781	0.04
75%-tile:	1.61390210261	0.08
90%-tile:	1.76609314593	0.15
95%-tile:	1.88876811869	0.22
99%-tile:	2.01609722021	0.46
Minimum:	0.00699999998324	0
Maximum:	3.68903049712	1.72
Mean:	1.2436215905	0.0674686660698
Median:	1.48282618472	0.04
Geometric Mean:	1.0192450669	N/A
Harmonic Mean:	0.484687813577	N/A
Root Mean Square:	1.35483348177	0.11256224446
Trim Mean (10%):	1.26576397554	0.0548897363621
Interquartile Mean:	1.38509003639	0.045119367353
Midrange:	1.84801524855	0.86
Winsorized Mean:	1.24670596122	0.0555849000298

TriMean:	1.34732055659	0.045
Variance:	0.289022227749	0.00811944947319
Standard Deviation:	0.537607875453	0.0901079878434
Interquartile Range:	0.804010134468	0.06
Range:	3.68203049714	1.72
Mean Difference:	0.588147272645	0.0755667201677
Median Abs. Deviation:	0.247527247621	0.03
Average Abs. Deviation:	0.42044165866	0.0502335123844
Quartile Dispersion:	0.331715529868	N/A
Relative Mean Diff.:	0.47293105647	1.12002688907
Standard Error:	0.00656694547459	0.00110068001235
Coef. of Variation:	0.432292169547	1.33555312551
Skewness:	-0.706794497413	4.76340792702
Kurtosis:	2.56523602337	50.4378706119
Sum:	8334.75189954	452.175
Sum Absolute:	8334.75189954	452.175
Sum Squares:	12302.0153619	84.916075
Mean Square:	1.83557376334	0.0126702588779

Complete Spatial Randomness

Lambda:	0.0133408138555
Clark and Evans:	0.287282658536
Skellam:	1031.1894422

APPENDIX 7: Grid Volume Computation Reports

(i) Grid Volume Computation Report for Moffat dam

Wed Jul 25 22:15:19 2018

Upper Surface

Grid File Name:	E:\Desktop\Moffat Bathy_processed.grd
Grid Size:	100 rows x 38 columns
X Minimum:	8490233.841
X Maximum:	8490668.405
X Spacing:	11.744972972954
Y Minimum:	771027.6409
Y Maximum:	772183.669
Y Spacing:	11.677051515151
Z Minimum:	0.376730
Z Maximum:	5.743347

Lower Surface

Level Surface defined by Z = 1339.629

Volumes

Z Scale Factor: 1

Total Volumes by:

Trapezoidal Rule:	1,180,462.043298
Simpson's Rule:	1,176,287.287654
Simpson's 3/8 Rule:	1,180,520.078653

Cut & Fill Volumes

Positive Volume [Cut]:	789,478.765687
Negative Volume [Fill]:	390,970.548767
Net Volume [Cut-Fill]:	1,180,448.654768

Areas

Planar Areas

Positive Planar Area [Cut]:	298,879.904323
Negative Planar Area [Fill]:	435,865.247222
No Data Planar Area:	0
Total Planar Area:	734,745.147324

Surface Areas

Positive Surface Area [Cut]:	298,808.6798365
Negative Surface Area [Fill]:	435,865.2473248

(ii) Grid Volume Computation Report for GRZ Weir

Wed Jul 25 22:25:13 2018

Upper Surface

Grid File Name:	E:\Desktop\GRZ Weir Bathy_processed.grd
Grid Size:	100 rows x 32 columns
X Minimum:	8487709.8
X Maximum:	8488006.7
X Spacing:	11.58497
Y Minimum:	764514.2
Y Maximum:	764473.92
Y Spacing:	11.4570515
Z Minimum:	0.633148
Z Maximum:	5.203347

Lower Surface

Level Surface defined by Z = 1306.157

Volumes

Z Scale Factor: 1

Total Volumes by:

Trapezoidal Rule:	197, 218.021789
Simpson's Rule:	196, 675.587650
Simpson's 3/8 Rule:	197, 289.563452

Cut & Fill Volumes

Positive Volume [Cut]:	120,115.434667
Negative Volume [Fill]:	77,103.897659
Net Volume [Cut-Fill]:	197,218.648763

Areas

Planar Areas

Positive Planar Area [Cut]: 59,894.958765
Negative Planar Area [Fill]: 88 661.464453
No Data Planar Area: 0
Total Planar Area: 148,556.411763

Surface Areas

Positive Surface Area [Cut]: 59,843.214534
Negative Surface Area [Fill]: 88 661.461563