Investigating Impacts of Sedimentation on Water Availability in Small Dams:
Case Study of Chamakala II Small Earth Dam in Malawi

By

Sydney Lixiel Kamtukule

A thesis submitted in partial fulfillment of the requirements for the Masters Degree of Integrated Water Resources Management

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ABSTRACT

The contribution of multipurpose small earth dams in ensuring equitable and sustainable water supply especially to rural communities cannot be emphasized. Water from small dams is basically meant to improve rural livelihoods of communities dependent on reservoir water. However, there are some issues of interest that need to be paid enough attention if small dam development projects are to achieve their intended goals. In Malawi small earth dams are normally not subjected to detailed sediment transport data assessment despite the fact that currently the Malawi Government has embarked on the construction of about 350 new small dams throughout the country. Reports from some parts of the country show that sedimentation problems of dams have reached levels of great concern leading to anxieties over the availability of useable water resources and examples are given of Nyakamba and Masambanjati Small Earth Dams which were actually silted up. The Ministry of Irrigation and Water Development admits that the problem has reached levels which require serious considerations regarding catchment management issues.

This study was therefore carried out at Chamakala II Small Earth Dam in order to assess the impact of sedimentation on water availability for the communities that are dependent on the reservoir water. Field reconnaissance surveys were carried out to collect catchment data on activities carried out by the local communities. Official data was referred to in many cases and interviews mostly unstructured with key informants were conducted. Currently in Chamakala Catchment there are about 8200 people, 1400 cattle, 1100 goats and 200 goats that are said to be direct beneficiaries from the reservoir water especially during dry seasons. The study looked at catchment characteristics and some activities such as cultivation practices, deforestation, land cover, soil characteristics, and grazing practices. Several studies have shown that these parameters are major causes of sedimentation of the small dams in some instances depending on other factors. The dam at Chamakala II had been desilted twice since its rehabilitation works in 2002 but continues to show signs of increasing sediment yield at an alarming average rate of 2250 m^3/yr. In addition to the methods described above, a hydrographic survey was conducted at the dam in order to determine impacts of sedimentation on water availability in the dam. In this study a small boat, a staff and a rope marked at known intervals of 10 and 20 metres, leveling instrument and many others were used The study found that reservoir capacity was reduced by 38.7% and its life expectancy reduced by 50%. From the study findings the current rate of sedimentation in the dam is at 2250 m^3/yr and 517 $Tkm^{-2}y^{-1}$ of sediment is transported from the catchment and get deposited in the dam. The assessment shows that if no appropriate measures would be put in place to arrest the current rate of sediment deposition, the dam would lose its capacity by the year 2015 thereby leaving a growing human population at 8.2 percent per annum plus the increasing population of livestock with no water for the most part of the year.

The findings from the study show that there is an inverse relationship between sedimentation and reservoir yield which indicates that sedimentation may lead to water scarcity if not controlled. The study sees the need for reconsideration on the need for proper sediment transport assessment if the availability of water resources in small dams is to be sustainable.

DECLARATION

I **SYDNEY LIXIEL KAMTUKULE** hereby do declare that all the work done in this study originates from my own work and that all secondary sources referred to in this work have been duly acknowledged and therefore this thesis is submitted for an award of the degree of Masters of Integrated Water Resources Management tenable in the Department of Civil Engineering of the University of Zimbabwe.

....

Date:...................

DEDICATION

This thesis is warmheartedly dedicated to my parents, wife Scolla, my son Rueben, brothers and sisters for their moral and spiritual support.

ACKNOWLEDGEMENTS

Glory and honour be to the Almighty God for the opportunity given to me to pursue this course at this point in time. The Lord has been good to me for the fact that He has taken me through many challenging moments which I will live to remember.

I thank the WaterNet Secretariat for enabling me to be part of this very important program by securing sponsorship for me so that I could study for a Masters Degree of IWRM. Thanks very much.

My sincere appreciations go to my supervisors: Engineer E. Kaseke, Mr. A. Mhizha both from University of Zimbabwe and Dr K. Wiyo of Bunda College of Agriculture in the University of Malawi. It was a challenge for me to come up with this thesis but your indefatigable love and enthusiasm have kept me sailing to this day. Thank you very much indeed and may the Lord our God bless you.

I would also like to thank all lectures and my fellow students for their contributions through their constructive criticisms and encouragements done in various ways which have helped me to finally come up with this thesis. I always remember that, *"speed is irrelevant if you are going in the wrong direction"* Gandhi.

Again I would like to thank Messrs Chavula, Mzee, Kanyenda, Tembewa and Mfuyeni the driver for their assistance in various ways during the study especially during the hydrographic survey. It would be impossible for one man to do it but with their assistance things worked out well. Special thanks to Messrs Chiumia and Chiwanda for the technical guidance and supervision during the survey.

Lastly, I would like to thank the Management of the Ministry of Irrigation and Water Development in Malawi for granting me the opportunity to participate in this programme despite staff shortages being experienced at the moment and for all the assistance and guidance that was rendered to me during the time of my study. I cannot mention them all but I can only say; thank you very much.

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ABBREVIATIONS

A	Area
AAR	Average Annual Rainfall
ADF	Average Daily Flow
BFI	Base Flow Index
BGS	British Geological Survey
BWB	Blantyre Water Board
CRWB	Central Region Water Board
EIA	Environmental Impact Assessment
EI	Evaporation Index
EVAP	Evaporation
FDC	Flow Duration Curves
GNP	Gross National Product
GWP	Global Water Partnership
HIV/AIDS	Human Immunodeficiency Virus/Acquired Immune Deficiency Syndrome
IWRM	Integrated Water Resources Management
LWB	Lilongwe Water Board
MASAF	Malawi Social Action Fund
MAR	Mean Annual Runoff
MDGs	Millennium Development Goals
MNWP	Malawi National Water Policy
NGOs	Non Governmental Organizations
NSO	National Statistics Office
RA	Reservoir Area
RC	Reservoir Capacity
SWIM	System Wide Initiative on Water Management
TBM	Temporally Bench Mark
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
USACE	United States Army Corps Engineers
USDA	United States Department of Agriculture
WRA	Water Resources Act
WRMPS	Water Resources Management Policy and Strategy
WRPS	Water Resources Planning Strategy
Y_{max}	Maximum Dry Season Yield
ZINWA	Zimbabwe National Water Authority

CHAPTER ONE

INTRODUCTION

1.1 Preamble

The ultimate destiny of all reservoirs is to be filled with sediment and the obvious consequence of sedimentation is the decrease of the live storage of the reservoir and hence its functions and life span (Linseley et al.1992). The volume of sediment material in reservoirs depends on the quality of inflowing water, catchment quality, sediment load, reservoir geometry, projected operation and life among other things. A reservoir changes the dynamics of river flow by forcing the energy gradient to approach zero and results in loss of transport capacity of the river with the resulting deposition. Following this, information such as design life of the reservoir, reservoir capacity, reservoir yield, and sediment yield from the catchment is required so as to effectively manage reservoir sedimentation.

In Malawi, many small reservoirs have their lives shortened due to both human activity and natural factors such as drought and excessive rainfalls. For example in the cases of Masambanjati and Nyakamba small earth dams in which the former failed due to human activity and the later due to heavy rains within a year of their construction as reported to the Ministry responsible for Water Affairs in Malawi (Mamba, 2007). The impact of sedimentation has resulted in some water supply projects being unsustainable thereby not meeting the intended goals of improving the livelihoods of rural communities who are in dire need of reliable sources of water for multiple uses such as domestic, irrigation, livestock watering and many more. In all, sedimentation has negatively affected some water resources development efforts being taken by Government and Non Governmental Organizations (NGOs) and the private sector. A random assessment of some reservoirs has revealed that the majority of them have their lives shortened mainly due to sedimentation and lack of maintenance (Ministry of Water Development, 2004).

1.2 Problem Statement

Collectively small reservoirs contribute very significantly to the availability of water resources for most of the rural communities for the improvement of their livelihoods. However, loss of storage due to sedimentation exacerbates the problem of providing enough storage for the rising population with its rising aspirations and standards (Ainworth, 2005).

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. Many researchers in this field estimate the reduction of the current reservoirs capacity up to 50% in few years within the first 10 to 15 years of their construction with obvious social, environmental and economic impacts strongly related with the growing water demand and in general with the water resources management. In support of the same argument, Giessen (2006) states that there is need to develop tools in collaboration with local and regional stakeholders, for the analysis and design of the small reservoirs to collaborate and ensuring long-term sustainability of local water supplies to improve rural livelihoods.

1.3 Justification

The problem of sedimentation in small reservoirs cannot continue to be ignored in rural areas of Malawi such as Chamakala. A report prepared by the Ministry of Water Development (MWD) in 2004 on the status of reservoirs in Malawi indicate, that most of the existing small reservoirs have lost their storage capacities and has led to notable shortages of productive water. In some cases, this has led to unsustainable development projects aimed at the improvement of rural livelihoods by providing portable water for domestic use, irrigation and livestock watering among many other uses (MWD, 2004). The reports further states that most of the small reservoirs that were built between 1950s and 1970s in the country have deteriorated and degraded due to lack of maintenance of the facilities and serious environmental degradation of the reservoir catchments. In a related development, recently it was stated by Kadewere, (2007), that the Mudi Dam which is the main sources of portable water being supplied to the City of Blantyre currently supplies about 20% of the yield and 10% of the water demand due to the problem of sedimentation.

Communities around Chamakala II Dam have persistently been experiencing productive water shortages from the reservoir despite the fact that the area has been receiving adequate average annual rainfall (AAR) of 831 mm. Reports reaching the Ministry of Irrigation and Water Development show that the earth dam had dried up due to sedimentation in 2005 and 2006 and the same is likely to occur this in 2008. Shortages of water in reservoirs and other sources result in several problems for the local communities in the area such that sometimes they have to walk long distances to fetch water mainly for domestic purposes and livestock watering. According to one village headman in the area, livestock owners and wardens sometimes have to walk long distances between 10 km to 15 km to find reliable water sources for watering the livestock mostly cattle.

Mchazime, (2002) reports that the reservoir at Chamakala had been silted up after several years of its construction in 1949 and it was consequently rehabilitated in 2002 to ensure that communities surrounding the reservoir have adequate water supply sources for livestock watering, irrigation and domestic uses. According to the report, the newly rehabilitated dam was redesigned for 34760 m^3 water holding capacity with the expected life of 30 years. The report states that the surrounding community had high expectations from the project so that during the rehabilitation exercise of the dam, they had very good participation and were optimistic about the positive changes that the project would bring. However, like the case of many dams, early siltation of the dam was deemed a threat to water accessibility so that since 2002, the local communities in the area have been involved in sediment excavation from the reservoir. Despite the efforts made, the level of sedimentation observed during the past five water seasons was more than expected and no reasons have been determined yet for the sudden change of events and sediment levels.

Aynekulu et al (2006) state that in order for one to plan properly for reservoirs, there is need for appropriate measurement interventions and knowledge of the existing sedimentation rates of the reservoirs. However, in the case of small dams in Malawi there is generally lack of data availability in the field of sedimentation and Chamakala II Small Earth Dam is no exception.

This study therefore focuses on a small dam called Chamakala II Community Small Earth Dam in Kasungu District which is in the central region of Malawi. The dam was rehabilitated in 2002 with new design data to supply water for multiple uses such as irrigation, livestock watering, domestic for the surrounding communities. However, recent reports show that it has been persistently faced with sedimentation problems for the past six years. The study aims at determining the impacts of sedimentation on the sustainability of water availability from the dam. In addition, to make projections of those impacts on the dam's ability to supply water resources for the improvement of rural livelihoods and the growing population dependent on Chamakala II Small Earth Dam.

1.4 Objectives

1.4.1 Main Objective

The main objective of this study is to make predictions on the impact of sedimentation on water availability for the rural livelihoods which are dependent on the water from Chamakala II Small Earth Dam.

1.4.2 Specific Objectives

1. To determine causes of sedimentation of the Chamakala II Small Earth Dam,

2. To determine the extent and rate of sediment accumulation at Chamakala II Small Earth Dam,

3. To analyze and make predictions on the impacts of sedimentation on the efficiency and reliability of the dam to supply water for the wellbeing of rural livelihoods in the area, and

4. To determine and predict the impact of sedimentation on the trap efficiency of the dam at Chamakala II.

CHAPTER TWO

DESCRIPTION OF STUDY AREA

2.1 Physiography

Chamakala II Small Earth Dam is located in a rural area of the Dwangwa Catchment on Chamakala River which is a tributary to Mpasadzi River which drains into Lake Malawi. The dam lies between latitude 12º45’0 South and longitude 33º28’0 East on Map sheet $1233C_2$, grid reference number 508918 and has an altitude of 1038 meters above sea level. The area receives an annual average rainfall of about 831 mm with temperature values ranging from 15ºC to 30ºC.

2.2 Study Area

This study focused on a small earth dam in a rural area at Chamakala in Malawi located in a major tobacco growing district of Kasungu in the central part of Malawi (see Fig. 3.1). The dam is located in Ndau/Ndawo village which is at a distance of about 50 km North West (NW) of Kasungu Town and about 4.5 km South of Chamakala Trading Centre. 300 m East away from the dam is the main road (M1) that runs through Kasungu Town to the Southern and Northern parts of Malawi running almost parallel to Chamakala River. The small reservoir at Chamakala was initially built in 1949 to conserve water for irrigation and livestock watering for the communities around in a catchment whose area is 5.3 km^2 and mainly communal lands (Ministry of Lands, 2006).

Kasungu District is one of the high productive areas in the agricultural sector (both subsistence and commercial) and contributes a lot to the economy of Malawi which is agricultural based. Agriculture accounts for about 38 percent of Gross National Product (GNP) and more than 90 percent of the country’s export earnings (Ministry of Commerce and Industry, 2001). Chamakala area has a population of 8121 people with a population growth rate of 8.216 percent per year (NSO, 2007). People in the area are basically subsistence farmers who rely on cultivation and livestock rearing for their daily living. Information gathered during the study through the village headmen in the surrounding villages show that currently the area has 1327 cattle, 1103 goats and 192 sheep and the main reliable source of water for the livestock is this Chamakala II Small Earth Dam.

According to an agricultural adviser working in the area in the Ministry of Agriculture; 5% of the catchment has scrub or medium grass, 80% is cultivated while 15% is bare or eroded land. Chamakala catchment has deep moderately drained soils estimated at 40% and has 40% fair permeability/depth drainage with 85% moderate slope while the remaining 5% is steep.

2.3 Definition and classification of dams in Malawi

A dam which is also termed as reservoir is defined as any structure capable of diverting or holding back water and in Malawi dams are classified based on either reservoir capacity or height (PEM Consult, 1999). Table 2.1 offers dam size classifications for Malawi based on the two classifications. Generally a reservoir refers to actual water body and the two words will be used in this paper interchangeably. In the context of Malawi all dams are subject to Environmental Impact Assessments (EIA) except those categorized as very small dams.

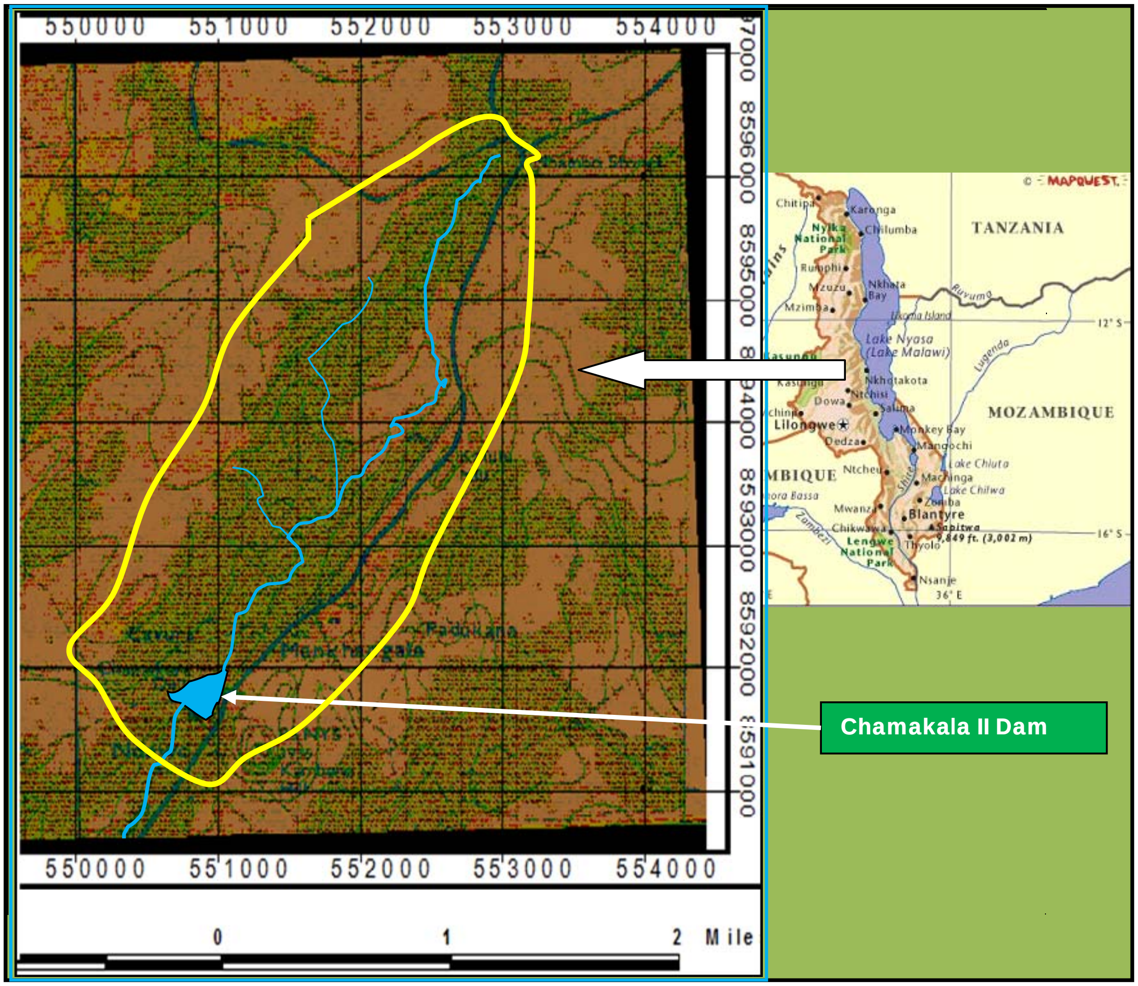

Fig. 2.1: Study Area at Chamakala II *(adopted from Department of Lands and Surveys)*

Table 2.1: Classification of Dam sizes in Malawi

Size	**Reservoir Capacity (10^3 m^3)**	**Height (m)**
Very small	<50	<4.5
Small	50-1 000	4 - 8
Medium	1 000-5 000	8 - 15
Large	5 000-20 000	15 - 30
Major	>20 000	>30

Adopted from PEM Consult (1999).

2.4 Issues of Sedimentation at Chamakala II Dam Reservoir

The issue of reservoir sedimentation is not new at Chamakala II Small Earth Dam which was initially constructed in 1949. Over the years, the small reservoir silted up and rehabilitation works were carried out in 2002 according to information gathered from the Ministry of Irrigation and Water Development. The small reservoir had completely lost its capacity to hold productive quantities of water due extensive sedimentation. Many factors are attributed to have contributed to the poor status of the reservoir at Chamakala II Small Earth Dam and they include poor land management in the catchment, deforestation, overpopulation, lack of sense of ownership and lack of education among others.

However, latest reports indicate that the reservoir is already showing signs of silting up again despite the fact that twice the reservoir has been desilted in 2005 and 2007 with funding from the Malawi Social Action Fund (MASAF). According to a local leader in the area, shortages of water from the reservoir result in several problems for the communities who normally use the water for livestock watering and domestic purposes especially when the available scarce boreholes cannot support them effectively.

In response to problems of water shortages due to issues like sedimentation, the Government of Malawi has a strategy to ensure the recognition and promotion of community based management and demand driven approaches in all rural water supply and sanitation interventions, with national guidelines and standards. The strategy known as the Water Resources Policy and Strategies (WRPS) is to ensure there is greater participation of stakeholders in the planning, development, management and investment in water supply and sanitation projects. This is being done as a way of empowering communities or beneficiaries to own, operate, maintain and manage their own water facilities and services with the involvement of the public and private sectors, NGOs and donors (Malawi Government, 1999). In the case of Chamakala II Small Earth Dam, a community committee is already in place to enforce and facilitate the smooth management of the reservoir catchment area and sustain all other water development projects in the area including borehole drilling projects.

CHAPTER THREE

LITERATURE REVIEW

3.1 Introduction

This chapter discusses some studies and work done on small dams and sedimentation of the small reservoirs in Malawi and elsewhere. The main focus in this literature review is on sedimentation of small reservoirs in general and how it affects the scarce fresh water resources and to identify different approaches to deal with issues of reservoir sedimentation.

