ESTIMATION OF SMALL RESERVOIR STORAGE CAPACITIES IN LIMPOPO RIVER BASIN USING GEOGRAPHICAL INFORMATION SYSTEMS (GIS) AND REMOTELY SENSED SURFACE AREAS:

A CASE OF MZINGWANE CATCHMENT

BY

TENDAI SAWUNYAMA

A thesis submitted in partial fulfilment of the requirements for the degree of Masters in Integrated Water Resources Management

Supervisors: Dr A Senzanje
Mr A Mhizha

DEPARTMENT OF CIVIL ENGINEERING
FACULTY OF ENGINEERING
UNIVERSITY OF ZIMBABWE

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ABSTRACT

The current interest in small reservoirs stems mainly from their utilization for domestic use, livestock watering, irrigation and fisheries enhancement on a sustainable basis. Rarely were small reservoirs considered as part of a water resource system, even though they have a significant effect in planning and management of water resource. The main limitation is lack of knowledge on small dams' capacities, for the methodologies used to quantify the parameters are costly, time consuming and laborious. The present study is an attempt to estimate small reservoir storage capacities using remotely sensed surface areas. A field study on 12 small reservoirs was carried out in Mzingwane Catchment in Limpopo River Basin, where depth of water and coordinates of each depth was measured. Both area and volume were calculated for each reservoir using geographical information system. The surface areas that were obtained from fieldwork and that from remote sensing were compared. The Pearson correlation analysis at 95% confidence interval indicates that the variances of the two surface areas (field area and image area) were not significantly different ($p<0.05$). Thus, there is a relationship between remotely sensed surface areas and storage capacities of small reservoirs. The findings from the study show that there is a power relationship between remotely sensed surface areas (m^2) and storage capacities of reservoirs (m^3), given as $Capacity = 0.023083 * Area^{1.3272}$ with 94.6% variation of the storage capacity being explained by surface areas. This was based on the assumed fairly uniform geology and topography where the reservoirs exist over the entire catchment. The relationship can be used as a tool in decision-making processes in integrated water resources planning and management. The applicability of the relationship to other catchments should be looked at in future as well as carrying out hydrological modeling to investigate the impacts of small reservoirs in water resources available in the river basin. The pertinent question the governments and water managers must address is: how can an effective water resources management help alleviate poverty and ensure that the poor are not the victims of bad water management decisions and policies.

DECLARATION

I *TENDAI SAWUNYAMA* hereby declare that this work has been done at my prior knowledge and in my own capacity in the Department of Civil Engineering at the University of Zimbabwe.

Date…………………………………

Name………………………………..Signed………………………………

DEDICATION

To my father, mother, brothers and sisters for all the moral support,

Mercy Chikandiwa for the encouragement and love,

Collins Chizanga and Takawira Kapikinyu for all the kindness and considerations.

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LIST OF ABBREVIATIONS

GIS	Geographical Information System
GPS	Global/Ground Positioning System
WRMS	Water Resources Management Strategy
ZINWA	Zimbabwe National Water Authority
WRD	Water Resources Development
ESA	European Space Agency
DFID	Department for International Development
WSSD	World Summit on Sustainable Development
TIN	Triangulated Irregular Network

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The study is part of Small Reservoir Project that is currently working in Limpopo River Basin in Southern Africa, San Francisco basin in Brazil and Volta Basin in Ghana on the theme: *planning and evaluating ensembles of small, multi-purpose reservoirs for the improvement of smallholder livelihoods and food security: tools and procedures*. However, in this study we will be looking at Limpopo River Basin, and specifically the Zimbabwean side. Water laws in some of the countries that make up the Limpopo River Basin have recently been reformed and the countries that form the basin are Botswana, South Africa, Mozambique and Zimbabwe. South Africa and Zimbabwe have new water acts. The acts brought with them a number of new institutions, processes and procedures that will impact planning and management of small reservoirs. In South Africa efforts were made in reallocating water to the previously disadvantaged groups. In Zimbabwe, the recent agrarian reform means that there was a shift in ownership, access to water, and responsibility for small reservoir maintenance.

However, civilization is primarily dependent on the availability of water, which is increasingly becoming a scarce resource in Zimbabwe (WRMS, 2000). As the trend towards increasing industrialization continues water resources scarcity increases and hence the need to increase the importance of water resources management in meeting the demands for drinking water of a larger population, sanitation, agriculture and industry in the Sub Saharan Africa (Cleaver and Schreiber, 1994). However, assisting the society by proposing and implementing systems that enhance better use of water resources and management in most river basins is therefore crucial. In this respect, small reservoirs are quite important and have been found to provide ready and convenient source of water for various uses to rural communities (Zirebwa *et al*, 2000).