3.2 Integrated Water Resources Management (IWRM) in Malawi

Integrated Water Resources Management (IWRM) is a process which promotes the coordinated development of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP, 2006). According to the Malawi National Water Policy (2006) the Government of Malawi and other stakeholders such as Non Governmental Organizations (NGOs) and the donor community have played vital roles in many different ways. The efforts made are aimed at ensuring that water resources development in Malawi is attainable in line with the Millennium Development Goals (MDGs) advocated by the United Nations (UN). The Millennium Development Goals as outlined by van der Zaag (2003) acknowledge the critical and multifaceted role of water in realizing a world where:

- prevalence of poverty and hunger is halved by 2015
- gender equity and empowerment of women are promoted
- HIV/AIDS, malaria and other diseases are combated
- environmental sustainability is ensured, and
- a Global Partnership for Development is developed.

In order to achieve these goals the role of small reservoirs need to be embraced as a tool to ensure equity, efficiency and sustainability and supplying of portable water to rural communities worldwide.

3.3 Development of Small Dams in Malawi

The history of dam development in Malawi dates back as far as early 1950s under the Nyasaland Government during which a number of small and medium-sized dams were built across the country for various purposes including drinking water supply, irrigation agriculture, fisheries, livestock watering and conservation. Reports from the Ministry show that over 700 small and medium size dams had been built across the country, mostly by government between 1949 and 1970s to address events of droughts in the aftermath of another drought that hit the country in 1949 and others (Malawi Government, 2004).

Of late the Malawi Government has embarked on an intensive development campaign to construct over 350 small dams all over the country with the Ministry of Irrigation and Water Development taking a leading role. It is reported by officials in the Ministry that in mostly the existing small dams do not have design and sediment data available. The same applies to Chamakala II Small Earth Dam which was initially built in 1949 to supply water to the surrounding communities of Chamakala II for multiple uses including domestic, livestock watering, irrigation, fisheries and many others in-order to improve rural livelihoods in area.
Worldwide dams are defined and classified differently depending on agreed standards in individual countries. However, in all countries a general description of a dam is that it is any structure capable of diverting or storing water (Sawunyama, 2005). Table 3.1 shows different classifications of dams based on height and capacity.

Table 3.1: Classification of Dams in Some Countries

Organization/Country	Unit	Dam/ Reservoir Classification			
		Small	Medium	Large	Major
Malawi	$x10^6$ m^3	<1	1-5	5-20	≥20
	Height (m)	<8	8-15	15-30	≥30
Zimbabwe	$x10^6$ m^3	<1 $x10^6$	<1 $x10^6$-3 $x10^6$	3 $x10^6$-20 $x10^6$	≥20$x10^6$
	Height (m)	<8	8-15	15-30	≥30
South Africa	$x10^6$ m^3	-	-	-	-
	Height (m)	5-12	12-30	≥30	-
United States of America*	$x10^6$ m^3	<0.123	0.123-5	≥5	-
	Height (m)	≤6	6-12	≥12	-
World Bank*	$x10^6$ m^3	-	-	-	-
	Height (m)	<15	-	≥15-	-
World Commission on Dams*	$x10^6$ m^3	0.05-1	-	-	-
	Height (m)	<15	-	-	-

Adopted from PEM Consult (1999) and *Sawunyama (2005)

3.4 The Role of Small Dams in Water Resources Development

The multiple uses of small reservoirs cannot be underestimated. They can contribute significantly to ensuring reliable domestic water supply and livestock watering, support small scale irrigation, promote tourism, and regulate seasonal flows to provide reliable flows all-year round. Small reservoirs on the other hand directly support local and commercial community initiatives to safeguard against water scarcity due to drought so that smallholder farmers can realize the ultimate goals of increased production of food, reduced poverty, and improved rural livelihoods. Therefore, there is need to develop tools in collaboration with local and regional stakeholders, for the analysis and design of the small reservoirs. This helps decision makers and other stakeholders such as the farming community to collaborate and ensuring long-term sustainability of local water supplies to improve their livelihoods (Van de Giesen, 2007).

In a study carried out in Zimbabwe on small dams it was observed that people living in arid areas with highly variable rainfall, experience droughts and floods and often have insecure livelihoods. As such small dams are widely used for water storage and provision of water services to the communities multiple uses such as domestic use, livestock watering, small scale irrigation, brick making and supporting wild life (Senzanje et al. 2006).

In another study carried out in Brazil's Preto River Basin by Balazs (2006), it was found that small reservoirs play very important roles especially for rural community livelihoods. According to the study findings, rural livelihoods benefited from small reservoirs are both economic and non economic. Small reservoirs provide a year round supply of water allowing small farmers to irrigate their crops during the wet and dry season and this supports a critical livelihood strategy of market oriented crop production, yields and a tangible outcome, and income generation. In the study it was found that 67% of the households interviewed in communities with small reservoirs produced crops using irrigation while 83% of farmers used water from small reservoirs for irrigation.

According to Balazs (2006) one role the small reservoirs can play at domestic level is to provide an important nutritional supplement to daily diets on the perspective of livelihoods well being. Thirdly, small reservoirs help to narrow inequality gaps in accessing water by rural communities and that when the small reservoirs are unequally distributed there is the problem of inequalities in as far as access to safe water is concerned.

As part of a strategy for realizing development goals of poverty reduction, the Malawi Government has decentralized political and administrative authority from the central government to district and community levels. The main purpose for this initiative is to:

- empower communities,
- promote popular participation in the governance and development issues, and
- improve service delivery at local level in all districts in Malawi.

Following this, some water services such as development of boreholes, piped water, protected wells, water distribution and gravity fed piped water schemes have been decentralized to district assemblies (National Decentralization Policy, 1998).

3.5 Definition of sedimentation

Different scholars have defined the concept of sedimentation worldwide and in general, sedimentation is defined as the deposition by settling of a suspended material due to gravity. In other words, sedimentation is a result of sediments which are defined as particulate matter that can be transported by fluid flow and eventually are deposited as a layer of solid particles on the bed or bottom of water body such as reservoirs (Wikipedia Free Encyclopedia, 2008).

3.6 Impacts of Sedimentation in Reservoirs

Sedimentation is common to all reservoirs and it is widely recognized that each year up to 1 percent of the world's reservoir capacity is lost to sedimentation (Howard, 2000). Several case studies have been conducted in the field of reservoir sedimentation and they point to the fact that sedimentation actually reduces reservoir storage capacities. Ainworth (2005) compiled a report on the World Water Storage in Man Made Reservoirs based on several studies carried out by many authors.

According to Ainworth (2005), loss of storage due to sedimentation exacerbates the problem of providing enough storage for the rising population with its rising aspirations and standards. The report states that demand for additional storage is assumed to be 1.6% in 2000 falling to 1.2% in 2030. The analysis shows that South America, Africa and Asia water storage demands would outstrip supply in the foreseeable future and the storage shortage is attributed to high sedimentation rates in these regions. In another study by Chao, (2004), observes 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. The study findings show that about 1% 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 as a result.

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. The author states further that there are a number of direct and indirect consequences of reservoir sedimentation on environment with the loss of water resources being the most obvious consequence.

According to Halcrow, (2001) there are both positive and negative impacts of reservoir sedimentation. The positive impacts include; generation of valuable wetland habitat with biological diversity, reduction of fine sediment discharge and hence improved water quality. Further, there is an opportunity for uses of sediment deposits in substitution of other peat based compost (manure) and finally the control on the use of reservoir catchments may significantly benefit the environment. However, negative impacts of reservoir sedimentation include;

- loss of reservoir water storage capacity,
- need for periodic operations of bottom outlet valves for safety reasons,
- need for restrictions on draw down of reservoirs through bottom outlet valves to prevent sediment being mobilized during storms, and
- environmental impacts in remote areas due to removal and transport of sediment deposits.

3.7 Problems of Sedimentation of Small Reservoirs in Malawi

The Malawi National Water Policy (MNWP) of 2006 acknowledges that Malawi as a country has abundant surface water and groundwater resources but these resources are of variable quality and quantities, unevenly distributed in time and space, and are subjected to poor conservation and management (Malawi Government, 2006).

Some small reservoirs have been subjected to problems of sedimentation, resulting in reservoir failures. For example Masambanjati Small Earth Dam which was built in 2004 in Thyolo District but was silted up in less than two years after its construction. A second reservoir was reported a failure in Chikwawa District after heavy rains resulting in the dam being overtopped and completely washed away (Department of Water Resources, 2007).

Kadewere (2007) states that by 1999 Mudi Dam which is owned by the Blantyre Water Board (BWB) had lost its storage capacity due to sedimentation by 30% of the design capacity of 1.5 Mm^3 in 1955. According to the study the reservoir was to supply about 8000 m^3 per day only by 2007 against the designed capacity of 45000 m^3 per day representing 20% of yield and 10% of total water demand by the Blantyre City residents. Unconfirmed reports show that similar cases are also being experienced by the Lilongwe Water Board (LWB) at the two Kamuzu Dams (I and II) and the Central Region Water Board's (CRWB) Chitete Dam in Kasungu.

In order to deal with issues of water shortages due to issues like sedimentation problems, the Government of Malawi has a strategy put in place to ensure the recognition and promotion of community based management and demand driven approaches in all rural water supply and sanitation interventions, with national guidelines and standards (Malawi Government, 1999). Further to that, the strategy will ensure greater participation of stakeholders in the planning, development, management and investment in water supply and sanitation projects. This is aimed at empowering communities or beneficiaries to own, operate, maintain and manage their own water facilities with the involvement of the public and private sectors, Non-Governmental Organizations (NGOs). In the case of the community at Chamakala II, a local committee is put in place to facilitate the development and management of the water services such as small reservoirs and borehole drilling.

3.8 Causes of Reservoir Sedimentation

The susceptibility of reservoir sedimentation depends on the sediment delivery of the watercourses, the retention characteristics of the reservoir and the manner in which the flow is delivered from the natural source to the reservoir (Halcrow, 2001). Hughes and Prosser (2003:12), stating that river erosion is the most uncertain of the sediment sources in terms of river budget modeling. According to the study, it is known that degradation of riparian vegetation and other impacts on the rivers have resulted in greatly increased rates of riverbank erosion, to the extent that this erosion process cannot be ignored as a sediment source in regional assessment.

Ainsworth, (2005) states that erosion of the land surface yields sediments which are transported downstream by rivers and eventually deposited in reservoirs while the rate of erosion depends on a complex interaction of:

- Climate - precipitation and runoff, temperature, wind speed and direction,
- Geotechnics – geology, volcanic and tectonic activity, soils,
- Topography – slope, catchment orientation, drainage basin area, drainage density,
- Vegetation cover, and
- Land use and human impact.

Topsoil and other light surface particles from a catchment are transported by rainwater from land to a reservoir where some of it settles to the floor of the reservoir as a layer of silt. Lindqvist, (2005); observed that a layer of silt that is only a few centimeters thick is good because it reduces seepage, but thicker layers of silt decrease the water storage capacity, reducing the period during which water can be drawn from a reservoir. Therefore, catchments without soil conservation and ponds or dams without silt traps may result in dam reservoirs that cannot store any water after only a few years.

In Malawi most of the reservoirs (both big and small) are said to be silted up due to poor catchment management practices. It is reported that most of the reservoirs in the country are greatly degraded due to lack of maintenance and serious environmental degradation of the reservoir catchment. Reservoir sedimentation is attributed to issues of catchment degradation through deforestation, river bank cultivation, and overgrazing, poor farming practices such as lack of terraces set by farmers. Vandalism and lack of maintenance of sediment preventing structures such as silt traps and weirs are part of the factors contributing to problems of reservoir sedimentation (Malawi Government, 2004).

A report on the Water Resources Management Policy and Strategies (WRMPS) in Malawi written in 1999 states that the country does not have a clear policy on the conservation of catchment areas. Apart from catchment areas, there also no clear policies on the control of development at local community level, for the protection and enhancement of water resources, and reservation of potential reservoir sites for future dam developments. The absence of the policy is assumed deliberate by authorities in order to avoid resettlement and payment of huge funds for compensation. As such, the country has obviously a very complex land use system with more than 16,000 km^2 of unsuitable and marginal land mainly steep slopes has been settled and is being cultivated, largely by subsistence farmers. Further, the reports states that in fact the area is more than this, as potential reservoir areas are also being settled or leased (Malawi Government, 1999).

3.8.1 Impact of Change of Land Use on Erosion and Reservoir Sedimentation

Land use practices have important impacts on both the availability and quality water resources and the impacts can be both positive and negative. However, it is very difficult to arrive at universally valid statements about land use impacts on water resources because the impacts depend on a host of natural and socio-economic factors. The natural factors include; climate, topography and soil structure while the socio-economic factors include economic ability and awareness of the farmers, management practices, and the development of infrastructure such as roads (Kiersch, 2000). For example a change of land cover from lower to evapotranspiration values will lead to a decrease in annual stream flow and vice versa according to Bosch (1982).

According to UNEP (2005), Malawi generally continues to face environmental degradation due to high population density and high growth rate. Currently population of Malawi is estimated at 13 million with an overall population density of 98 persons per square kilometer and is one of the highest in Africa. Malawi is basically an agro based economy and use of traditional fuels particularly fuelwood and charcoal is so pervasive accounting for 90 percent by 2004.

However, a small proportion of the population (16 percent) has electricity within 100 meters of their dwelling. Due to the high population density and dependence on the land great pressure is put on the environment for more farmland and fuelwood and Malawi has one of the highest rates of annual deforestation in Africa, at 2.4 percent based on reports for 1990 and 2000. As a result a according to the report there is an increasing removal of natural land cover in most parts of the country hence affecting the hydrological regimes of most catchments.

Land use and stream management can also trigger erosion responses and the responses can be complex often resulting in accelerated rates of erosion and sometimes affecting stability of streams for decades. Queensland Government (2006) observes that the following activities contribute very significantly to soil erosion and consequently reservoir sedimentation:

- over clearing of catchments and stream bank vegetation
- poorly managed sand and gravel extraction
- stream straightening works

According to Queensland Government (2006) the activities listed above 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. Further to these poor land management practices, soil erosion is also accelerated by factors such as stream bed lowering or infill, saturation of banks from off-stream sources, redirection and acceleration of flow around infrastructure, obstructions, debris or vegetation within the stream channel, removal of disturbance of protective vegetation from stream banks as a result of trees falling from banks or through poorly managed stock grazing, clearing or fire and excessive or inappropriate sand and gravel extraction.

Another major cause of land use change is due to resource scarcity which results in pressure on the production of resources. Natural population growth and division of land parcels, domestic life cycles that lead to changes in labour productivity on sensitive areas following excessive or inappropriate use, failure to restore or to maintain protective works of environmental resources and heavy surplus extraction away from the land managers are some of the examples that may slowly lead to land use changes in many areas. However fast land use changes may occur due to; spontaneous migration, forced population displacement, refuges, decrease in land availability due to encroachment by other land uses such as natural reserves (Lambin E.F. et al., 2003).

Caldel et al in 1995 carried out a case study on Lake Malawi on how land use change in Malawi (southern Africa) has altered the water balance of the Lake Malawi levels. In the study a water balance modeling was carried out to determine the causes of the changes in the lake levels and to determine to what extent these changes in level might have been the result of land use changes. The study concluded that the most significant among other causes was the clearance of the dry deciduous miombo woodland for rainfed agricuklture Caldel (1998). According to the findings of the study, without the decrease in forest cover predictions showed that the lake levels would have been almost 1 meter lower than what was actually observed on the onset of the Southern African drought of 1992.

3.8.2 Impact of Climate Change on Water Resources

Nangoma (2008) states that impacts of climate change have affected almost all development sectors in Malawi which include the water sector. According to the author, Malawi has experienced a number of adverse climatic hazards over the past 20 years and the most serious ones have been dry spells, seasonal droughts, intense rainfall, riverine floods and flash floods. As a result droughts and floods have been on the increase in frequency, intensity and magnitude for the last two decades thereby adversely impacting on food and water security, water quality and sustainable livelihoods of the most rural communities.

Land change use is also an indirect result of climate changes experienced in different parts of the world because communities tend to respond to climate change by adopting measures for survival by changing use the land resources as noted by Bie et al (2007). According to UNDP (2008), the map of Malawi shows the sub-national drought–related disaster risk data upon which the global map is based and the country is vulnerable for a number of reasons:

- Under present and historical climate, Malawi experiences a single rainy season and the climate change impacts which may be beginning to manifest, will decrease the length of the rainy season with increased rainfall intensity and flood risk.

- Malawi is a largely agricultural country, with 85% of the people living in rural areas and four fifth of export revenues coming from the agricultural sector.

- Climate models consistently report that Southern Africa which includes Malawi will be very likely to dry significantly in the coming century while the rain that falls will come in increasingly concentrated bursts which are nor useful for agriculture and heightening flood risks

- Climate change through drought and flood has the potential to exacerbate soil erosion and this will further exacerbate ongoing land degradation pressures while also impacting water resources.

Historic rainfall records from the Department of Meteorological Services in Malawi show that the area surrounding Chamakala area in Kasungu has increasing rainfall intensities for the past decades and on average the rainfall amounts have changed from about 800 mm per annum to 830 mm per annum.

3.9 Techniques of Sediment Removal from Reservoirs

There are a number of practical means of removing sediments from reservoirs such as hydraulic methods by flushing as well as mechanical methods such as dredging, excavation and siphoning. Sediment removal methods depend on the reservoir characteristics and quality of the sediments and as such sediment may be removed from the shore or from a boat. Since some dredging techniques have a disadvantage in that they may increase turbidity and causing water quality problems, hydraulic methods or mechanical excavation methods that usually require the reservoir level to be lowered or by-passed and emptied are more preferred (Brabben, 1988).

An example is given of Dashidaira Dam in Japan by Kashiwai (2002) which had a major inflow of sediment during 1995 but subsequent flushing resulted in the reduction of sediment volume stored in the reservoir by approximately 40%. Kashiwai (2002) outlines five methods used in Japan to mitigate sedimentation in reservoirs. The five methods are; sediment flushing, sediment bypassing, excavation and dredging, discharging turbid water and reservoir emptying. However, most of these methods may be very costly in other circumstances so proper assessment should be made before a particular method is applied.

The World Bank has made a contribution to promote conservation of water storage worldwide by concentrating on the specific issue of reservoir sedimentation and how it might be reduced or possibly eliminated. The concept of "reservoir life cycle management" was then developed and looked at the physical processes by which sediment could be removed on a regular basis from reservoirs. This resulted in the development of a simple mathematical model (RESCON) which enables decisions to be made on the financial and engineering viability of preserving storage (Ainsworth, 2005). Following this development, several ways of removing sediments from reservoirs were then considered by the World Bank:

- **Flushing:**

A technique whereby the flow velocities in a reservoir are increased to such an extent that deposited sediments are remobilized and transported through low-level outlets in the reservoir.

- **Sluicing:**

An operational technique by which a substantial portion of the incoming sediment load is passed through the reservoir before the sediment particles can settle. This is accomplished in most cases by operating the reservoir at a lower level during the flood season to maintain sufficient sediment transport capacity through the reservoir.

Mechanical removal:

Mechanical removal of deposited sediments from reservoirs takes place using conventional techniques, dry excavation or hydrosuction.

- **Dredging:**

It is the process of excavating deposited sediments from under water. Dredging is a highly specialized activity which is mostly used for clearing navigation channels in ports, rivers, and estuaries and reservoirs.

- **Dry excavation:**

Also known as trucking and requires the lowering of the reservoir during the dry season when the reduced river flow can be adequately controlled without interfering with the excavation works. The excavated sediment is transported for disposal using traditional earth equipment and the method is mostly suitable for small reservoirs because it attracts lower costs of excavation and disposal for small reservoirs compared to big reservoirs.

- **Hydrosuction:**

It is a variation of traditional dredging in that the hydraulic head available at the dam is used as the energy for dredging instead of pumps powered by electricity or fuel. As such where there is sufficient head available, the operation costs are substantially lower than those of traditional dredging.

3.10 Determination of Sediment Accumulation in Small Reservoirs

All reservoirs formed by dams on natural water courses are subject to some degree of sedimentation but the problem confronting the project planner is to estimate the rate of sedimentation and the period of time before the sediment will interfere with the useful functions of the reservoir. Provisions therefore should be made for sufficient sediment in the reservoir at the time of design so as not to impair the reservoir functions during the useful life of the project or during the period of economic analysis (Strand, 1977).

Reservoir surveys are necessary to get more realistic data estimate regarding the rate of siltation and to provide reliable criteria for studying the implication of annual loss of storage over a definite period of time. Particular reference should be paid to the reduction of intended benefits in the form of irrigation potential, hydropower, flood absorption capacity and water supply for domestic and industrial uses among other uses and periodic reallocation of available storage for various pool levels Martinko et al. (2006). In addition reservoir surveys help in proper estimation of loss of storage designed at the planning stage besides evaluating the effectiveness of soil conservation measures carried out in the catchment area of river valley projects. Again, Martinko et al. (2006), state that since the major cause of change in storage capacity of reservoirs is sediment deposition a reservoir monitoring program can be put in place to periodically determine the following:

- storage depletion caused by sediment deposition since closure of reservoir,
- annual sediment yield rates,
- current location of sediment deposition,
- sediment densities,
- lateral and longitudinal distribution of deposited sediment, and
- reservoir trap efficiencies.

Martinko et al. (2006), state that it is generally recommended to carry out survey of reservoirs periodically so that the quantities of sedimentation taking place can be assessed and timely remedial measures taken. Prior knowledge of total storage capacity of a given reservoir and the availability of data on determined volumes at a time, would provide enough prerequisites for the determination of sediment yield in a reservoir (Agarwal and Idiculla, 2006).

3.10.1 Methods of Estimating Small Dam Capacities

There are several approaches used to determine and estimate storage capacities of small dams. Sawunyama, (2005), states that in general, there are direct and indirect methods of estimating reservoir capacities and the direct methods are grouped into two groups of quick and detailed methods.

A. Direct Methods

Direct methods of estimating reservoir capacities are based on the actual field measurements made in the field by the surveyor on characteristics of the reservoir. They require a number of mathematical calculations and apply a wide range of equations.

(i) Hydrographic Surveys

Hydrographic surveying encompasses the topographic mapping of the sea bottom and tidal mudflats as well as the determination of the positions of stationary objects at sea, both above and below the water surface (ELLMER 1998, in Bondesamt 2007). 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. The strongest merit of the 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 over year average of the sediment yield but not its temporal evolution. It is therefore very important to conduct hydrographic surveys of reservoirs for example every five years so that sediment yields can be computed in finer scales. Zarris et al, (2002), observe that alternatively, this method can be combined with hydrological models as well as sediment discharge measurements in upstream locations to reconstruct the temporal evolution of reservoir sedimentation.

One way of carrying out the hydrographic survey is use of a fathometer. During a hydrographic survey, depth measurements are typically taken with a fathometer, which is a sonar-based device for measuring depth based on the velocity of the speed of sound. Position information locating the boat at the time of the depth measurement is typically based on common land survey technology. The inflow and outflow method involving measurement of inflows into and outflows from the reservoir comprising discharges and sediment concentrations is also being used in some cases. Of late, use of Hi-Tech methods has been started in which hydrographic surveys are carried out by employing computerized methods both for data collection and analysis. This method requires fast moving boats so that it is possible to obtain data at closer intervals (Agarwal and Idiculla, 2006).

Sawunyama, (2005), states that the first step in determining the capacity of water available in a reservoir at a particular time is to estimate the shape of the reservoir as accurately as possible. However, according to the Sawunyama (2005) in most cases, this is not very easy to do because generally the reservoirs have irregular shapes longitudinally and in cross sections. Secondly, areas enclosed by contours at appropriate intervals are considered and are used to calculate volumes at each interval before summing up the volumes to get total capacity of the reservoir.

(ii) Quick Survey Methods

In order to use the quick survey method, the surveyor needs to have knowledge of the following information about the reservoir; throwback, maximum depth and maximum width. The capacity C of the reservoir is therefore calculated using the equation:

$$C = K_1 * K_2 * W * D * T \qquad \textit{Equation 3.1}$$

Where K_1 and K_2 are constants and K_2 is a constant related to the shape of the valley cross-section. D is maximum water depth obtained from the difference in elevation between the lowest point in the reservoir and the spillway crest level. W is the width of water surface at the reservoir at spillway crest level while T is the throwback at the spillway crest level. Note: Throwback is the distance starting from the dam wall along the reservoir axis to the point of entry of the river into the reservoir (Lawrence and Lo Casio, 2004 in Sawunyama, 2005).

USAID (1982) and Fowler (1977) developed two similar equations to be used when calculating reservoir capacities which have valley cross sections shapes. The two methods are presented below respectively:

i. $C=0.4*1*D*W*T$ *Equation 3.2*

Where $K_1=0.4$ and $K_2=1$ (USAID, 1982)

ii. $C=0.25*1*D*W*T$ *Equation 3.3*

Where $K_1=0.25$ and $K_2=1$ (Fowler 1977).

(Nelson, 1999), states that determination of capacities for reservoirs that are represented as triangular prisms can be made by applying the 1/6 rule given by the following equation:

$C=0.22*1.2*D*W*T$ *Equation 3.4*

Where $K_1=0.22$ and $K_2=1.2$.

According to Sawunyama (2005) reservoirs which have shapes of a pyramid and with the dam wall acting as bases, their capacities can be calculated using the equation below and this is applicable in the case of Zimbabwe:

$C= (D*W*T)/6$ *Equation 3.5*

For a reservoir at full supply level, and whose shape is that of a pyramid, assuming the water surface at full supply as the base the equation 3.6 is said to be more accurate.

$C= (A*D)/3$ *Equation 3.6*

Where: A = Surface area
D = depth of the water.

The methods outlined above in equations 3.2 to 3.6 provide inaccurate results and are not very reliable and hence there is need to consider application of some more detailed methods in estimating reservoir capacities. In that case the Mid Area Method and Prismoidal methods are recommended for estimation of reservoir capacities (Sawunyama, 2005),

a. Mid Area Method

The Mid Area method is based on assumptions that areas contained within successive contours represent cross sections and the distances between the contours are contour intervals. This is known as the Mid Area Rule and the equation is given by:

$$C=\sum_{i=1}^{n}\left[\frac{A_i + A_{(i+1)}}{2}\right]dh \qquad \textit{Equation 3.7}$$

Where C = reservoir capacity,

A_i = surface area at contour *i,*

$A_{(i+1)}$= Surface area at the next contour level above contour level *i.*

dh = contour interval

This method has a limitation in that it is more suitable for reservoirs with small contour intervals.

b. Prismoidal Method

Another method of calculating reservoir capacities is the Prismoidal Method also known as the Simpson's Rule and reservoir capacity is calculated using the following equation:

$$C=\sum_{i=1}^{n}\left\{dh\left[A_i + \sqrt{A_i A_{(i+1)}} + A_{(i+1)}\right]/3\right\} \qquad \textit{Equation 3.8}$$

Where *C, A*, and *dh* are as defined above.

These methods have a disadvantage in that they are very demanding and time consuming and therefore some indirect methods are also considered in determining reservoir capacities.

B. Indirect Methods

Indirect methods are useful in estimating surface areas for reservoirs from topographic maps or satellite images, from which a power relationship between surface area and capacity of a reservoir is used to estimate reservoir capacity. In a study carried out in Italy by Brandani et al, (2006) the possibility to use remote sensing data to estimate the reservoir sedimentation has been investigated in the framework of reservoir sedimentation management and control. In the study high - resolution data from QuickBird sensors of La Penna reservoir, on the Arno River in Italy, were used to evaluate the bathymetry of the lake. According to the researchers, the multispectral images from QuickBird satellite were also used, in Italy, with good results for estimating the bathymetry of Venice lagoon. The depth of penetration zone method was applied for La Penna reservoir at the same time, and results showed that the method is well established for bathymetric mapping in shallow coastal waters. In addition, the depth of penetration zone method applied on high-resolution multispectral QuickBird data seemed to be able to correctly assess the spatial extension of the sediment deposit.

A similar approach was used in Botswana as reported by Meigh, (1995) in which 1:50,000 topographic maps were used to estimate surface areas of small reservoirs when studying the impact of small farm reservoirs on urban water supply in Botswana. However, it is reported that the results had shown that the area estimates were of poor quality because some of the reservoirs were too small to be well represented on the topographic maps or satellite images and it was concluded that the method would be best favourable for large reservoirs than small ones.

3.10.2 Reservoir Resurvey Data

Resurveying of an existing reservoir provides valuable data in determining rates of sediment yield. Aynekulu et al (2006) estimated the rate of reservoir sedimentation in two selected irrigation small scale reservoirs in Ethiopia, after two years of their construction 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. 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 analyzed in a laboratory.

The following equations were used to compute the parameters as follows:

- $SV = area*depth$ *Equation 3.9*
- $SR = \frac{SV}{y}$ *Equation 3.10*
- $LE = \frac{RSC}{SR}$ *Equation 3.11*
- $SY = SV*dBD$ *Equation 3.12*
- $SSY = \frac{SY}{A}$ *Equation 3.13*

Where, **SV** is sediment volume (m^3); **area** is the area of contour of sediment thickness (m^2), **Thickness** is the thickness of the sediment measured from the pits (m); **SR** is rate of sedimentation (m^3y^{-1}); **y** is age of reservoir (year); **LE** is the life expectancy of the reservoir (years); **RSC** is the reservoir storage capacity (dead) (M^3); **SY** is sediment yield (ty^{-1}); **dBD** is dry bulk density (tm^{-3}); **SSY** is Specific Sediment Yield (t $km^{-2}y^{-1}$); and **A** is catchment area (km^2). The results of the survey on silt deposit in Filiglig and Grashito reservoirs according to Aynekulu et al, (2006) are summarized in the Table 3.2:

3.11 Estimation of Water Resources Availability

Storing water in a reservoir gives the silt time to settle on to the floor, forming a relatively water tight seal, which, after a few years, will reduce the seepage “losses”. However, an excessive silt load could lead to the silting up of the storage and this is a hazard in catchments with soil erosion problems and may lead to dam failure once it is silted up. In practice, it is essential to have a balanced relationship between catchment and storage if the catchment is the source of supply in order to provide sufficient runoff to fill the storage (Nelson, 1985).

De Araujo et al, (2006), carried out a study in Brazil in which it was determined that there is a direct relationship between reservoir yields and storage volumes of reservoirs. In one of the case studies it was found that for a particular reservoir whose storage capacity had been reduced by 0.2% per year due to siltation, had a risk of water shortages almost doubling in

less than 50 years for a most critical reservoir. Further, it was deduced that the reduction of storage had three times more impact on yield reduction than the increase in evaporation.
The estimation of water resources in a catchment which is also referred to as reservoir yield starts with analysis of runoff from the particular catchment.

Table3.1: Results of survey on silt deposit in Filiglig and Grashito

Variable	Filiglig	Grashito
Sediment volume (SV) (m^3)	13856	23974
Age (y)	2	2
Annual Sediment rate (SR) (m^3y^{-1})	6928	11987
Reservoir storage capacity (m^3)	39697	53201
Lifetime, estimated (y)	5.7	4.4
Lifetime, designed (y)	30	20.6
Catchment area (A) (km^2)	6.12	5.11
Dry bulk density (SY) (tm^{-3})	1.3	1.3
Sediment yield (SY) (ty^{-1})	9006	15583
SSY ($t\ km^{-2}\ y^{-1}$)	1472	3049

3.11.1 Runoff and Reservoir Yield Analysis

Reservoir Yield is defined as the rate at which water can be drawn from the reservoir throughout a dry period of specific severity without depleting the contents that withdrawal at that rate is no longer feasible (Shaw, 1987).

A number of ways are used to estimate and compute reservoir yield for a catchment with varying characteristics. According to Nelson, (1985), the quantity of runoff from a catchment depends on such factors as rainfall, permeability of the soils, the nature and condition of the catchment cover, and the slope of ground. Forests and areas sown to improved pasture give a considerably reduced runoff, as do sandy and well cultivated areas. Conversely, rocky and bare soils can produce increased volumes, which in turn produce muddy water and silted-up reservoirs. It is necessary to make an estimation of the likely catchment runoff in those catchments where seldom have any record of actual flows in their streams.

Nelson, (1985), suggests two methods of estimating runoff yield so that the planning for water supply could be made on a reasonably sound basis. The first method is reportedly used in Australia while the other is used by the United States Department of Agriculture (USDA). The method is used to estimate daily runoff, based on daily rainfall records for the particular area its reliability is said to be dependent on long period data records. Another procedure for estimating yield is to assume that it is a percentage of the average annual rainfall especially in catchments which are ungauged.

On the other hand PEM Consult, (1999) states that estimation of reservoir yield requires long term hydrological information such as flow characteristics at the site and estimates of open water evaporation. However, at the locations of most existing and future small reservoirs in Malawi there are no flow records, and as such an empirical method approach of estimating the yield for small reservoirs which does not require the simulation of inflows is adopted. According to the approach estimation of catchment yield is done by using empirical equations which are derived by regression that relate mean annual runoff (MAR) to catchment rainfall and catchment characteristics such as the base flow index (BFI) in some cases. Another approach recommended suitable for Malawi to determine reservoir yield is one adopted from Bullock et al, (1990) which uses derivations of flow duration curves. Computation of reservoir yields for some studies were made using stochastic modeling for several reliability levels and the water yield reductions were quantified for the areas of the study sites as reported by De Arauja et al, (2006).

3.11.2 Rainfall and Runoff Relationship

Hill and Kidd, (1980) developed a non-linear relationship for estimating mean annual runoff from catchments that contain dambos in order to provide a crude index of available water resources from average annual runoff. The relationship between the mean annual runoff and average annual runoff is given by the following equation therefore:

$$MAR = -92 + 0.16AAR + 0.00018AAR^2 - 640DAMBO \qquad \textit{Equation 3.14}$$

Where:	MAR	=	mean annual runoff (mm)
	AAR	=	average annual rainfall (mm)
	DAMBO	=	proportion of the catchment that is dambo, as determined from 1:50000 maps (takes value 0-1)

Furthermore, Bullock *et al,* (1990) developed a regional equation (see equation 3.15) based on data from 102 catchments, for use in Malawi, Tanzania, and Zimbabwe but unlike equation 3.14 above, this does not take into account dambos and is suitable for ungauged catchments:

$$MAR = 0.0000467AAR^{2.204} \qquad \textit{Equation 3.15}$$

The MAR is used to determine how easily the reservoir will fill by estimating the reservoir capacity as a proportion of the mean annual rainfall using the equation:

$$RV(\%) = \left(\frac{RC}{MAR^* A}\right)x0.1 \qquad \textit{Equation 3.16}$$

Where:	RV	=	reservoir volume a percentage of average annual runoff
	RC	=	reservoir capacity (m^3)
	MAR	=	mean annual runoff (mm)

A = catchment area (km^2)

3.11.3 Derivation of a Flow Duration Curve

A flow duration curve for a particular point of a river shows the proportion of time during flow discharge at that point equals or exceeds certain values Wilson, (1990). Base flow index represents the proportion of flow from a catchment that arises from stored sources and not from storm runoff. The proportion of total runoff that is base flow depends on the ability of the catchment to infiltrate and percolate rainfall and the BFI is strongly dependent on the geology and soil in the catchment. According to studies by the British Geological Survey (BGS) carried out in 1989 in Malawi, the BFI values for Malawi are between 0.301 and 0.600 (PEM Consult, 1999).

Drayton *et al,* (1980) first developed a method which was based on the development of a dimensionless flow duration curve and generalized reservoir capacity for Malawi. Secondly, the method was updated by Bullock *et a,l* (1990) to be able to derive a flow duration curve. However, Mitchell, (1987) described an approach based on the geometry of small dams in Zimbabwe which is also appropriate for use in Malawi. The approach of this method is outlined below as follows:

Step 1: Estimating ADF

In order to estimate the average daily flows from a catchment with a known area and determined value of mean annual runoff equation 3.17 can be used as follows:

$$ADF = \frac{MARxA}{31600} \qquad \textit{Equation 3.17}$$

Where: ADF = average daily flow (m^3s^{-1})

MAR = mean annual runoff (mm)

A = catchment area (km^2)

Step 2: Estimating the 50 percentile flow, Q50 (as a multiple of ADF)

Percentile flows are determined from flow duration curves (FDC) and for a particular point on a river, the flow duration curve shows the proportion of time during which the discharge at that point equals or exceeds certain values (Wilson, 1990). The determination of the percentile flows for reservoir data analysis is done by first determining the 50 percentile flow using the equation:

$$Q50 = -0.234 + 0.000209AAR + 0.649BFI \qquad \textit{Equation 3.18}$$

Where: AAR = average annual rainfall (mm)

BFI = the catchment base flow index

Step 3: Estimating Q90, Q80, Q70, Q60 and Q40 percentile flows and gross yields

Estimation of percentiles flows is done by using Standardized Regional Flow Duration Curves alternatively a table of standardized values is used (See Appendix 2B). The percentile flows are presented as a fraction of ADF and are then converted to volumes (gross yield) by multiplying with ADF x 31.6 x 10^6.

Step 4: Selecting a chosen acceptability of failure to supply a yield

Having obtained the gross yields in the step above, it is needed to choose an acceptability of failure to supply a yield for each of the gross yields. The choice of the acceptability of failure depends on the purposes of the particular reservoir and for reservoirs whose purposes are to supply water to irrigation schemes the recommended level of acceptability is 5 years.

Step 5: Estimating evaporation "losses"

Every reservoir is affected by evaporation "losses" and as such there is always need to take evaporation "losses" when estimating reservoir yields. Estimating evaporation "losses" is estimated by assuming that the reservoir has a storage-area relationship of the form given by equation 3.19:

$$RA = cV^{0.667} \qquad \textit{Equation 3.19}$$

Where: RA = surface area of the reservoir (m^2)

V = volume of reservoir

c = a constant

The value of the constant in equation 3.19 can be can be derived if the area and volume of the reservoir at full supply level are known or can be estimated. With the known value of c, the reservoir surface areas for each of the six storage volumes determined in step 3 can be computed by the equation 3.19. The volume of evaporation "losses" for each of the storages is then estimated using an equation of open water evaporation as given by equation 3.20.

$$EVAP = \frac{RAxE}{1000} x \frac{2}{3} \qquad \textit{Equation 3.20}$$

Where: EVAP = the volume of water evaporated in a year (m^3)

E = open water evaporation (mm)

Step 6: Derivation of reservoir net yields

Net yield is the difference in volume obtained by subtracting evaporation "losses" (EVAP) from the gross yields. In this case the gross yields derived in step 3 are used to determine net yields of the reservoir by subtracting the evaporation "losses" determined in step 5. The storage–yield relationship for a reservoir is determined by plotting the net yields against storage volumes. In the case that there is an already existing reservoir and that the storage at the full supply level is known, or can be estimated, then the reservoir net yield can be read from the graph (PEM Consult, 1999).

3.11.4 Estimation of Dry Season Yield

Calculation of sustainable yield is difficult in Sub-Saharan Africa since most small reservoirs are located in ungauged catchments (Mutiro et al, 2006) and as such special methods with certain assumptions have to be used when calculating reservoir yields especially during the dry season for example Mitchell's method. According Mitchell, (1987) the method of estimating dry season yield is based on the following four assumptions, that:

a. Reservoirs are full at the end of the wet season

b. During the dry season inflows into reservoirs are negligible

c. Draw-off and evaporation of water are at a constant rate

d. Reservoirs are non carry-over

In order to use this method, three steps are followed when estimating the dry season yield:

i. *Determination of an Evaporation Index (EI)*

$$EI = 0.001\left(\frac{E_D x RA_{max}}{RC_{max}}\right) \quad \textit{Equation 3.21}$$

Where;	E_D	=	evaporation over the dry season (mm)
	RA_{max}	=	surface area of the reservoir at full supply level (m^2)
	RC_{max}	=	full supply capacity of the reservoir (m^3)

ii. *Determine a K-factor using the equation:*

$$K = e^{-(0.9EI)} \quad \textit{Equation3.22}$$

Where: K is a parameter of variation between reservoir surface area (RA) and capacity (RC).

iii. *Determine the maximum dry season yield (Y_{max}) using the equation*:

$$Y_{max} = \left[\frac{0.9K}{1-K} - 0.15\right] EIxRC_{max} \quad \textit{Equation 3.23}$$

Where: Y_{max} is the maximum dry season yield.

An example is given for most Zimbabwean reservoirs with capacities (RC) whereby the variations of surface area (RA) closely follow a power law: For most reservoirs, this relationship closely follows a power law:

$$RA = K(RC)^u$$ *Equation 3.24*

Where; K and u are parameters of variation between reservoir surface area (RA) and capacity (RC). Mean value of “K” is 0.523 while the average for the power “u” is 0.667 for an average reservoir of capacities ranging from 11 to 1300 mega cubic metres (Mamba, 2007).

3.12 Small Reservoir Trap Efficiency

Reservoir trap efficiency is defined as the percentage of incoming sediment which is trapped by the reservoir or the ability of a reservoir to trap and retain sediment, expressed as a percentage of sediment yields or inflowing sediment (Bupe and Timble, 1986). Linsley et al, (1992) defines trap efficiency as the percent of inflowing sediment that remains in the reservoir. Equation 4.25 gives a mathematical explanation of trap efficiency as defined by the United States Army Corps of Engineers (USACE) in 1989:

$$E = [Ys(in) - Ys(out)] / Ys(in)$$ *Equation 4.25*

Where:

Where:	E	=	Trap efficiency expressed as decimal
	Ys	=	Sediment yield in weight units
	in	=	inflow
	out	=	outflow

Trap efficiency is of particular importance when determining the annual sediment rate or capacity loss as expressed by equation 4.26:

$$CI = EYs / C$$ *Equation 4.26*

Where:	CI	=	annual sedimentation rate
	E	=	trap efficiency, in percent
	Ys	=	annual net sediment yield from the drainage area
	C	=	original reservoir storage capacity in same units as Ys

According to USACE, (1989) the reservoir storage capacity is decreased as sediment is trapped and in turn the trap efficiency decreases. For practical purposes, the initial trap efficiency can be used as a constant up to 50 percent storage depletion; however, if storage depletion is rapid, the trap efficiency should be updated at time increments with an adjustment of C to reflect the sediment retained.