The small reservoirs are storage structures used to store and capture runoff water.
In addition, the definition or categorization of a reservoir as being large or small

varies widely across the world. The distinction is basically a function of dam wall height and/or capacity of the reservoir. (*See Table 1.1*)

Table 1.1: World definitions of small reservoirs as compared to Zimbabwe.

Organization	**Reservoir Size**		
	Small (Height / capacity)	**Medium (Height / capacity)**	**Large (Height / capacity)**
Zimbabwe	<8m / < 1×10^6 m^3	8 – 15m / 1 – 3 x 10^6 m^3	≥ 15m / ≥3 x 10^6 m^3
World Bank	< 15 m	# or *	≥ 15 m
World Commission on Reservoirs	<15m / 50 000 – 1 x $10^6 m^3$	-	-
USA	≤ 6m / 0.123 x 10^6 m^3	>6m – 12m / 0.123 – 5 x 10^6 m^3	≥12m / ≥5 x 10^6 m^3

*NB: # =Reservoirs between 10 and 15m in height are considered large if they present special design complexities. * = Reservoirs under 10m in height are treated as large if they are expected to become large reservoirs during operation.*

Source: Senzanje and Chimbari, 2002

These are the classifications commonly used though there is a variation in defining small reservoirs depending on institutions and purpose of the reservoirs in Zimbabwe. In this study small reservoirs will be defined as storing less than 1 million cubic meters of water and less than 8m in height.

Agriculture being the backbone of the society and, for the majority, the principle source of income, is in most of the semi-arid parts of the country, Zimbabwe, not viable without irrigation (Stevenson, 2000). Small reservoirs are therefore, in addition to other sources of water widely used, a form of infrastructure for the provision of water for irrigating vegetable gardens (Liebe, 2002), and actions to conserve available water has been sporadic in most parts of Zimbabwe (Chenje *et al* 1998). The development of small reservoirs needs to be pursed in a strategic manner and requires water resources planning and management that takes into account environmental effects. While their wide spread distribution had the advantage of serving many people, in turn it complicates the evaluation of their environmental effects. Thus from hydrological point of view, the existence of a large number of small reservoirs as well as their spatial distribution and storage capacities must be known. To note is that, efficient water management, and sound reservoir planning and management are hindered by inadequate knowledge of storage volumes. Although, in most arid areas, small reservoirs store large amounts of water and have significant effect on downstream flows, rarely were they considered as part of water resources systems of a river basin and/ or catchment. In addition, available water in most catchments rarely matches the demand during drought periods. The absence of adequate knowledge on small reservoir storage capacities is a constraint in decision-making process regarding planning and management of existing water resources. Thus in order to quantify available water in these reservoirs their capacities must be known to assist planners in analyzing the water dynamics in the river basin.

1.2 PROBLEM IDENTIFICATION

People living in arid areas with highly variable rainfall, experience droughts and floods and often have insecure livelihoods (Stevenson, 2000). Small reservoirs have often brought positive changes in people's lives and found to be important sources of water for communities (Liebe, 2002), but planning and management of these small reservoirs has been hindered by inadequate investigation on their impacts on catchments water resources in terms of their spatial distribution and storage capacities. Mugabe *et al* (2004) cited that the sustainable use of the limited water resources is constrained by insufficient knowledge of the resources, in terms of quantity, and lack of proper water resource management. It is therefore, unfortunate that the current knowledge on the development and management of small reservoirs is sketchy.

This problem had been identified in the river basin because there are no capacity-area figures for small reservoirs mainly because there are no gauging plates and readers to provide information on water storage levels. This information is available for large reservoirs; see *Photo 1* of Mzingwane dam below.

Photo 1: Photo taken from a large reservoir

As a result there is no comprehensive record of capacities or water levels of small reservoirs in most river basins; and merely local inventories were carried out. The associated potential problem with small reservoirs is their rapid rate of siltation especially when built on large catchments (WRD Report, 1998), which significantly contributes to determination of storage capacities of small reservoirs at any given time but this aspect will not be considered in the study.