Verstraeten and Poesen, (2000) state that sediment volumes in small ponds can be used to reconstruct sediment yield values and to study the spartial variation in sediment yield over large areas. The technique can be very helpful in establishing large data sets on sediment delivery as there are often no resources for expensive monitoring programmes especially in developing countries. In addition, when such studies are undertaken, one has to take into account the efficiency of the pond in trapping the sediments.

Prediction of trap efficiency of a particular reservoir can be done using Brune Curve which expresses trap efficiency as a function of the capacity-inflow ratio of the reservoir. Another way of predicting is by use of Churchill Curves introduced in 1949. Use of Churchill Curves requires prior knowledge of average velocity of water in the reservoir so that the sediment index of the reservoir can be calculated (Bupe and Timble, 1986).

3.12.1 Factors Affecting Trap Efficient

According to Verstraeten and Poesen, (2000), trap efficiency is dependent on the characteristics of the inflowing sediment and the retention time of the water in the pond which in turn are controlled by pond geometry and runoff characteristics. Further, Linsley et al, (1992), states that trap efficiency is primarily dependent on the retention time, with the deposition increasing as the time in storage increases. Trap efficiency is basically affected by hydraulic characteristics of the reservoir and sediment characteristics of the inflowing sediment (USACE, 1989).

a. Hydraulic Characteristics

Hydraulic characteristics that affect trap efficiency are; the ratio of storage capacity to inflow rate, reservoir shape, type of outlets and reservoir operation. The capacity-inflow ratio is a measure of retention time and greater retention time means that the average transit velocity and the turbulence associated with it are low thereby resulting in a greater rate of deposition. The shape of the reservoir determines the effective retention time and could cause "short circuiting" in which the effective time becomes much less than the retention time as determined by the capacity-inflow ratio. In principle, this means that the shape of the reservoir makes some portions of the pool to have ineffective flow areas. Placement of bottom outlets, particularly if they are timely opened to pass density currents (also referred to as mud or gravity flows) out of the reservoirs, can reduce trap efficiency of clays. Lowering of the pool elevation decreases the retention time which subsequently decreases the trap efficiency. This can be very effective if done during periods of higher flows with its high sediment concentrations. Sluicing and reservoir operations are, however, limited by storage and environmental requirements, (USACE, 1989).

b. Sedimentation Characteristics

Sediment characteristics affecting trap efficiency are; particle size distribution of the inflowing sediment load, particle shape, and the behavior of fine sediments under varying temperatures, concentration, water chemical composition, secondly currents, and turbulence. Grain size distribution and particle shape determine particle fall velocities, and in conjunction with water depth and determination time, determine the percentage of sediment that deposits or remains in suspension. Fine sediments (clay and silt sizes) are usually the only sediments that remain in suspension long enough to reach the outlets. Temperature concentration and water chemical composition affect the aggregation properties of these fines which determine the resuspension of deposited sediments, and aid in transporting the fines closer to the dam, (USACE, 1989).

3.12.2 Methods of determining trap efficiency

There are a number of methods used to determine trap efficiency of reservoirs. The first set of methods is empirical models that predict trap efficiency, mostly of normally ponded large reservoirs using data on a mid to long-term basis.

a. Capacity-Watershed Method (Brown's Curve).

Brown developed a curve relating the ration of reservoir capacity C in m^3 and watershed (catchment) area W in square kilometers to trap efficiency E in percent (see Annex 2C) and the relationship is given by the equation 3.27:

$$E = 100[1 - 1/(1 + KC/W)] \qquad \textit{Equation 3.27}$$

The coefficient K ranges from 0.046 to 1.0 with a median value of 0.1. *K* increases for regions of smaller and varied retention time, as the average grain size increases, and for reservoir operations that prevent release of sediment through sluicing or movement of sediment toward the outlets by pool elevation regulation. The variations are mainly due to the fact that reservoirs having the same *C/W* ratio can have different capacity inflow ratios. Brown's curve is useful if the watershed area and reservoir capacities are the only parameters known, (USACE, 1995).

b. Capacity-Inflow Method (Brune's Curve)

According to USACE, (1995), Bruce developed an empirical relationship between trap efficiency and the ratio of reservoir capacity to mean annual inflow, both in the same units. Since the curves, (see Annex 2D) were generated by the use of data from normal ponded reservoirs, they are not recommended for use in determining trap efficiencies of de-silting basins or dry reservoirs. Dendy added more data to Brune's curve and developed a prediction equation for the median curve:

$$E = 100\left(0.97^{0.19^{\log C/I}}\right) \qquad \textit{Equation 3.28}$$

The variations, as shown by the envelope curves, are due to the same factors that influence the *K* coefficient in Brown's curve; however, Brune's curve is considered to be more accurate than Brown's curve.

c. Sediment Index Method (Churchill's Curve).

The method was developed in 1948 by Churchill. According to USACE, (1995), Churchill presented a relationship relating sedimentation index (SI) to trap efficiency (see Appendix 2E). The sedimentation index of a reservoir is the period of retention divided by the reservoir mean velocity. If the retention time or mean velocity cannot be obtained from field data, approximation can be made by assuming the effective retention time to be equal to the retention time as computed by using the *C/I* ratio. The period of retention (*R*, in seconds) can then be computed by obtaining the capacity (*C*, in cubic meters) of the reservoir at the mean operating pool elevation and dividing by the average daily inflow rate (*I*, in cubic meters per second). The mean velocity (*V*, in meters per second) is obtained by dividing the average daily inflow rate by the average cross-sectional area (*A*, in meter squared) in which the average cross-sectional area is obtained by dividing the capacity by the reservoir length (*L*, in feet, at the mean operating pool elevation). This can be written mathematically as:

$$S.I = R/V \qquad \textit{Equation 3.29}$$

$$R = C/I \qquad \textit{Equation 3.30}$$

$$V = I / A$$ *Equation 3.31*

$$A = C / L$$ *Equation 3.32*

$$S.I = CA / I^2 = \left(C / I^2\right)\left(C / L\right) = \left(C / I\right)^2 / L$$ *Equation 3.33*

The S.I. can be reduced to the C/I ratio squared divided by the reservoir length. It must be noted that Churchill's relationship has "percentage of incoming silt passing through reservoir" on the ordinate, which necessitates determining the difference between the value obtained and 100% to get the trap efficiency. The term "silt" on the ordinate axis meant all the size classes of sediment when Churchill developed this relationship.

d. Comparison of Methods.

Brown's method is the simplest relationship because it requires only the reservoir capacity and watershed area. If the annual inflow rate is known, Brune's curves were generally more accurate. Churchill's method requires the additional information of reservoir length. It must be noted that none of these methods include an analysis of sediment characteristics; therefore, judgment must be exercised in the use of these methods if these characteristics have a significant effect on the deposition qualities of the reservoir being analyzed, (USACE, 1995).

e. Other methods

According to ZINWA, (2007) Trap efficiency of a reservoir can be estimated by first estimating the mean annual inflow into the reservoir by using the equations below:

$$MAI = AxMAR$$ *Equation 3.34*

Where:
- MAI = Mean annual inflow into the reservoir (m^3)
- A = Catchment area (km^2)
- MAR = Mean annual runoff (mm)

Having calculated the mean annual runoff, a ratio of gross storage to inflow is also determined using the equation:

$$SR_g = DC / MAI$$ *Equation 3.35*

Where:
- SR_g = Gross storage-inflow ratio
- DC = Gross dam capacity (m^3)
- MAI = Mean annual inflow into the reservoir (m^3)

There after the ratio of gross storage and inflow is marched and checked using either the Brune's Curve or Churchill Curve in order to determine the trap efficiency of the reservoir.

CHAPTER FOUR

RESEARCH MATERIALS AND METHODS

4.1 Introduction

This chapter presents a variety of research methods which were used during data collection in order to: identify causes of sedimentation of Chamakala II Small Earth Dam, determination of the extent and rate of sediment yield of the dam, and predict the impacts of sedimentation on the availability of useable water resources for the well being of rural livelihoods of the communities dependent on the reservoir water.

A number of methods were used to collect data for this study in order to achieve all the four objectives outlined above for the purpose of the study. In the chapter section 4.2 discusses methods used to identify causes of sedimentation, section 4.3 discusses the methods and materials used to determine the extent and rate of sediment yield, section 4.4 discusses methods used to determine water availability from the catchment so that the predictions of impacts of sedimentation on water availability are made as discussed in section 4.5. Section 4.6 gives an overview of how domestic water demands were determined and finally section 4.7 discusses the impact of sedimentation on trap efficiency of the dam under study.

4.2 Identification of Causes of Reservoir Sedimentation

In order to collect data for the causes of sedimentation reconnaissance surveys within the catchment were carried out, interviews with key informants were carried out, and official data records were consulted to be able to interpret and relate field data that was collected by the observation during the reconnaissance surveys. The visits and interviews with local communities were carried out for a period of 10 days while official data collection was done throughout the whole period of data collection for the study.

The purpose of the surveillance visits was to obtain first hand information data on the nature and type of activities carried out by the communities that might be contributing to sedimentation of the reservoir and the areas within 500 m from the reservoir site also visited during the exercise. The official records of data were collected from the government offices such as Ministries responsible for Water Development, Lands, Agriculture and MASAF officials at Kasungu Boma.

The survey looked at the following parameters; land use, ground cover and rainfall pattern among other things. Interviews with main stakeholders were conducted to establish the likely main causes of reservoir sedimentation based on their knowledge of the area and experiences. Main informants that were involved in this exercise included traditional leaders, experts in agriculture, water and land, farmers, teachers, students and local communities surrounding the reservoir.

4.3 Determination of the Extent and Rate of Sediment Yield

In order to determine the extent and rate of sediment accumulation into the reservoir at Chamakala it was necessary to first carry out a hydrographic (bathymetric) survey of the reservoir. The hydrographic survey in this case was necessary since there are no historical sediment data records available for the reservoir. Again the reservoir does not have structures that can be used to determine the extent of sedimentation without actually carrying out the hydrographic survey and hence its requirement in this study. The hydrographic survey helps to determine the current storage capacity of a particular reservoir and the approach has been used in many studies and is recommended as being very reliable. The extent of sediment accumulation in the reservoir at the time of this study was determined by calculating the differences in volume between the designed reservoir capacities and the current water storage capacity that was determined during the survey.

4.3.1 Determination of Reservoir Storage Capacity by Hydrographic Survey

The hydrographic survey for the reservoir at Chamakala II was carried out from 11th February to 23rd February, 2008. At the beginning of the survey a temporary benchmark (TBM) valued at 50 m was identified and all readings were evaluated in reference to the temporary bench mark in order to have a common base for the survey at the site. A total of fifteen lines were surveyed at the site with the first line (line 1) on top of the main embankment (dam wall) and the final line (line 15) running from top of the embankment running across the reservoir longitudinally to the point where Chamakala River enters the reservoir. Survey stations were marked at 10 meter intervals on top of the embankment while markings for the middle line (line 15) were at intervals of 20 metres. The remaining 13 lines (lines 2 to 14) were surveyed across the reservoir with each of them extended to about 2 m above the spillway level of the reservoir on each side.

The following is therefore the outline of the way lines 2 to 14 were organized during the hydrographic survey:

- Line 2 was taken at spillway level on the dam wall 5 metres from the middle of the dam wall (horizontal distance from top of embankment).
- Lines 3 to 6 were spaced at 10 meter apart.
- Lines 7 to 10 were spaced at 20 metres apart.
- Lines 11 to 14 were spaced at 30 metres apart.

Readings of distances for each line started with a value of 0.0 metres from a peg fixed on a point beyond spillway level on the right bank of the reservoir with the end point on the opposite bank reading the maximum distance measured for the particular line. On the right bank the pegs were fixed in a straight stretch at right angles to the dam wall one after another upstream. In addition to these pegs, some pegs were fixed by the spillway level on both banks of the reservoir each line so that along each line there were four pegs with two of them at spillway level. In that case all distances between the pegs at spillway level were recorded as width measurements of the reservoir (see Fig.4.1).

Before readings would be recorded for each survey line a nylon rope with markings at 10 m intervals with floaters would be tied to the two pegs fixed above the spillway level. The materials that were used to collect depth measurements during the survey included: a small boat and a staff with a small flat bottom plate so that the presence of the mud could be easily sensed when taking measurements. In this study the word station also implies the point along a line where a floater marker was fixed for the recording of depth measurement.

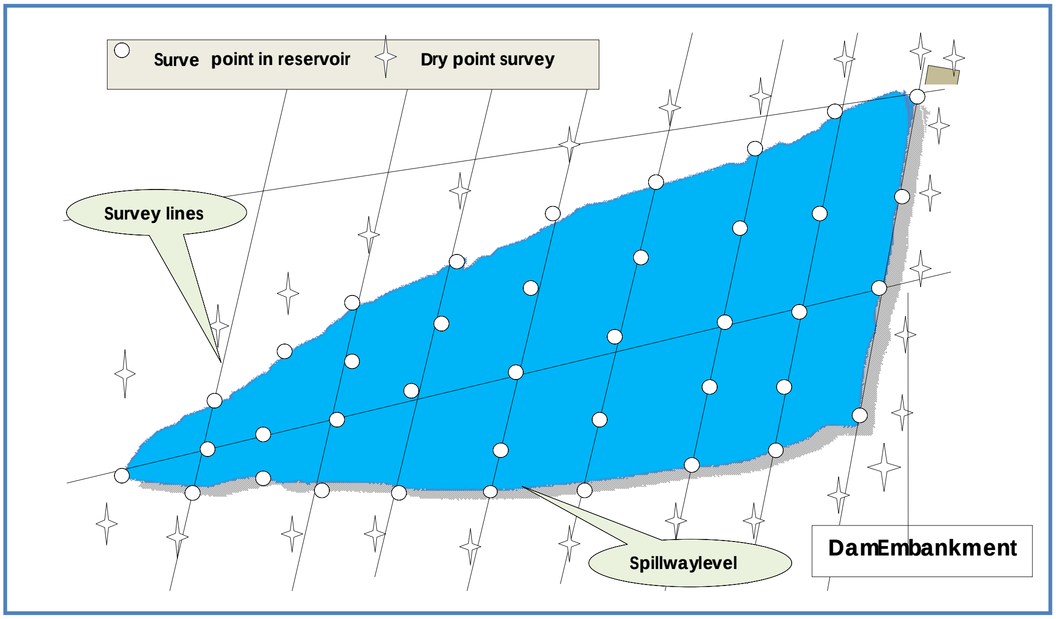

Fig. 4.1: Schematic diagram showing layout of survey lines

In order to take depth measurements of the water from the surface (*which in this case is at spillway level*), a staff was used by dipping at each station and depth measurements recorded as vertical distances from the bottom (*which in this case was the sediment level at a particular station*) to the water surface. In addition to the hydrographic (bathymetric) survey for each line, a topographic (dry land) survey was carried out around the reservoir using a leveling instrument so that each of the line was extended to a level above that of the spillway on both banks. Level readings for the topographic survey were reduced from the temporal benchmark (TBM) of value 50 m described above. Fig. 4.2 is a schematic diagram demonstrating how depth measurements were taken from the boat using the staff.

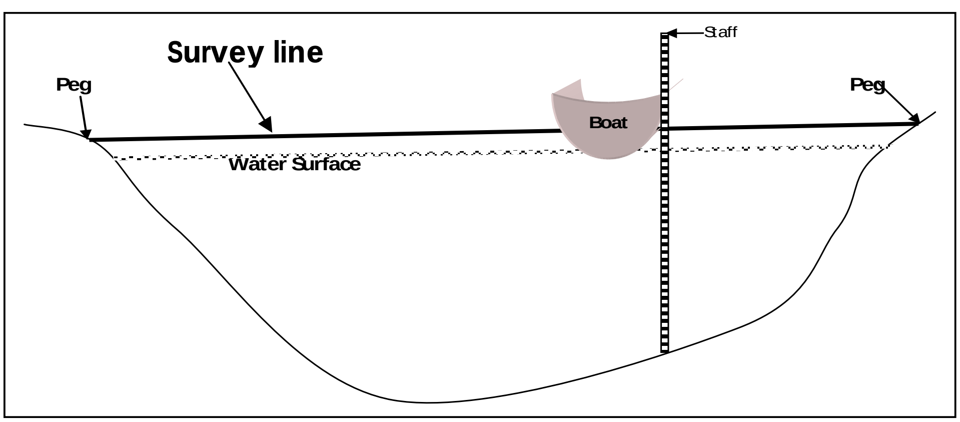

Fig. 4.2: Schematic diagram showing method of data collection

During the survey, the reduced level at spillway level was determined to be 48.505 m. Consequently all depth measurements were added to the reduced level at the spillway level as negative values so that the depth measurements were read as reduced levels from the same temporal bench mark of 50 m.

4.3.2 Determination of the Current Reservoir Capacity

The first step in determining the current reservoir capacity is to calculate areas surrounded by contours from a contour map (Nelson, 1985). In this study, two contour maps were drawn; one map was drawn manually and another using a computer program called Surfer 8 which uses data presented in grid form (see fig. 5.1). The manual map was used to calculate estimated storage volumes of the reservoir based on the spillway reduced level by first calculating the areas enclosed by contours at 0.5 m interval.

Determination of the storage capacity of the reservoir was done as follows:

a. A contour was drawn using values obtained from the reduced levels for the entire reservoir which were reduced from the spillway level at 48.505 as a stable datum.

b. Determining surface areas enclosed by the contours at 0.5 meter intervals by using a planimeter and graphical methods.

c. Storage volume between two respective contours was determined by using equation 3.8 and results are shown in Table 5.3.

d. The tabulated results were plotted on a graph of reservoir height against cumulative storage (see Fig. 5.2).

e. From the graph, the water storage capacity was determined and its difference from the required capacity at design level was attributed to volume of sediment yield.

f. Total capacity of the water available in the reservoir was determined by summing up the volumes between two consecutive contours at 0.5 metre intervals.

In order to calculate storage capacity, the Prismoidal also known as Simpson Rule method (Equation 3.8) was used because of its reliability and accuracy in estimating reservoir capacities. Results of the computations of the areas from a manually plotted contour map that was drawn on a graph paper at a scale of 1cm to 4 metres are given in Table 5.3. The calculated surface areas and their respective contour height differences were then used to determine cumulative volumes of the current reservoir capacity which are also given in the same table.

4.3.3 Determination of Volume of Sediment Accumulation

In order to determine volume of sediments accumulated in the reservoir the model described in section 3.6.3 was adopted as they have shown to be reliable from the two cases done in Ethiopia and Zimbabwe. Determination of sediment volume is done by subtracting the current reservoir capacity from the design capacity of 34760 m^3. The difference between the two volumes is attributed to the volume of sediment accumulation in the reservoir.

4.3.4 Determination of the Rate of Sediment Yield

Determination of sediment yield was done by using methods that did not require sediment sampling data from a river flow. Therefore, a simple mathematical model of calculating sediment data was adopted from Zimbabwe's ZINWA and the Ethiopian case studies as described in section 3.8. The method relies on sediment data that is already accumulated in the reservoir and the following are the sediment yield parameters that were determined for the reservoir at Chamakala II:

a. Sediment Volume (SV)

The volume of sediments in the reservoir was found by subtracting the calculated current reservoir capacity from the designed capacity of 34760 m^3.

b. Rate of Sedimentation

Rate of sedimentation is measured in cubic metres per year and using equation 3.10. The sediment volume determined in part (a) above was accumulated for a period of 6 years and as such the sediment volume was divided by the number of years.

c. Life Expectancy of Reservoir

The life expectancy of the reservoir is the estimated time for the reservoir to survive from the time reservoir operation starts to the day it will completely be filled with sediments and thereby rendering it ineffective for water storage. Therefore using the current rate of sedimentation that was determined in part (b) above and using equation 3.11 the expected reservoir life was determined by dividing the designed reservoir capacity by rate of sedimentation.

d. Sediment Yield and Annual Sediment Yield

Sediment yield is the mass of the amount of sediment accumulated in the reservoir and is measured in tons. In order to calculate the sediment yield for the reservoir at Chamakala II, equation 3.12 was used by first determining dry bulk density of the sediment accumulated in the reservoir. Determination of the dry bulk density was therefore made by first collecting 6 sediments samples at two points, with three samples at both collected from different levels of depths; the top, middle and bottom layers of the sediments by use of a shovel and a pail.