Moreover, there are no efficient management tools and procedures for the assessment, sustainable use and planning of water resources in most of the country’s catchments, case of Mzingwane Catchment, with respect to small reservoirs. If there is such information, its contribution to water resources planning and management still needs further investigation. Thus, the need to investigate the benefits of using satellite images to identify small reservoirs in terms of their spatial distribution as well as to estimate small reservoir storage capacities for an efficient planning and management.

1.3 PROJECT JUSTIFICATION

In Limpopo River Basin, it is estimated that there are approximately 1000 small reservoirs (Senzanje and Chimbari, 2002; Zirebwa and Twomlow, 1999), but the importance of these reservoirs is not readily realized. Despite this, the water authorities/boards such as Zimbabwe National Water Authority (ZINWA) were mainly concerned with construction and management of medium and large reservoirs foregoing the importance of small reservoirs in the society. However, the use of satellite images to locate reservoirs and estimate their surface areas is less-time consuming. From work undertaken to date using other techniques to estimate surface areas of reservoirs, it is apparent that it is labour intensive and time consuming to estimate surface water resources of a catchment and with appreciable costs. However, it is evident from work done in Savannah climate (Liebe, 2002) that use of remotely sensed surface areas is indeed feasible. If the errors involved in transposing the results from site with information to another are tolerable in comparison to the uncertainty of the original estimates, then this approach has the potential to provide estimates with appreciable uncertainty for greatly reduced costs. More so, ESA Earth Observation at WSSD (2002) meeting indicated that it would provide free satellite to water managers and water institutions in order to facilitate water resources planning and management as well as flood mitigation measures. Little work has been done on small reservoirs to establish relationships between depth, area and volume in semi-arid regions and no tool to aid decision making process and to monitor reservoir storage volumes is available, hence the need for this study.

1.4 OBJECTIVES AND RESEARCH QUESTIONS

1.4.0 Main Objective

To estimate small reservoir storage capacities using Geographical Information Systems (GIS) and remote sensing techniques for use in planning and management of water resources in the Limpopo River Basin.

1.4.1 Specific objectives

1. To identify small reservoirs in the study area in terms of their numbers and spatial distribution.

2. Develop a methodology to estimate small reservoir storage capacities as a function of their remotely sensed surface areas in the Limpopo River Basin.

3. Compare small reservoir storage capacities determined from the model using surface areas obtained from field survey and that from satellite images.

1.4.2 Research Questions

1. What is the recent existence in number and spatial distribution of small reservoirs in the basin?
2. Is there really a relationship between remotely sensed surface areas and storage capacities for small reservoirs?

1.5 HYPOTHESES

1. Remote sensing is a suitable means to detect small reservoirs and adequately measure their surface areas.

2. There is a relationship between remotely sensed surface areas and storage capacities of small reservoirs.

2. LITERATURE REVIEW

2.1 Water Resources Assessment in Zimbabwe

According to Mugabe *et al*, 2004 about 10% of rainfall is lost as runoff in semi-arid areas of Zimbabwe. This runoff is sufficient to fill the small to medium reservoirs, on which rural communities depend on in most years except the very dry ones when there is little or no runoff. There is improper management of the water resources and in most cases crisis management is employed at last moment when shortages are apparent. More than 600 small reservoirs were constructed in drier parts of the country in the last 30 years (Zirebwa and Twomlow, 1999) and vary in capacity from 6×10^4 and 3×10^4 m^3 and a catchment area of between 2 and 55 km^2. Small reservoirs are quite important in improvement of livelihoods of rural society, as they are a convenient source of water for various purposes (domestic use, livestock watering, and small scale irrigation). Moreover, water resources are critical for improving rural livelihoods and their natural environment (Stevenson, 2000). This study recognized the opportunity to use small reservoirs as a community development platform to address, in a holistic manner, the wider range of environment, technical and socio-economic issues. Most common in carrying out water resources assessment is the use of a capacity-area relationship for medium and large reservoirs that exists in Zimbabwe, foregoing small reservoirs relationships irregardless of their importance to rural society.