The sediment samples were dried for a period of two weeks and thereafter weighed on a scale using a container of 1000 cm^3 (1 litre) and average density of the sediments was determined to be 1.22±0.2 (n=6) tons per cubic volume. Having found sediment yield for the reservoir in the 6 year period, annual sediment yield was determined by dividing the sediment yield by the number of years, in this case 6, to obtain sediment yield per year.

e. Specific Sediment Yield

Specific sediment yield is a measure of mass of sediment yield for a particular catchment in one year and it is measured in tons per unit area per year ($Tkm^{-2}y^{-1}$). To determine specific sediment yield for the reservoir catchment at Chamakala II, equation 3.13 was used in this study.

4.4 Determination of Reservoir Yields

A number of methods were engaged to collect and analyze data for determination of catchment and reservoir yields. The analysis was made in three major steps: estimating reservoir storage as a percentage of mean annual runoff, determining reservoir storage-yield relationship and estimating dry season yield. In order to achieve these goals reference was also made to a Manual for Hydrological Design Guidelines for Small Earth Dams Malawi developed by PEM Consult in 1999, rainfall and evaporation data from the Meteorological Department in Malawi, maps and expert knowledge from professionals and the community around the reservoir area.

4.4.1. Estimating Reservoir Storage as a Percentage of Mean Annual Runoff

In order to estimate Reservoir Yield as a percentage of Mean Annual Runoff for Chamakala II, equation 3.15 was used since the catchment is ungauged. Analysis of average annual rainfall data for the past 12 years obtained from the Meteorological Department in Malawi (see Appendix 1A) , was made in order to find mean annual runoff for the area and equation 3.16 was used to determine the mean annual runoff (MAR) with the calculated value of Average Annual Rainfall (AAR) being 831mm. Having obtained the MAR for the catchment, the reservoir is then estimated as a proportion of the mean annual runoff using equation 3.16. In this case therefore the value of 127mm was used to determine the percentage.

4.4.2 Determining Relationship of Reservoir Storage and Yield

Since Chamakala II catchment is ungauged, an approach which is developed in a design manual for Hydrological Design Guidelines for Small Earth Dams in Malawi is adopted and to a larger extent the same approach was used when estimating reservoir yields at the design stage according to Mchazime, (2002).

a. Estimating the average daily flow (ADF) for the catchment

Estimation of the average daily flow (ADF) for the catchment was done using equation 3.17 so that later percentile flows for the catchment could be calculated.

b. Estimating the 50 percentile flow, Q50 as a multiple of ADF using the equation:

In order to estimate the 50 percentile flow (Q50), equation 3.18 was used and the value of BFI of 0.35 obtained from table of Average Base Flow Index for FAO Soil Classes (Drayton et al, 1990) as outlined in Appendix 2A.

c. Estimating Q90, Q80, Q70, Q60 and Q40 percentile flows

Estimation of Q90, Q80, Q70, Q60 and Q40 percentile flows were done in reference to the Standardized Regional Table of values derived from Standardized Regional Flow Duration Curves where the values of key exceedance percentiles are expressed as fraction of ADF (See Appendix 2B).

From the table in Appendix 2B, curve D was chosen since Q50 was found to be 0.167 and lies between 0.15 and 0.20 as a fraction of ADF. The subsequent estimated percentile flows were then converted to Gross Yields (m^3) by multiplying each of them by ADF which in this case is $0.021m^3s^{-1}$ and again the resultant product is multiplied by $31.6x10^6$.

d. Deciding on the acceptability of failure to supply a yield

In order to decide on the appropriate return period of failure to supply a yield, reference was made to the standardized storage -yield relationships for Malawi which are expressed as % of ADF (after Drayton et al., 1980) and the return period of 5 years was chosen since the Chamakala Small Earth Dam is small (see Table 4.1).

Table 4.1: Standardized storage -yield relationships for Malawi expressed as % of ADF (after Drayton et al., 1980)

Percentile flow, Q%	Return period (yrs)		
	2	5	10
Q90	0.20	0.48	0.75
Q80	0.70	1.60	2.00
Q70	1.50	3.00	3.90
Q60	2.80	5.80	7.30
Q50	5.00	10.00	13.00
Q40	8.50	18.00	23.00

Adopted from PEM Consult (1999).

e. Estimation of storage for each of the Gross Yields

In order to estimate the required storages for each of the gross yields that were derived in part (c) above, the standardized storage-yield relationships for Malawi expressed as % of ADF (after Drayton et al., 1980) shown in Table 4.1 were adopted.

The return period values for each percentile flow given in the Table 4.1 above represents the yield as a percentage of ADF and each of them is converted to volume by multiplying by ADF and again their product multiplied by $31.6x10^6$. The required volumes for each of the gross yields were determined and results are presented in Table 5.7 in Chapter 5.

f. Determining the reservoir storage–area relationship

The relationship between reservoir storage and reservoir surface area was determined by analyzing data that was collected during the hydrographic survey carried out at the dam site (see table 5.3). The values of surface areas for each contour were obtained from a contour map that was produced after the survey and volumes were determined from surface areas and contour intervals. The results in Table 5.3 are plotted to determine relationship between reservoir storage and surface area for Chamakala II (see Fig. 5.3).

g. Estimation of RA and Evaporation volumes

Using the Fig. 5.3 reservoir surface areas for each of the storages determined in part (e) are estimated from the relationship derived from the plot which was found to be a power function as follows:

$$RV = 0.036A^{1.386} \qquad (R^2=0.98) \qquad \textit{Equation 4.1}$$

Where: RV = Reservoir Storage (m^3)

A = Surface Area (m^2)

Equation 4.1 was adopted after being statistically analyzed and tested and results of the analysis showed that it is very reliable as it has also a good correlation coefficient of 0.98 and a significance level of 0.00064 at 95% interval.

The reservoir surface areas are first estimated in order to estimate reservoir evaporation volumes so that net yields from the reservoir may be estimated. Equation 3.20 was therefore used to estimate the evaporation volumes and results are given in Table 5.8. Calculation of the net yields was done by getting differences between gross yields that were determined in step part (c) and the results are presented in Table 5.9 followed by a plot showing the relationship of reservoir storage and net yield (see Fig. 5.6).

4.5 Determination of Impacts of Sedimentation on Reservoir Yields

4.5.1 Estimation of Current and Projected Net Yields

In order to determine the impact of sedimentation, it was very necessary to first estimate net yields for the projected reservoir volumes that were determined from results obtained in section 4.5 and results of the projected reservoir volumes are given in section 5.5.1. Again, consideration was made for the dead storage which according to design data is 5000 m^3 by subtracting the dead storage volume from each of the estimated net yields to obtain useful yields for each of the projected reservoir storages.

In order to easily estimate the net yields, a mathematical power relationship was determined from the plot of storage and net yield in Fig. 5.6 and it is given by equation 4.2.

$$N_y = 39.31V^{0.688} \qquad (R^2 = 0.98) \qquad \textit{Equation 4.2}$$

Where: N_y = Net Yield (m^3)
V = Storage volume (m^3).

This relationship of storage volume and net yield given by equation 4.2 which was statistically tested and analyzed and was eventually found to be reliable with a coefficient of correlation of 0.98 and significance level of 0.00004 at 95% level of confidence. The equation was then adopted as a tool for the estimation of net yields for the projected storage volumes for the years 2002 to 2017 which were obtained after earlier projections of sediment yield for the same period of time.

4.5.2 Estimation of Dry Season Yields

Estimation of dry season yield starts by determining the evaporation index for the reservoir under consideration. Determination of the evaporation index (EI) for Chamakala II Small Earth Dam was determined by using the projected values from the surface area and storage volume curve in Fig. 5.3. Therefore, the corresponding surface area and volume at design stage were applied to equation 3.21 taking into account the value of evaporation values for the area during the six months during the dry season. In the study for the case of Chamakala area, the six months of dry season evaporation data starts from April to October.

The estimated value of evaporation index is then applied to equation 3.22 in order to determine the K factor which is used in equation 3.23 so that the maximum dry season yield is determined. Correspondingly, all the projected reservoir storage capacities and surface areas are used in the similar manner so that their respective maximum dry season yields are also determined. A plot of the determined maximum dry season yields and values of sedimentation accumulation with time can therefore be used show the impact of the later on the former.

4.6 Assessment of Impact of Sedimentation on Water Availability for Domestic Uses

Domestic water demands for the communities was determined by using the daily per capita water requirements as discussed using average values obtained from interviews and literature reviews. Consideration was also made for the fact the area does not have enough alternative sources of fresh water for domestic uses. An assumption was therefore made that for the population of 4000 use the reservoir as their only source of water supply. Again this was based on the scenario that human population would continue to rise at the current rate of 8.2 percent per annum for the area according to National Statistics Office in Malawi and therefore deaths were not considered in this analysis. The projected population values were used to project the corresponding water demand and compare the results with reservoir yields which were projected for the same period of time.

4.7 Determination of Impact of Sedimentation on Trap Efficiency

In order to determine trap efficiency for Chamakala II Dam, equations 3.34 and 3.35) were used since related data for the method was available unlike the other methods reviewed in chapter 3 section 3.12.2. The trap efficiency of the dam at the time of this study was then found by marching the ratio of gross storage and mean annual inflow with the Brune's Curve assuming both the envelope and median curves.

By using the projected reservoir volumes given in Table 5.5 as gross storage volumes, the corresponding trap efficiencies were also determined and their results are given in Table 5.13 while Figures 5.12 and 5.13 show the relationship of sedimentation and loss of storage capacity with trap efficiency respectively. From the logarithmic relationship of the capacity and trap efficiency, it was possible to estimate the expected storage volumes and trap efficiency of the dam at Chamakala II.

4.8 Materials Used

The following materials were used during the survey; a hired boat, 2 tape measures, nylon ropes 250m long, several pegs cut from trees, 2 panga, 2 mason hammers, floaters, 1 GPS, 1 leveling instrument, 2 staffs, 2 stadia rods, stationery, protective clothing gumboots, 1:50,000 map sheet, 1 vehicle, fuel, four hired labourers, a shovel and a pail.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Introduction

This section presents and discusses results of the analyzed data that was collected through physical measurements in the field, interviews and desk studies. The results and discussions follow the outline of specific objectives, which are to: determine causes of reservoir sedimentation at Chamakala II Small Earth Dam determine the extent of sediment accumulation in the reservoir and determine its impacts on availability of water resources from the reservoir. The chapter starts by outlining some basic information on the catchment characteristics that were noted during the study of the reservoir.

5.2 Catchment Description

During the study some catchment characteristics were studied and determined using established standards for catchments less than 20 Km^2 in area as provided for by the PEM Consult (1999). In this case the Rational Method for catchments less than 20 km^2 is adopted. The catchment for the reservoir at Chamakala II is ungauged and has a catchment area of 5.3 km^2 that receives an average annual rainfall of 831 mm with catchment evaporation of 1650 mm.

a. Slope of catchment

The catchment slope for Chamakala is 0.022mm^{-1} (2.2%) and was determined by taking the difference in elevation (m) between the outlet and the most remote point in the catchment and dividing that difference by the maximum length (m) of flow in the catchment which in hydrological terms is the distance to the point furthest from the outlet.

b. Land cover and use

Observations during surveillance visits in the catchment showed that most of the catchment is cultivated. Almost 80% of the catchment is cultivated and in some instances the land along river banks is heavily cultivated while 15% is bare land.

c. Coefficient of runoff for the catchment

The overall runoff coefficient for catchment at Chamakala II was determined to be 0.575. Studies on values of runoff coefficient indicate its values vary from 0.05 for flat sandy areas to 0.95 for impervious urban surfaces (Shaw, 1988). This means that the runoff coefficient for the catchment is significantly at a higher level than normal average. For Malawi, values of runoff coefficients normally range from 0.3 to 0.6 and therefore 0.575 is within the range.

Table 5.1: Summary of catchment characteristics for Chamakala Dam

Parameter	Description	Estimated proportion of catchment	Value	Weighted value
C1. Vegetation/Land use	Scrub or medium grass	5%	0.15	0.205
	Cultivated land	80%	0.20	
	Bare or eroded land	15%	0.25	
C2. Soil type and drainage	Deep moderately drained soil	60%	0.20	0.22
	Fair permeability/depth	40%	0.25	
C3. Slope	Moderate	85%	0.10	0.15

5.3 Causes of Sedimentation at Chamakala Dam

a. Change of land use practices and loss of land cover

As already pointed out in section 5.1b, one major cause of reservoir sedimentation is probably the increasing loss of land cover from the catchment. Loss of land cover may be attributed to the intensive cultivation and overgrazing. The study found out that almost 80% of the catchment is heavily cultivated while 15% percent is bare land while 5% is covered by diminishing grass and shrubs.

Residents of Chamakala are generally subsistent farmers who normally cultivate for food and a few grow tobacco for economic gains to improve their livelihoods. The study established that about 50% of the farmers in the catchment do not apply good farming practices as required by the Ministry of Agriculture and Ministry Land for example construction of terraces and contour bands across slopes.

It was also observed during the study that stream bank cultivation is common in the catchment such that river banks are disturbed in one way or another. According to an agriculture adviser in the area farmers are involved in water diversion by digging canals for irrigation which are normally not well done so that in most cases some of the canals could lead to loss of significant quantities of soils in the form of sediment load which eventually gets deposited in the reservoir.

Encroachment in the reservoir area was noted to be one the major causes of sedimentation of the reservoir. During the study some farmers were actually seen farming just about 6 m from the reservoir and rough estimates showed that about 75% of land surrounding the reservoir is cultivated for maize production. Some of the gardens were observed to be as close as 10 m from the reservoir bank. Currently there are no clear policies on protection of areas surrounding water bodies in Malawi. However, according to a draft Water Resources Act (2007) which is yet to be enacted by Parliament in stipulates that all land within 50 m and 100 m from all rivers and dams shall not be cultivated so that catchment and water bodies are protected.

b. Pressure on Natural Resources due to Population Growth

Population growth in the area is reportedly exerting pressure on the scarce natural resources such as land for housing and farming. Local communities attributed extensive farming and deforestation to rapid population growth in the area since the inhabitants are forced to farm and settle even in reserved and protected land so that they can sustain their livelihoods. A Senior Chief in the area noted that since the introduction of multiparty politics in Malawi, traditional leaders in the area have compromised authority on their subjects. As a result some subjects take advantage of the political situation to abuse their rights. However, another local leader observed that even if people were restricted from the catchment, there would no alternative because of land shortage yet they have families and livestock to take care of.

c. Lack of Sense of Ownership and Responsibility

About 85% of people interviewed randomly felt that management and protection of the reservoir is the responsibility of government and political leaders in the area and not themselves. Several reasons were given for that reasoning for example poverty. Others interviewees attributed lack of participation due to frustrations that their expectations from the reservoir were not being met.

d. Compromised Engineering Standards

An official in the Ministry of Irrigation and Water Development confided during interviews, that in the past, development of small reservoirs is generally not subjected to rigorous engineering standards or specifications in Malawi. Engineering standards and specifications play a crucial role in selection of dam sites for the sustainability of such services. However, it was not definitely stated whether the alarming rate of sedimentation at Chamakala II Dam is also due to poor site selection. In addition, it was stated that exemption of the small dams from Environmental Impact Assessments (EIA) at planning stage may contribute to the poor state of the small reservoirs in Malawi and that includes Chamakala Small Earth Dam.

Literature reviews and interviews with some experts indicate that other engineering problems result into poor estimates of catchment yield potentials and sometimes it is due to inaccuracies at the design stages. Nelson (1985), states that small dams should not be built on very large catchments as they would normally fill up with sediments within a very short time. However, Nelson's observation may not apply to the dam at Chamakala II because the catchment area is only 5.3 km^2 but possibly some inaccuracies at design level could be possibly a major cause.

The results found in this study reflect that the designing of the dam at Chamakala II might have been done with some critical errors. The dam was found to be 5.2 % of the mean annual runoff and comparing with other standards in dam designs 5.2% shows that the Chamakala Small Earth Dam is very small for the catchment. In the case of Zimbabwe, 10 % is the minimum requirement to avoid such problems and this is excluding a provision made for sedimentation in the reservoir capacity at the design stage (ZINWA, 2007).

5.4 Determination of the Extent and Rate of Sediment Yield

5.4.1 Hydrographic Survey

The hydrographic survey was carried out between 11th February and 23rd February, 2008 and showed signs of sedimentation in the reservoir. Throughout the survey the deepest point surveyed was 2.8 m from the water level which was at spillway level by that time. The point was located along line 4 from first line of the survey setup at a distance of 50 m from the dam wall. The higher depth values could be attributed to an excavation exercise which was concentrated to areas close to dam embankment just a few months before this survey was carried out. The study also established that the stretch of the reservoir at full supply was only about 230.0 m this means that the current reservoir stretch is 20 m less than the one at the design stage and the difference may be due to the sediment accumulation in the reservoir over the past 6 years. Table 5.2 gives a quick summary of the survey findings of some determined parameters for the current status of the reservoir at Chamakala II compared to those at design stage to determine the loss percentage.

Table 5.2: Summary of results from hydrographic survey compared to design data

Parameter	Design (2002)	Current (2008)	% Loss
Stretch (m)	250	230	8.0
Maximum depth (m)	4	2.8	30.0
Maximum width (m)	150	140	6.7

The hydrographic survey revealed that the reservoir is silted despite the fact that just a month earlier the local communities had been involved in a desilting exercise sponsored by the Malawi Social Action Fund (MASAF) a Government Development Organization. The amount of silt excavated during the exercise had not been properly quantified but information gathered from the District Hydrological Officer for the area who was also one of the leading team members that had supervised the desilting exercise, estimated that the volume of the excavated sediments was between 800 m^3 and 1000 m^3.

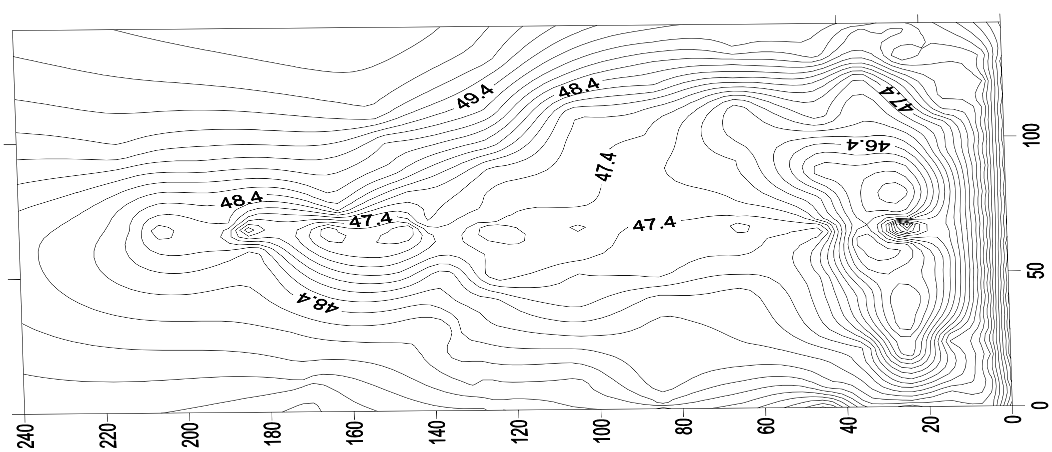

Fig. 5.1: Contour Map of Chamakala II Dam site by application of Surfer 8

From data collected from this survey two contour maps were drawn using distances between survey lines and depth measurements which were reduced from the spillway level as a stable datum at 48.505 m. One contour map was drawn manually on a graphing paper at a scale of 1cm to 4 m while the other was drawn using Surfer 8 a computerized model (see fig 5.1).

5.4.2 Determination of Current Reservoir Storage Capacity

Determination of reservoir capacity for the small reservoir at Chamakala II was done by using equation 3.8. Table 5.3 gives the calculated volumes and a graph of dam height (m) versus cumulative reservoir capacity volumes (m^3) is given in Fig. 5.2, and Fig. 5.3 gives the relationship between surface area and storage for the reservoir.