2.2 Small reservoirs development in Zimbabwe

At this juncture a clear distinction between a reservoir and a dam is provided. A dam is defined as the wall and water body behind it including the ancillary works whereas a reservoir is the water body behind the wall. In the early 1990s, Zimbabwe went through one of the most vicious droughts in the country and the Matebeleland South Province where the Limpopo River Basin is, was hard hit. This drought had the effect of energising the country into developing more reservoirs to mitigate against droughts. This is the period when programs such as “A dam a district” and “Give-a-dam” campaign were launched. Recently there have been further efforts towards medium and small dam construction in the rural areas through the government’s “Medium sized dam” programme and the “Rural Development Fund” (Senzanje and Chimbari, 2002). Thus, the objectives of most governments in semi arid countries like Zimbabwe and aid organizations in developing small reservoirs were to provide sources of water for domestic uses, creation of new irrigated areas and recharge groundwater (Vermillion and Al-Shaybani, 2004). A number of programs, funding sources and external procedures were used by aid organizations to develop small reservoirs in Zimbabwe, including Care Zimbabwe. The Department of Irrigation under the Ministry of Agriculture and Land Resettlement in general has little, if any, funds for development, operations or maintenance of small reservoirs and water delivery systems. In general, they lack the capacity to provide support to rehabilitate deterioration of irrigation systems, to regulate over-extraction of groundwater and to plan small reservoirs development according to basin level analysis and planning for integrated water resources management.

The construction of a large number of small reservoirs and their spatial distribution throughout most basins enables access to water to a wide population. In turn there are feedback effects on the environment that need to be waved away. Small reservoirs are constructed on small rivers draining small catchments and full involvement in the ‘ownership’ of communal small reservoir projects by communities was considered to be essential to ensure sustainability (DFID, 2004). Often small reservoirs were constructed I in a series of projects funded by different agencies in semi-arid areas, at different times, with no proper coordination between implementing partners. As a result small reservoirs were not used optimally and are falling into disrepair an indication that there is room for improvement in the planning, operation, and maintenance.

Reservoirs may not be sustainable as they eventually lose their storage capacity through filling up with sediments. High levels of siltation rates of up to 30% of reservoir capacity (over a period of about 40 years) have been recorded in some reservoirs found in Masvingo Province in southern Zimbabwe (Zirebwa and Twomlow, 1999). Most of small reservoirs have initial storage capacities that are only a fraction of mean annual runoff (Zirebwa *et al* 2000). ‘Small’ reservoirs silt up far more rapidly than ‘large’ reservoirs and they save a purpose to ensure large reservoirs downstream are not silted up.

2.3 Role of small reservoirs in water resources

Small reservoirs have been found to provide a ready and convenient source of water for different purposes to rural communities and this makes them indispensable, and they are quite important in improvement of livelihoods of rural society (Stevenson, 2000). The old Conex (Conservation and Extension Services) Unit of the then Ministry of Agriculture developed reservoirs mainly for livestock watering and for conservation works in Zimbabwe. This aspect had gone unnoticed in many cases with respect to the role of small reservoirs in Africa. Thus, catchment management was enforced by Conex to try and extend the life of the reservoirs by minimizing catchment degradation, which leads to siltation. This trend however changed after independence when enforcement became weak leading to possibly siltation problems of most small reservoirs thereby posing a threat to benefits realized from the reservoirs (Senzanje and Chimbari, 2002).

However, there are several advantages for using small reservoirs other than the above-mentioned uses. The following are some of the advantages:

a) Resource conservation through flood control and enhanced groundwater recharge, and through local people instinctively seeing the need to protect the local catchment to reduce siltation of the reservoirs.

b) Readily accessible, needing only low lift pump technology and incurring lower operation and maintenance costs according to research by Care Zimbabwe (DIFD, 2002).

c) Livestock can be watered without need to pump water.

d) Can increase bio-diversity providing a sanctuary for wild life and birds.

Small reservoirs and other community projects can assist local communities to improve their livelihoods through the development of small-scale irrigation from small reservoirs. Additionally, Care Zimbabwe carried out a research aimed to increase income and improve nutrition for up to 800 000 needy people in selected districts of Masvingo Province by rehabilitating small and medium sized reservoirs that were under used and/or in poor condition (DFID, 2002). However, the only disadvantage of small reservoirs is that they can silt up quickly in especially dry land areas prone to overgrazing and erosion.

2.4 Methods for estimation of small reservoir capacity

In order to have a water resources assessment it is crucial to know the capacities of reservoir in question. To calculate the volume of water contained in the reservoir requires estimating the shape of the reservoir as close as possible. This is not easy as the reservoir is usually irregular both in cross and long sections. A more accurate method of estimating capacity would be to consider area enclosed by contours at appropriate intervals. The volume between two successive contours can then be calculated and these volumes are then summed up to get the total capacity of the dam. In many cases small reservoirs are designed without carrying out a full topographic survey, and the storage volume is estimated from the reservoir width, the throwback, and maximum impounded water depth (Lawrence and Lo Cascio, 2004). Thus estimation of reservoirs capacities is based on direct and indirect methods.