Table 5.3: Calculated Surface Areas and Cumulative Volumes

Contour	Height (m)	Surface Area by each contour (m^2)	Computed Volume (m^3)	Cumulative Volume (m^3)
45.7	0.0	0	0	0
46.0	0.3	1286	563	563
46.5	0.8	2541	1707	2271
47.0	1.3	4371	3325	5595
47.5	1.8	9226	5668	11263
48.0	2.3	13585	7374	18637
48.5	2.8	15942	2657	21294

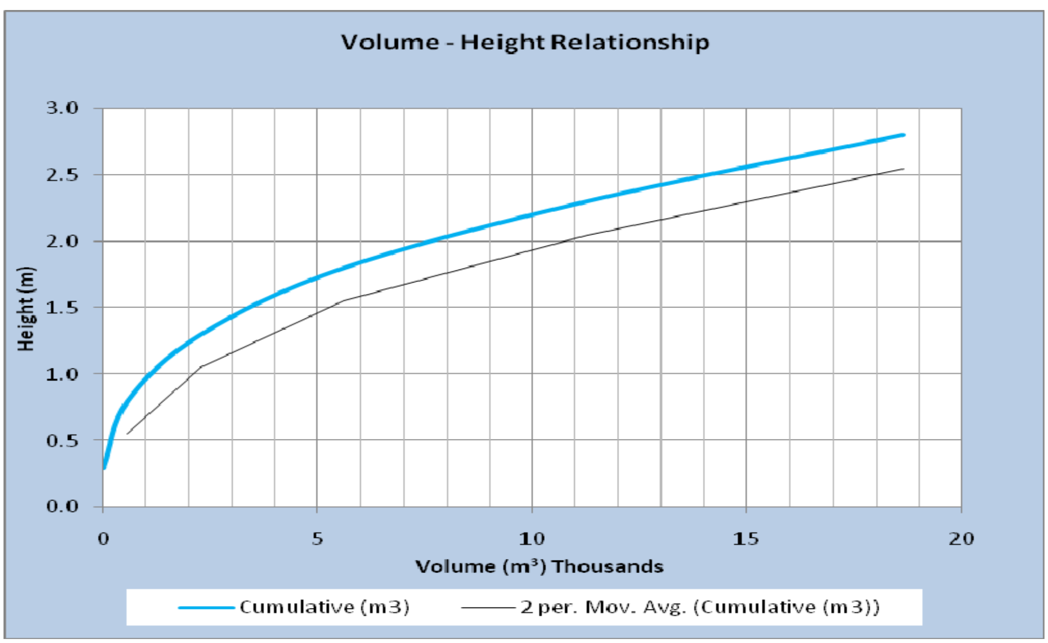

Fig. 5.2: Relationship between cumulative storage and dam height

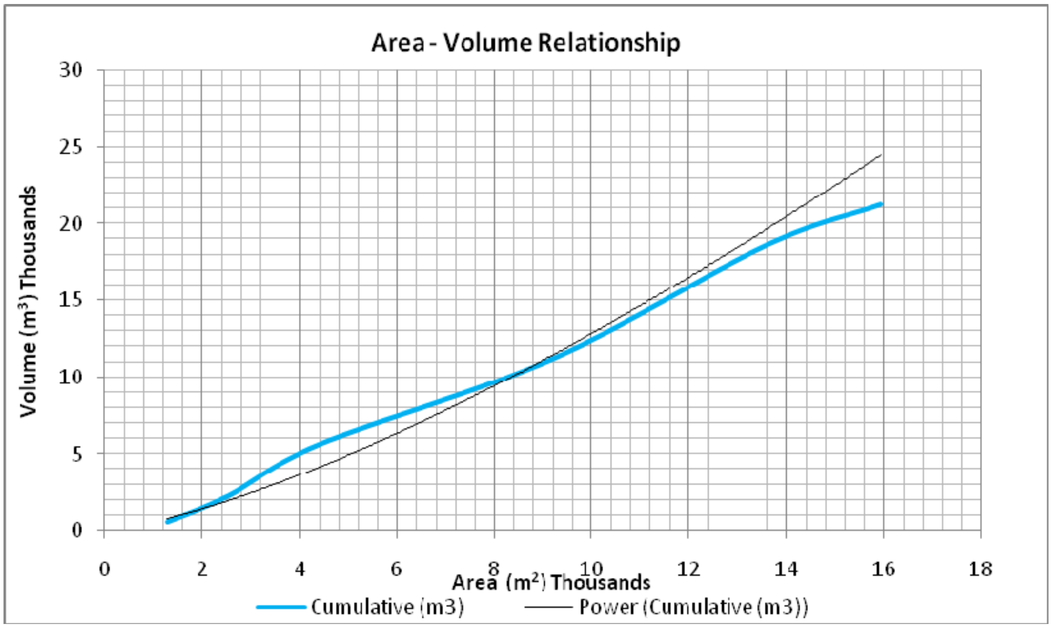

Fig. 5.3: Relationship of Reservoir surface area and volume

From the Table 5.3 and the two graphs in Figures 5.2 and 5.3, it is clear that the reservoir capacity at the time of the hydrographic survey was only 21294±1000 m^3 with a surface area of 15942±1000 m^2. Therefore, using the calculated reservoir capacity and the current surface area, on average the depth of water in the reservoir is estimated to be about 1.3±0.5 m only compared to original depth of 4 m. This means that the current reservoir capacity was 61.3% of the designed volume and water depth in the reservoir is 32.5% of the original depth and normally this is a great loss for a period of 6 years.

5.4.3 Determination of Volume of Sediment Accumulation

The volume of sediment accumulation was found to be 13466±1000 m^3 after subtracting the current reservoir capacity of 21294±1000 m^3 from the design reservoir capacity of 34760 m^3. The current sediment accumulation volume therefore represents 38.7%. It can be argued that the volume of sediments is on higher side than expected values considering that the reservoir at Chamakala II has been in operation for only 6 years since it was rehabilitated in 2002. These results are fundamental for the calculation of other parameters for sediment yield in the reservoir.

5.4.4 Determination of Rate of Sediment Yield and Projected Volumes

Table 5.4 gives the summary of results which are obtained after applying the mathematical model as described in section 3.8 using the equations 3.9 to 3.13**.**

The results in Table 5.4 show that there is a high rate of sediment accumulation in the reservoir at Chamakala II and this has indeed resulted in the reduced life of the reservoir. This impact has negative effects on the sustainability of the reservoir project to meet and support the communities' livelihoods dependent on it for water supply. The values are in sharp contrast to initial expectations on the reservoir's sustainability which was projected to effectively supply adequate water to the surrounding communities for a period of not less than 30 years. However, if the trend of rate of sedimentation is to continue it means that by the year 2017 the reservoir will be completely filled up (see Fig. 5.4).

Table 5.4: Summary of sediment yield for Chamakala II Small Earth Dam

Parameter	Measure	Error margin
Design reservoir capacity (m^3)	34760	
Designed reservoir life (yr)	30	
Current reservoir capacity (m^3)	21294	±1000
Sediment Volume (m^3)	13466	±1000
Sediment Volume as (%)	39	±1
Period of dam in operation (yr)	6	
Rate of sedimentation (m^3/yr)	2244	±500
Life Expectancy (yr)	16	±2
Percentage loss of reservoir life (%)	48	
Dry Bulk Density (T/m^3)	1.22	±0.1
Sediment Yield (Tons)	16429	±1000
Annual Sediment Yield (Tons/yr)	2738	±500
Specific Sediment Yield (Tons/yr/km^2)	517	±100

The results show that if no efforts are put in place to reduce the current rate of sedimentation in the reservoir, the current trend of rate of sedimentation would continue and sediment accumulation can be forecasted. In this study projections of the sediment volumes and the reservoir capacities were made both backward and forward in order to get a clear picture of the trend of sedimentation in the reservoir. The projections at this point in time are imperative since there is no historical data on rates of sedimentation for the reservoir. The projected storage volumes for the reservoir at Chamakala II are given in Table 5.5, and following that is Fig. 5.4, which shows the relationship between storage volume and sediment accumulation in the reservoir.

Table 5.5: Relationships between sediment accumulation and storage volumes

Year	2002	2003	2004	2006	2008	2010	2012	2014	2016	2017
Sed acc	----	4485	6730	8975	13466	17956	22447	26938	31428	33674
Storage	34760	30275	28030	25785	21294	16804	12313	7822	3332	1087

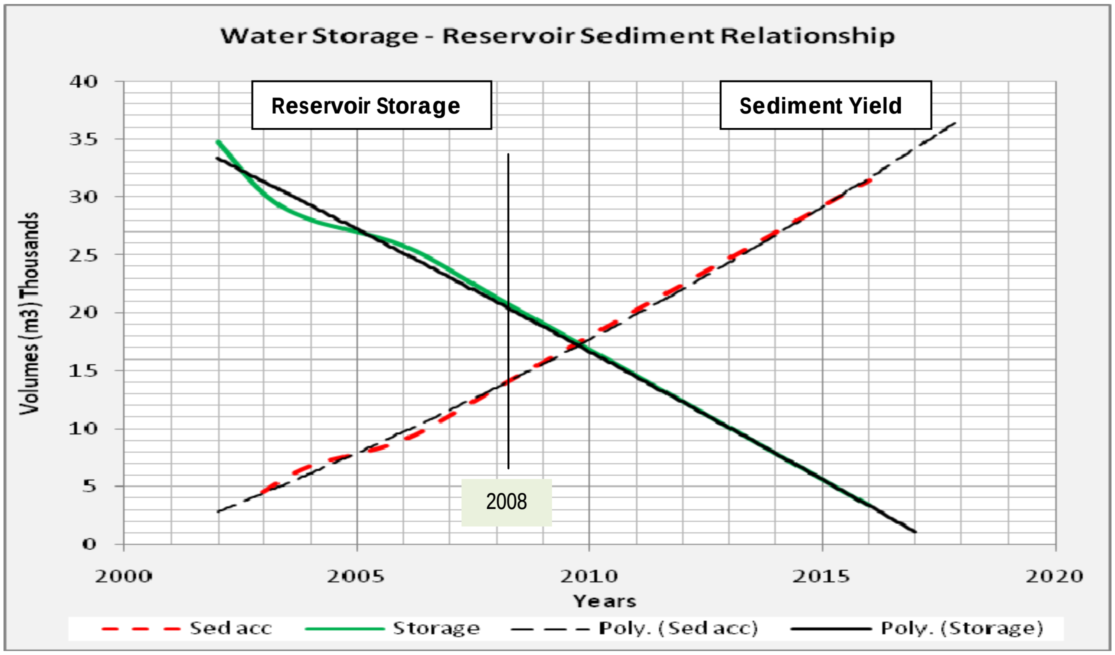

Fig. 5.4: Projection of sediment yield and reservoir storage capacity with time

It is worth noting again that by the time the study was being carried out, it was just a few months from the time that the reservoir had been desilted for the second time in the period of only 6 years of its operation. However, volumes of excavated sediments during the two exercises were not quantified but information gathered from the office of Ministry of Irrigation and Water Development in the area estimated that the volume of sediments excavated in the second exercise could be between 1800 m^3 and 2000 m^3.

The results have further shown that the reservoir at Chamakala II is in poor state and its useful life has been reduced very significantly from the expected designed life of 30 years to just 16±2 years representing 51.7% of reservoir life and a loss of 48.3%. Taking into consideration the two desilting exercises in 2005 and 2007, it could be expected that the reservoir life therefore would have been reduced even further below 12±2 years which would imply that by the year 2014 the reservoir would have been completely filled up with sediments and thereby declared a failure.

5.5 Determination of Reservoir Yield

\5.5.1 Estimation of Percentile Flows

The results from the analysis of rainfall and catchment data show that the mean annual runoff (MAR) is 127 mm which is obtained by using equation 3.15. This shows that the reservoir storage at Chamakala II Small Earth Dam is 5.2% of the mean annual runoff while the catchment average daily flow (ADF) was found to be $0.021m^3s^{-1}$. Again, the 50 percentile flow (Q50) expressed as multiple of ADF is found to be $0.0036m^3s^{-1}$ and the consequently percentile flows for the following percentiles flows: Q90, Q80, Q70, Q60 and Q40 were determined as outlined in step 3 of section 3.9.4 and section 4.6.2 respectively. Table 5.6 gives the subsequent percentile flows and their corresponding Gross Yields and the relationship between percentile flows and gross yields is given in Fig. 5.5 where the gross yields are plotted against percentile flows.

Table 5.6: Percentile flows converted to Gross Yields

Percentile flow	Q90	Q80	Q70	Q60	Q50	Q40
Fraction of ADF	0.024	0.045	0.075	0.116	0.167	0.311
Gross Yield (m^3)	15926	29862	49770	76978	110821	260380

From the Table 5.6 it is shown that gross yield for the reservoir at Chamakala II reduce with increasing percentile flows and it means that for most of the time there is enough water from the catchment to fill the reservoir and enough water to release for downstream users.

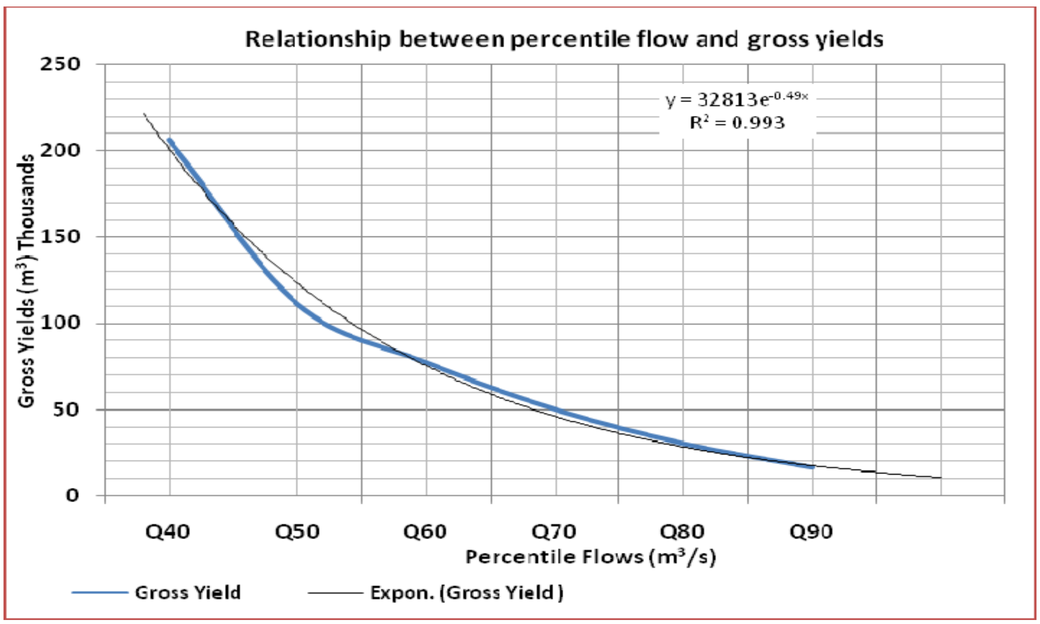

Fig. 5.5: Determination of relationship between gross yields and percentile flows

From the Fig. 5.5, it is shown that the gross yield are reducing with time however the yield would be adequate to fill the reservoir for almost 75% of the time in a year of normal rainfall in the area. The relationship between percentile flows and gross yields is found to be exponential with a correlation coefficient of 0.99 showing that there is a good relationship between the two variables.

5.5.2 Estimating Storage Volumes for each Gross Yield

Storage required for each gross yield is expressed as percentage of the average daily flow (ADF). Table 5.7 gives the determined storage volumes for the subsequent percentile flows for each gross yield determined in Table 5.5.

Table 5.7: Estimated Storage Volumes for the gross yields

Percentile flow	Q90	Q80	Q70	Q60	Q50	Q40
Storage as % of ADF	0.48	1.60	3.00	5.80	10.00	18.00
Volume for Gross Yields (m^3)	3185	10618	19908	38489	66360	119448

The results given in Table 5.6 show a decrease in volumes required for each gross yield with increasing percentile flows. This means that for most of the time of a year the reservoir would be filled in the lower percentile levels from Q40 to about Q65 and the reservoir would be releasing more water for the downstream users but for the rest of the time the reservoir would not be filled. In other words the reservoir would be considered dry for the higher percentiles from about Q80 to Q90.

5.5.3 Derivation of Net Yields

Derivation of Net Yields was mathematically computed by subtracting evaporation volumes (EVAP) from gross yields volumes and the net yield volumes are given in Table 5.8

Table 5.8: Net yield volumes derived from gross yields

Gross Volumes (m^3)	3185	10618	19908	38489	66360	119448
Net yield (m^3)	11847	20139	34467	52354	74343	150634

Fig. 5.6 gives the plot of net yields and storage volumes. Statistical analysis of the two parameters show a power relationship with correlation coefficient of 0.98 with the significant level of 0.00064 showing that there is a good relationship between the two variables. .

The graph shows that as storage increases the yield is also increased significantly. Readings from Fig. 5.6, shows the corresponding values of reservoir net yield for the reservoir's current storage capacity is found to be 36000 m^3 while net yield for the design capacity is at 48000 m^3. Since the reservoir had been designed for the capacity of 34760 m^3 and loss due to dead storage of 5000 m^3, then useable yield from the reservoir is 43000 m^3.

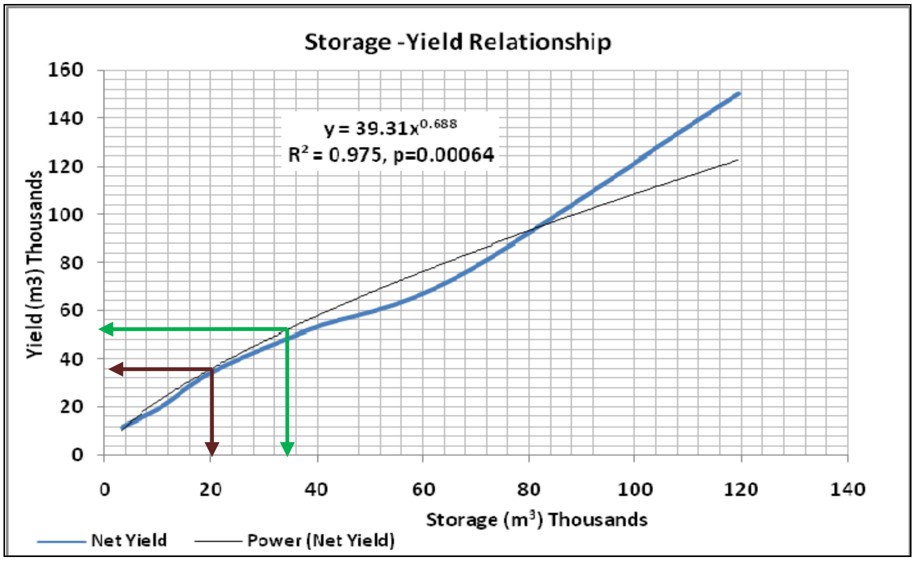

Fig. 5.6: Plot of net yield versus storage volumes

5.6 Determination of Projected Impacts of Sedimentation on Reservoir Yields

5.6.1 Estimation of Reservoir Yield and Projected Yields

The yields being investigated at this point in time are Net Yields and Useable Yields from the reservoir. From the graph of Net yield and reservoir storage the Net Yield is read to be 52332 m^3 for the design capacity of 34760 m^3. However, using the current reservoir capacity of 21294 m^3 the Net Yield was found to be 37355 m^3. In order to determine the projected impacts of sedimentation on reservoir yields it was necessary to first estimate the reservoir storage capacities from the relationship of sediment accumulation and reservoir capacity as shown in Table 5.5.

Table 5.9: Projected volumes of sediment and reservoir yields

Years	Sediment Yield (m^3)	Storage Volume (m^3)	Net Yield (m^3)	Useable Yield (m^3)
2002	0	34760	52332	47332
2003	4485	30275	47587	42587
2004	6730	28030	45130	40130
2006	8975	25785	42611	37611
2008	13466	21294	37355	32355
2010	17956	16804	31738	26738
2012	22447	12313	25626	20626
2014	26938	7822	18755	13755
2016	31428	3332	10426	5426
2017	33674	1087	4823	0

Using equation 4.2, for the subsequent reservoir capacities with time, Net Yields were projected and results are shown in Table 5.9. By subtracting dead storage volume from each of the Net Yields, the corresponding projected Useable Yields were also determined.

In order to determine the relationship and impact of sedimentation on the reservoir yields given in Table 5.9, a graph was used and Fig. 5.7 shows the projected relationships. The yields given in Table 5.9 were plotted against time (years) to determine the relationship with sediment accumulation with change of time in years.

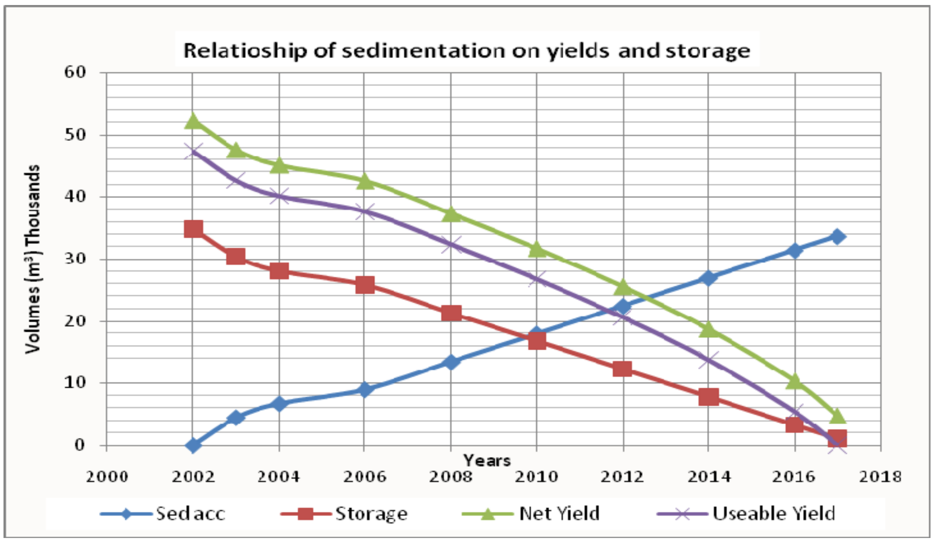

Fig. 5.7: Determination of impact of sedimentation on reservoir yields and storage

From Fig. 5.7, it is found that from the plot of reservoir yields and sedimentation there is a general trend in the fact that increasing sediment accumulation in the reservoir results in reduced storage volume of the reservoir, the Net Yield, the Useable Yield. The relationship shows that net yield depends on reservoir volume which in this case is affected by the problem of increasing sedimentation and consequently useable yield is also affected by continuously decreasing storage with time. It is therefore very clear that within a few years, from the day of this study, the reservoir will be completely filled up with sediments before its intended life time. In other words the reservoir at Chamakala is showing signs that its life has been drastically reduced by 48.3% in six years only for the reservoir that was meant to serve the communities for 30 years. The projections show that between the year 2014 and 2015 communities around Chamakala will have no access to portable waters for their rural livelihoods.

5.6.2 Estimating Dry Season Yield

Analysis of the dry season yield for the reservoir at Chamakala II Small Reservoir was done using equations 3.21 to 3.23. The value of evaporation over the six dry season months (E_D) was found to be 887 mm from data gathered from the Meteorological Services department in Malawi using equation 3.21 and results determined are given in Table 5.10.

Table 5.10: Determination of Dry Season Yields with Change of Time

Years	2002	2003	2004	2006	2008	2010	2012	2014	2016	2017
Sediment Vol		4485	6730	8975	13466	17956	22447	26938	31428	33674
RC	34760	30276	28030	25785	21294	16804	12313	7822	3332	1087
Y_{max}	24350	20876	19151	17438	14051	10728	7493	4387	1524	317

A plot of sediment accumulation, reservoir storage and dry season maximum yield is given in Fig. 5.8.

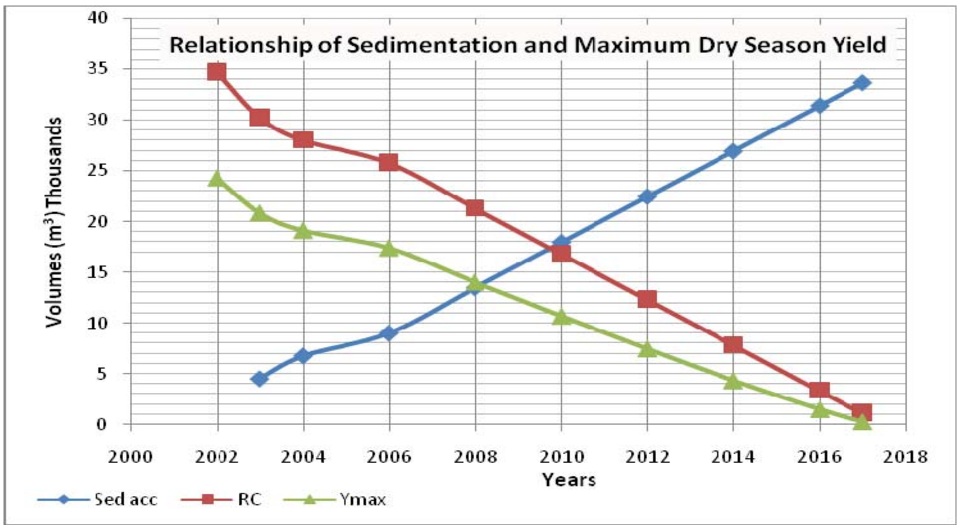

Fig. 5.8: Impact of reservoir sedimentation on the dry season yield

From the Fig.5.8 it can be shown that as sediment accumulation in the reservoir increases the reservoir yield in the dry season is negatively affected as it is continually decreasing with time. In order to determine differences of rates of variation for each of the yields their slopes were determined from Figures 5.7 and 5.8 and the results are given in Table 5.10 and Fig. 5.10 shows the compared rates of variation.

Table 5.11: Comparison of Rates of Variation of Reservoir Yields to Sediment Yield

Volumes (m^3)	RC	Sediment yied	Net yield	Useadle yield	Dry season yield
Rate of Variation (m^3/yr)	-2275	2250	-2975	-2975	-1688

From Fig. 5.9, it is observed that reservoir sedimentation affects all three reservoir yields namely; net yields, useable yields and the dry season yield in addtion to reservoir capacity. The negative values indicate “losses” in volumes of those parameters while the positve one means that there is gain in capacity. In this case the net and useable yields have the highest rate of volume "losses" of 2975 m^3 per year followed by the reservoir capacity at 2275 m^3 per year while thae maximum dry season yield loss is at 1688 m^3 per year.

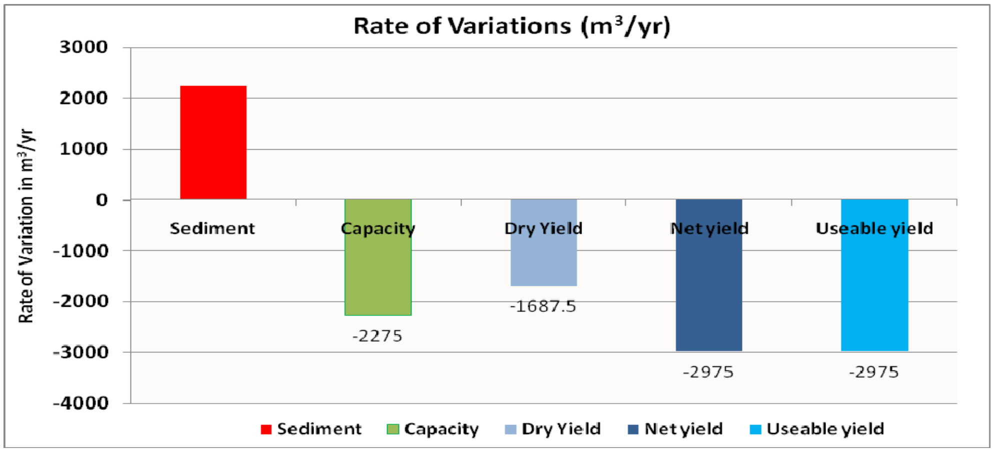

Fig. 5.9: Comparison of Rates of Variation of Reservoir Yields to Sediment Yield

5.6.3 Assessment of Availabilty of Water Resources for Domestic Uses

Table 5.11 gives analyzed data for the assessment of water resources availability from Chamakala II Small Earth Dam to meet the requirements of domestic uses. The two uses were chosen based on priority of use principle as recommended by Mamba (2007). Information gathered during the study revealed that almost 4000 people have direct access to the reservoir water and they depend on the water for all daily needs. On average it was found that per day an individual uses 21 litres of water from the reservoir. Mamba (2007), states in Tanzania water consumption per capita per day is 25 litres and in general the threshold of water consumption for reservoir water in rural un- piped water supply is 25 litres. In this study the quantity 20.5 litres per capita per day was used in order to have a better estimate. Since during rainy season there are alternative sources of water resources this study only analyzed the dry season water requirements for the domestic uses. The dry season in Malawi is from May to October.

Table 5.12: Water demands for Livestock watering and Domestic Uses

Years	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Population	4000	4320	4666	5039	5442	5877	6347	6855	7404	7996	8636
Demand	15088	16295	17599	19007	20527	22169	23943	25858	27927	30161	32574

From Fig. 5.10 it is observed that demand for water is increasing with the growing population which according to the National Statistics Office in Malawi population growth rate is 8.261 percent per year. In order to have a better of the impact of sedimentation on the availability of water resources at Chamakala II Small Earth Dam another plot is given in Fig. 5.10.

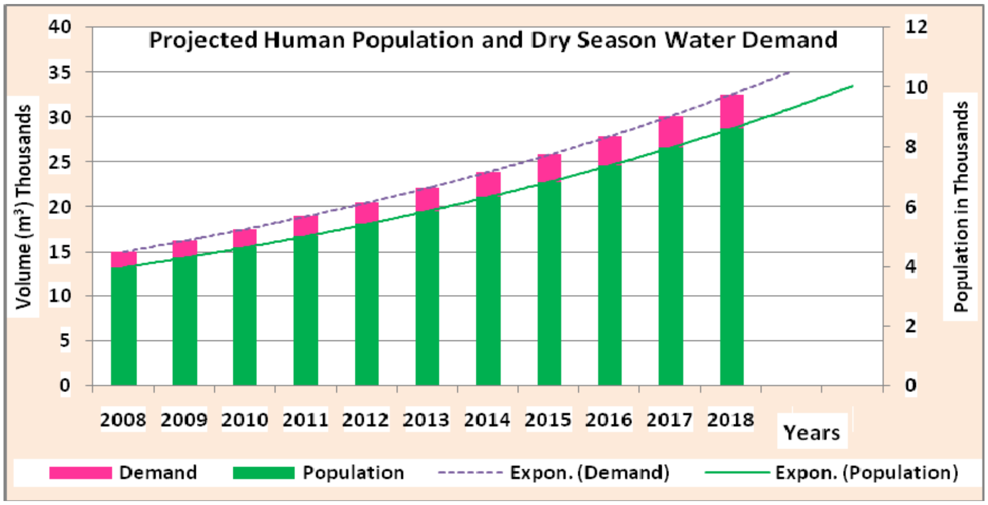

Fig. 5.10: Projected human population based on 2008 figures and domestic water demands

From the plot of projected impacts of sediment on water availability in Fig. 5.11, it is noted that population growth has an exponential growth with time and its correlation coefficient is 0.992, and water demand will be increasing as a polynomial function with coefficient correlation of 0.995. On the other hand, both the useable yield and dry maximum yield are decreasing with time. From the plots of the two it is determined that both are polynomial functions with coefficient of correlation of 0.997 and 0.996 respectively.

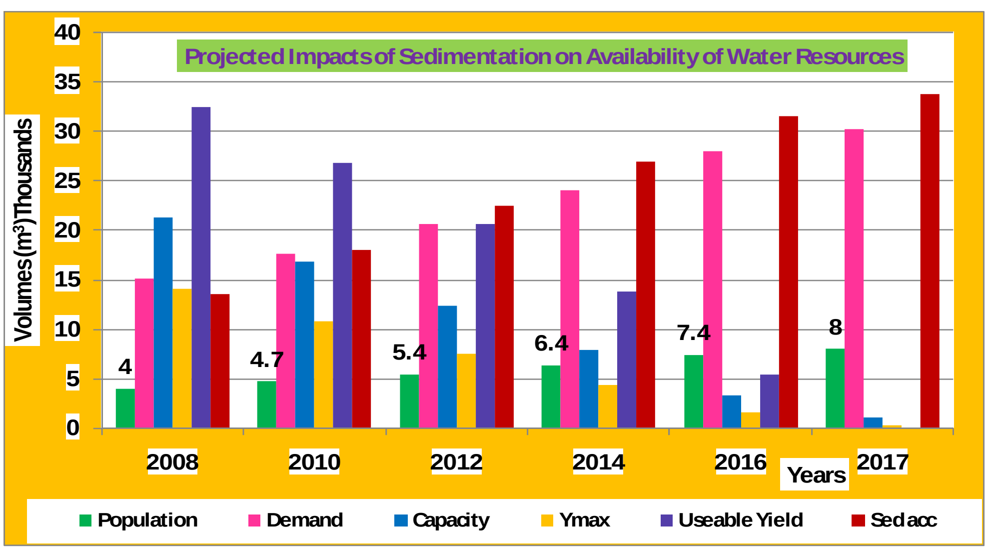

Fig. 5.11: Projected Impacts of sedimentation on availability of water resources

5.7 Determination of Reservoir Trap Efficiency

Table 5.13 gives determined results of the gross storage ratios (SR_g) and gross dam capacities (DC) with change over time. From equation 3.25 the value of MAI was found to be 673 as a product of catchment area and mean annual runoff.

Table 5.13: Relationship of Sediment accumulation and the Gross Storage Ratio

Year	Sediment	DC	SRg	Trap Efficiency	
				Median	Envelope
2002		34760	0.052	77	86
2003	4485	30275	0.045	75	84
2004	6730	28030	0.042	74	83
2006	8975	25785	0.038	72	82
2008	13466	21294	0.032	70	80
2010	17956	16804	0.025	64	76
2012	22447	12313	0.018	58	69
2014	26938	7822	0.012	49	61
2016	31428	3332	0.005	28	42
2017	33674	1087	0.002	3	20

The figures given in Table 5.13 were plotted in order to determine the impact of sedimentation on the trap efficiency of the dam. The plot is given in Fig. 5.12.

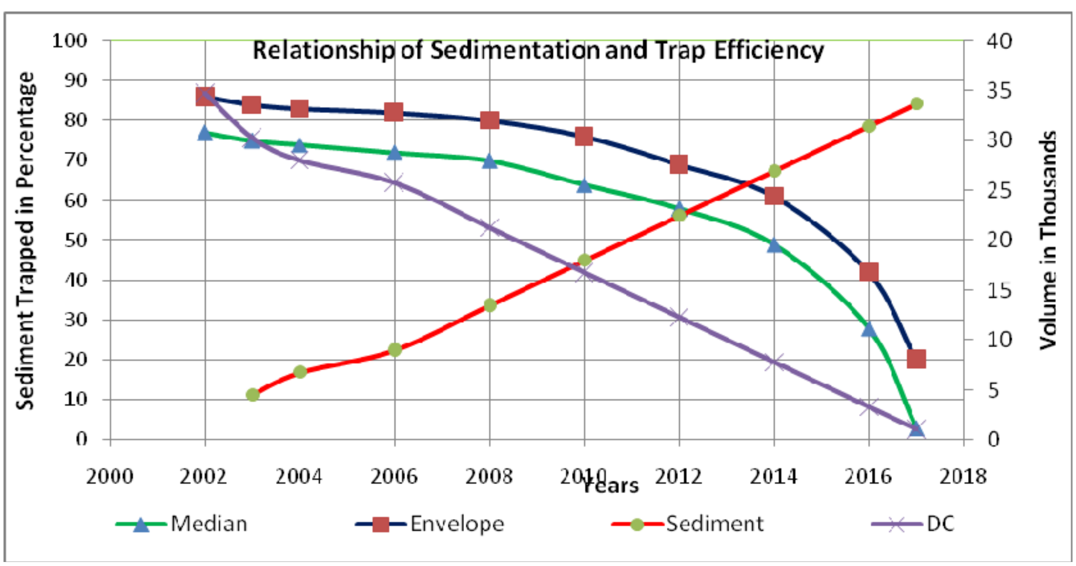

Fig. 5.12: Relationship of storage capacity and trap efficiency of Chamakala Small Earth Dam

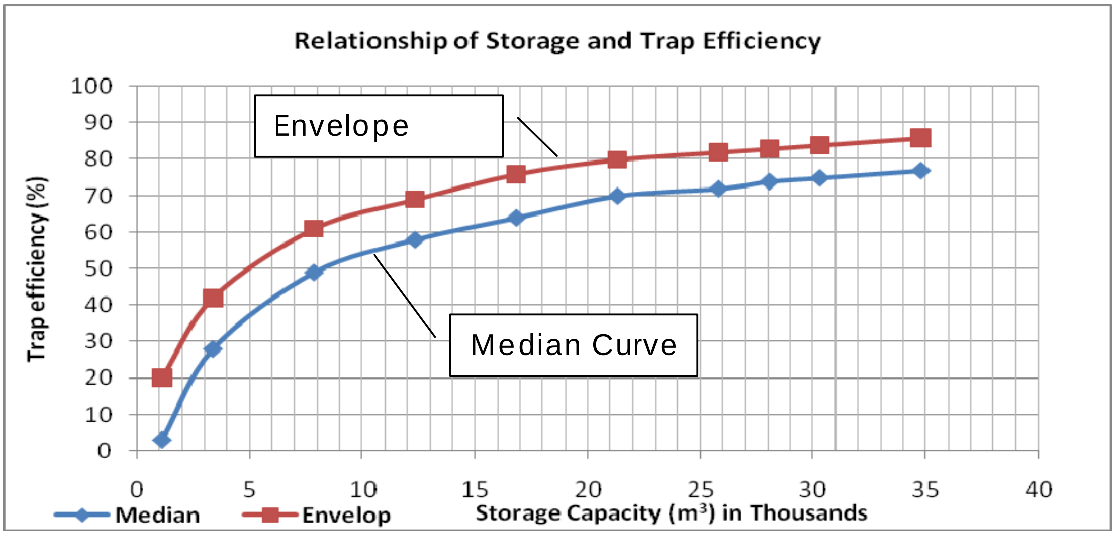

Fig. 5.13: Relationship of Gross Storage Capacity and Trap Efficiency

Using the logarithmic functions derived from the two curves above, estimated values of the trap efficiency were determined. The estimated values show that in the case of Chamakala II Small Earth Dam, a trap efficiency of 100 % would be attained by a dam with a capacity of at least 65000 m^3 assuming the envelope curve of Brune's Curve (see Table 5.14 and Fig. 5.14). This situation supports the observation that a larger dam of about 65000 m^3 would be more sustainable in comparison the one with 34760 m^3 of storage capacity.

Table 5.14: Estimated values of gross storage capacities and expected trap efficiencies

Storage	1724	2893	4855	8149	13678	22958	38534	64677
E	30	40	50	60	70	80	90	100

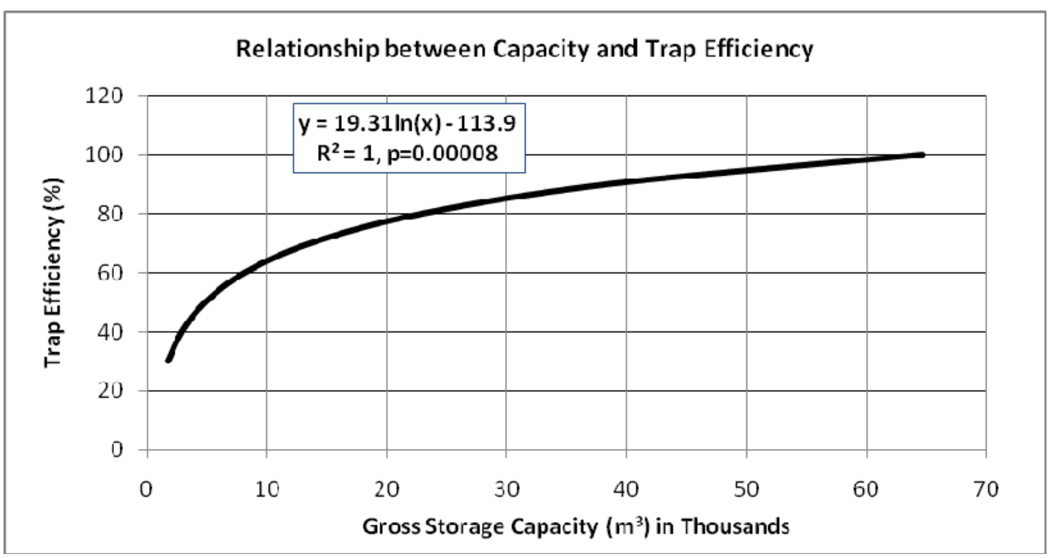

Fig. 5.14: Estimated Gross Storage Capacities with respect to trap efficiency

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter presents conclusions based on the findings of the study of reservoir sedimentation at Chamakala II Small Earth Dam. The chapter also provides some recommendations that may be useful in dealing with the problem of reservoir sedimentation based on the findings of this study.

6.2 Conclusions

- Change of land use, climate change, lack of community empowerment, and poor farming practices are some of the major causes of sedimentation at Chamakala II Small Earth Dam in the catchment are enhancing the rate of sedimentation of the dam,

- Chamakala II Small Earth Dam is infested with problems of sedimentation and 13466±1000 m^3 which is 39% of the total reservoir capacity was occupied by sediments. The rate of sediment transport from the catchment is high and currently it is 517±100 $T/yr/km^2$ (2738±1000 T/yr). The useful life expectance of the reservoir has been reduced to about 15±2 years representing 50% of the designed reservoir life,

- The study therefore concludes that there is a looming problem of water scarcity at Chamakala II for both the domestic uses and livestock watering. Projected population figures for the area show that 6400 people and livestock mainly cattle will have no sustainable source of water resources if the trend continues at the current rates.

- Currently the dam at Chamakala II has trap efficiency of 70% and 80% assuming the median and envelope curves respectively while at design stage the trap efficiency was 77% and 86% respectively. This means that construction of a larger dam with storage capacity of about 65000 m^3 would have been a much better option. This also supports the view that the dam at Chamakala II is very small for the potential yield of its catchment.

6.3 Recommendations

The study recommends that:

- Issues of change concerning land use at Chamakala II should be studied in detail to determine their impacts on water resources,

- Seasonal flows and seasonal sediment accumulation in small reservoirs should be studied in detail for all catchments in Malawi,

- The principle of priority of use of the scarce resources should be adopted especially during the dry season and first priority in case should be livestock watering and domestic uses,

- The reservoir at Chamakala II should be considered for dry excavation so that storage capacity would be restored to a considerable degree,

- A study should be conducted to see the feasibility of raising the dam which would also take into account a provision for a storage to take care of sedimentation,

- Small reservoir should undergo Environmental Impact Assessment so that some unforeseen circumstances at design level could be addressed adequately if the development of small dams is to be economically viable and realistic to improve rural livelihoods, and

- The IWRM approach should be adopted by the communities surrounding Chamakala II at catchment level and so that there is coordinated planning and management of land, water and other environmental resources for their equitable, efficient, and sustainable uses.

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APPENDICES

Appendix 1A: Monthly Rainfall Data (Mm) for Chamakala II

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1995/96	0.0	7.7	153.6	309.4	274.9	164.8	0.5	0.0	0.0	0.0	0.0	0.0	910.9
1996/97	0.6	0.0	256	119.6	341	52.7	86.6	0.0	0.0	0.0	0.0	0.0	856.4
1997/98	14.9	164.0	143.1	339.2	66.9	108.4	31.5	0.0	0.0	0.0	0.0	0.8	868.0
1998/99	46.8	56.4	151	162.2	217.5	178.2	26.2	0.0	0.0	0.0	0.0	0.0	837.9
1999/00	0.0	0.8	64.5	141.7	162	169.6	6.6	0.0	0.8	0.0	0.0	0.0	546.3
2000/01	7.8	105.8	137.8	356.2	174	114.9	1.0	0.0	0.0	0.0	0.0	0.0	897.1
2001/02	0.0	3.6	105.5	185.1	208	65.6	29.2	0.0	0.0	0.0	0.0	0.0	596.8
2002/03	0.0	10.6	231.0	179.7	268	323.9	32.6	0.0	0.0	0.1	0.0	1.8	1046.2
2003/04	0	2.2	257	120.4	308	75.2	53	0	0.0	0	0	0.2	815.6
2004/05	2.9	60.0	451.0	150.3	151.7	61.2	5.1	15.1	0.0	0.0	0.0	0.0	897.3
2005/06	0.0	86.4	91.4	137.2	55.1	150.6	30	2.4	0	0.0	0.0	0.0	553.1
2006/07	0	65.3	300	513.2	250	18.2	2.5	0	0.0	0.7	0	0	1149.3
2007/08	1.7	8.6	144	197.9						2	0	0	

Adopted from Department of Meteorological Services in Malawi

Appendix 1B: Mean Monthly Evaporation (Mm) for Chamakala II

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
134	114	126	122	110	99	102	134	175	206	183	142

Adopted from Department of Meteorological Services in Malawi

Appendix 2A: Average Baseflow Index for FAO Soil Classes

Soil Class	Soil Name	Lithology	BFI	Standard Deviation.	Range
Fo75	Orthic ferrasols	Polymorphic sandstone consolidated and unconsolidated sand and conglomerate	0.59	-	0.37-0.86
Fo94	Orthic ferrasols	As Fo75	0.85	-	0.85
I-Bc	Lithic cambisols	Precambrian: schist, quartzite, syenite, dolerite, graphitic schist, gnesis, amphobolite, charnockkite, crystalline limestone, granitic batholiths	0.51	0.07	0.37-0.58
Lc49	Chromic luvisols	Precambrian: gnesis, schist, phyllite, greenstone	0.35	0.13	0.16-048
Lf10	Ferric luvisols	Basement complex: granite, gnesis, migmatite, basic intrusive rocks: dolerite, gabbro	0.39	0.17	0.18-0.61
Lf81	Ferric luvisols	As Lf10	0.42	0.13	0.22-0.61
Lf82	Ferric luvisols	As Lf10	0.21	0.06	0.14-0.30
Lf90	Ferric luvisols	Precambrian: schist, quartzite, syenite, dolerite	0.60	-	-
Lf91	Ferric luvisols	Same as I-Bc	0.41	-	0.35-0.46
Nd8	Dystric nitosols	Same as Lf90	0.83	-	0.80-0.86
Ne1	Eutric nitosols	Same as I-Bc	0.83	-	-
Ne41	Eutric nitosols	Same as Lc49	0.33	0.41	0.30-0.58
Ne54	Eutric nitosols	Same as I-Bc	0.40	-	0.30-0.58
Q12	Luvic arenossols	Basement complex: migmatite, basic intrusive rocks: dolerite, gabbro	0.14	0.41	0.00-0.30

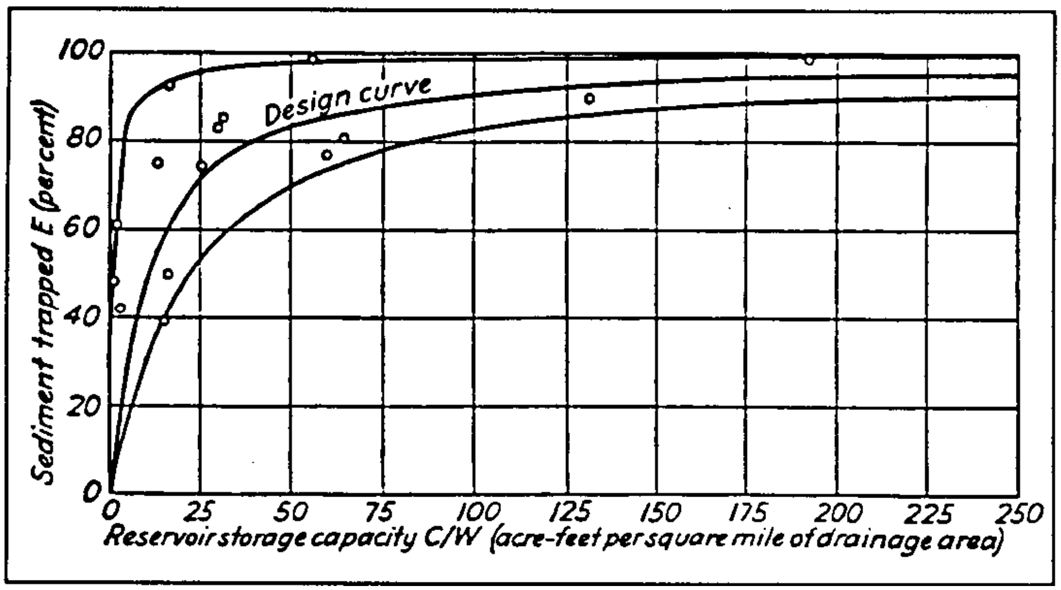
Adopted from PEM Consult (1999)

Appendix 2B: Values of key exceedance percentiles expressed as fractions of ADF

Q50 as fraction of ADF	curve	Q95	Q90	Q80	Q75	Q70	Q60	Q50	Q40	Q25	Q10	Q5
0.00-0.05	A	0.000	0.000	0.000	0.001	0.002	0.005	0.015	0.040	0.179	1.420	3.778
0.05-0.10	B	0.000	0.001	0.004	0.008	0.012	0.029	0.068	0.141	0.423	1.842	4.367
0.10-0.15	C	0.004	0.007	0.016	0.025	0.034	0.064	0.120	0.222	0.560	2.342	4.753
0.15-0.20	D	0.014	0.024	0.045	0.061	0.075	0.116	0.177	0.311	0.727	2.387	4.373
0.20-0.30	E	0.022	0.037	0.064	0.084	0.105	0.162	0.251	0.412	0.865	2.625	4.192
0.30-0.40	F	0.029	0.047	0.087	0.119	0.147	0.225	0.345	0.517	0.947	2.429	3.981
0.40-0.50	G	0.104	0.134	0.191	0.228	0.262	0.345	0.455	0.632	1.035	2.415	3.688
0.50-0.60	H	0.178	0.217	0.279	0.317	0.350	0.428	0.523	0.700	1.082	1.191	2.955
0.60-0.70	I	0.200	0.247	0.326	0.375	0.421	0.531	0.669	0.838	1.176	1.062	2.884
0.70-0.80	J	0.222	0.279	0.369	0.424	0.474	0.594	0.743	0.950	1.373	2.144	2.515
0.80-0.90	K	0.288	0.356	0.466	0.533	0.585	0.703	0.846	0.995	1.269	1.839	2.239

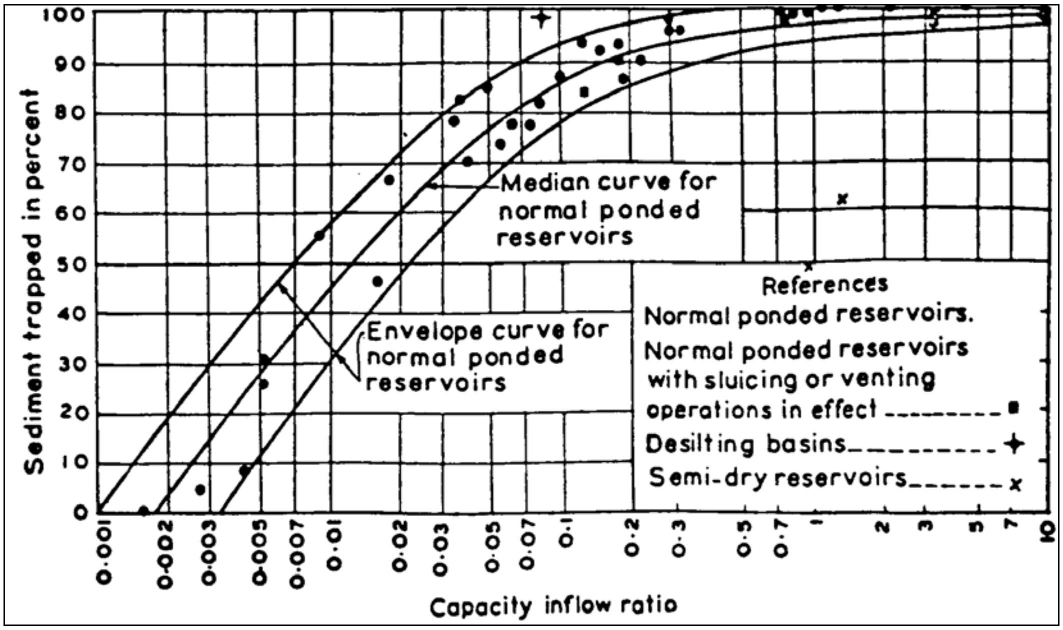
Adopted from PEM* Consult *(1999)

Appendix 2C: Trap Efficiency Curve by Brown



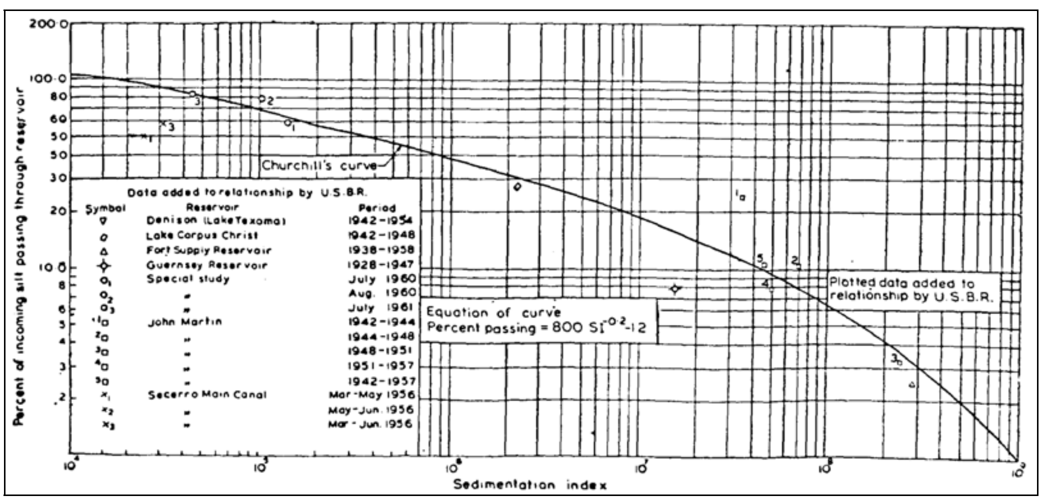
(Adopted from USACE, 1995)

Appendix 2D: Trap Efficiency Curve by Brune



Adopted from USACE, (1995)

Appendix 2E: Trap Efficiency Curve by Churchill



Adopted from USACE, (1995)

Appendix 3A: Hydrographic Survey Data Collected from Chamakala II

Station No.	Distance along line (m)	Distance between lines (m)	Depth (m)	Reduced level (m)	Comment
1	0	0	-1.4	49.9	Start of line 1. embankment
2	10	0	-1.4	49.9	
3	20	0	-1.7	50.2	
4	30	0	-1.8	50.3	
5	40	0	-1.9	50.4	
6	50	0	-1.8	50.3	
7	60	0	-1.6	50.1	
8	70	0	-1.5	50	
9	80	0	-1.5	50	
10	90	0	-1.5	50	
11	100	0	-1.6	50.1	
12	110	0	-1.6	50.1	
13	120	0	-1.5	50	
14	128	0	-1.4	49.9	End of line 1
15	0	5	-0.2	48.7	Start of line2 spillway level
16	6	5	0	48.5	
17	10	5	0	48.5	
18	20	5	0	48.5	
19	30	5	0	48.5	
20	40	5	0	48.5	
21	50	5	0	48.5	
22	60	5	0	48.5	
23	70	5	0	48.5	
24	80	5	0	48.5	
25	90	5	0	48.5	
26	100	5	0	48.5	
27	110	5	0	48.5	
28	120	5	0	48.5	
29	130	5	-0.3	48.8	End of line 2
30	0	15	-0.2	48.7	Start of line 3
31	5	15	0	48.5	
32	15	15	0.2	48.3	
33	25	15	1	47.5	
34	35	15	1.6	46.9	
35	45	15	1.8	46.7	
36	55	15	1.9	46.6	
37	65	15	1.6	46.9	
38	75	15	1.7	46.8	
39	85	15	1.7	46.8	
40	95	15	1.2	47.3	
41	105	15	1.1	47.4	
42	110	15	0.3	48.2	
43	116	15	0	48.5	End of line 3
44	130	25	-0.5	49	Start of line 4
45	0	25	-0.5	49	

46	1.3	25	0	48.5	
47	10	25	1.1	47.4	
48	20	25	2.4	46.1	
49	30	25	2.7	45.8	
50	40	25	2.8	45.7	
51	50	25	2.8	45.7	
52	60	25	2.7	45.8	
53	70	25	2.6	45.9	
54	80	25	2.8	45.7	
55	90	25	2.5	46	
56	100	25	1.9	46.6	
57	120	25	0.7	47.8	
58	130	25	0.4	48.1	
59	140	25	0	48.5	
60	142	25	-0.3	48.8	End of line 4
61	0	35	-0.3	48.8	Start of line 5
62	2	35	0	48.5	
63	12	35	0.4	48.1	
64	22	35	0.7	47.8	
65	42	35	1.9	46.6	
66	52	35	2.5	46	
67	62	35	2.8	45.7	
68	72	35	2.7	45.8	
69	82	35	2.7	45.8	
70	92	35	2.4	46.1	
71	102	35	1.8	46.7	
72	112	35	1.7	46.8	
73	122	35	1.4	47.1	
74	132	35	0.1	48.4	
75	140	35	0	48.5	
76	142	35	-0.5	49	End of line 5
77	0	45	-1.4	49.9	Start of line 6
78	7.6	45	0	48.5	
79	17.6	45	0.3	48.2	
80	27.6	45	0.8	47.7	
81	37.6	45	1	47.5	
82	47.6	45	1.1	47.4	
83	57.6	45	1.3	47.2	
84	67.6	45	1.5	47	
85	77.6	45	1.9	46.6	
86	87.6	45	2.6	45.9	
87	97.6	45	2.1	46.4	
88	107.6	45	1.2	47.3	
89	117.6	45	0.9	47.6	
90	127.6	45	0	48.5	
91	130	45	-0.4	48.9	End of line 6
92	0	65	-0.6	49.1	Start of line 7
93	1.1	65	-0.6	49.1	

94	2.3	65	-0.5	49	
95	12.3	65	0	48.5	
96	22.3	65	0.3	48.2	
97	42.3	65	0.4	48.1	
98	52.3	65	0.8	47.7	
99	62.3	65	1	47.5	
100	72.3	65	1.2	47.3	
101	82.3	65	1.4	47.1	
102	92.3	65	1.5	47	
103	102.3	65	1.8	46.7	
104	112.3	65	1.8	46.7	
105	122.3	65	0.5	48	
106	128.8	65	0	48.5	
107	132.3	65	-0.5	49	
108	142.3	65	-0.6	49.1	End of line 7
109	0	85	-0.6	49.1	Start of line 8
110	2.2	85	0	48.5	
111	10	85	0.2	48.3	
112	20	85	0.2	48.3	
113	30	85	0.2	48.3	
114	40	85	0.4	48.1	
115	50	85	1	47.5	
116	60	85	1	47.5	
117	70	85	1.2	47.3	
118	80	85	1.2	47.3	
119	90	85	1.3	47.2	
120	100	85	1.1	47.4	
121	110	85	1	47.5	
122	120	85	0.3	48.2	
123	127	85	0	48.5	
124	137	85	-0.6	49.1	End of line 8
125	0	105	-0.6	49.1	Start of line 9
126	2.2	105	-0.4	48.9	
127	10	105	-0.4	48.9	
128	20	105	0	48.5	
129	30	105	0.4	48.1	
130	40	105	0.8	47.7	
131	50	105	0.9	47.6	
132	60	105	1.3	47.2	
133	70	105	1.2	47.3	
134	80	105	1	47.5	
135	90	105	1	47.5	
136	100	105	1	47.5	
137	110	105	0.9	47.6	
138	120	105	0	48.5	
139	130	105	-0.6	49.1	End of line 9
140	0	125	-0.7	49.2	Start of line 10
141	1.7	125	-0.5	49	

142	10	125	-0.3	48.8	
143	20	125	0	48.5	
144	30	125	0.3	48.2	
145	40	125	0.4	48.1	
146	50	125	1.3	47.2	
147	60	125	1.1	47.4	
148	70	125	1	47.5	
149	80	125	1	47.5	
150	90	125	0.7	47.8	
151	98.5	125	0	48.5	
152	100	125	0	48.5	
153	110	125	-0.6	49.1	
154	130	125	-1.3	49.8	End of line 10
155	0	126	-0.6	49.1	Start of line 11
156	10	128	-0.4	48.9	
157	20	129	-0.1	48.6	
158	23	130	0	48.5	
159	30	132	0.2	48.3	
160	40	135	0.3	48.2	
161	50	137	0.3	48.2	
162	60	139	1	47.5	
163	70	142	0.6	47.9	
164	80	145	0.6	47.9	
165	86.4	148	0	48.5	
166	90	149	-0.2	48.7	
167	100	150	-0.5	49	
168	110	153	-1.4	49.9	End of line 11
169	0	128	-0.7	49.2	Start of line 12
170	10	130	-0.3	48.8	
171	20	134	0	48.5	
172	23	135	0	48.5	
173	30	138	-0.3	48.8	
174	40	143	0.1	48.4	
175	50	147.5	0.8	47.7	
176	60	152.5	1.5	47	
177	70	157.5	1.1	47.4	
178	75	162.5	0	48.5	
179	80	165	-0.3	48.8	
180	90	168	-0.6	49.1	End line 12
181	0	168	-1.2	49.7	Start line 13
182	10	170	-1	49.5	
183	12.9	172	-0.6	49.1	
184	30	175	-0.3	48.8	
185	50	180	0	48.5	
186	80	190	0	48.5	
187	90	193	-0.5	49	
188	91	195	-0.6	49.1	End line 13
189	0	198	-1	49.5	Start line14

190	10	201	-0.3	48.8	
191	60	214	0	48.5	
192	70	219	0.3	48.2	
193	80	220	0	48.5	
194	90	224	-0.6	49.1	
195	96.8	230	-1	49.5	End line 14
196	67.5	0	-1.5	50	Start Middle line
197	67.5	5	0	48.5	
198	67.5	25	2.8	45.7	
199	67.5	45	1.5	47	
200	67.5	65	1.1	47.4	
201	67.5	85	1.1	47.4	
202	67.5	105	1.3	47.2	
203	67.5	125	1.1	47.4	
204	67.5	145	0.8	47.7	
205	67.5	165	0.6	47.9	
206	67.5	185	0.3	48.2	
207	67.5	207	0.2	48.3	
208	67.5	210	0.1	48.4	
209	67.5	215	0	48.5	
210	67.5	230	-0.4	48.9	End Middle line
			2.8	**45.7**	**Deepest point: lines 4 and 5**
	142.3	**230**		**50.4**	**Highest point surveyed**