2.4.1 Direct Methods

Several formulae are used for estimating small reservoir storage capacities. The formulas are based on equation below, with different values for the two constants.

$$C = K_1 * K_2 * D * W * T \text{.....................} \textit{Equation 1}$$

Where: K_1 = a constant, K_2 = second constant related to the shape of the valley cross-section, D = the maximum water depth, i.e. the difference in elevation between the lowest point in the reservoir bed and the spillway crest level, W = the width of water surface at the dam at the spillway crest level, T= the "throwback" at the spillway crest level (the throwback is the distance from the dam wall along the reservoir axis usually to the point where river enters).

Some examples derived from dam design manual (Lawrence and Lo Cascio, 2004) are listed below:

a) USAID (1982), where K_1= 0.4 and K_2= 1, for valley cross section shapes

$$C = 0.4 * 1 * D * W * T \text{ ....Equation 1.1}$$

b) Fowler (1977), where K_1 = 0.25 and K_2 = 1, for valley cross section shapes

$$C = 0.25 * 1 * D * W * T \text{ ....Equation 1.2}$$

c) The "1/6" rule where a dam is represented as a triangular prism, K_1 = 0.167 and K_2= 1

$$C = 0.167 * 1 * D * W * T \text{ ....Equation 1.3}$$

d) Nelson (1996), where K_1 = 0.22, and K_2 is selected on the basis of the valley cross-section, in all cases in this study K_2 is selected as 1.2

$$C = 0.22 * 1.2 * D * W * T \text{ ....Equation 1.4}$$

Volume predictions from each of these methods were compared with the surveyed volumes for nine small reservoirs in Zimbabwe, covering a range of dam heights and river valley cross-section shapes. It was seen that on average the USAID relationship over-predicts small dam volumes by 36%, the 1/6-rule under-predicts dam volumes by 43% while the Nelson and the Fowler relationships performed quite well, with an average under-prediction of 10% to 15% (Lawrence and Lo Cascio, 2004).

However, volume is also estimated from a simple calculation, used in Zimbabwe (Hudson, 1998) by the following equation:

$$C = (D * W * T)/6 \text{ ....Equation 2}$$

Where D=Depth of water, W= Width of dam, T= Throwback, and in most cases results in an under-prediction of storage volumes. This equation is quite similar with equation 1 except that in this case the constants are represented by 1/6. This assumes the reservoir is a pyramid whose base is the dam wall (Figure 2.1a). In addition, capacity of a reservoir can be estimated by measuring the surface area at fully supply level, which also assumes reservoir as a pyramid whose base is the water surface, (Figure 2.1b). This method is slightly more accurate than the one in Figure 2.1a and is given by the equation:

$$C = (A * D)/3 \text{ ....} \textit{Equation 3}$$

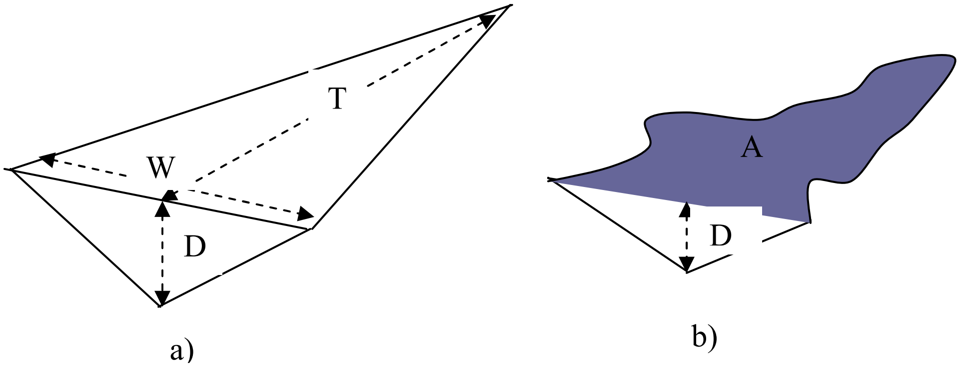


Figure 2.1: Estimation of storage capacity of a reservoir

However the above are not quite accurate as they are based on quick surveys. More accurate methods used to determine the capacity of small reservoirs are given below:

Mid area method, which assumes the areas contained within successive contours represents cross sections, and the distance between the contours being the contour interval.

Mid area rule;

$$C = \sum_{i=1}^{n} \left(\frac{A_i + A_{(i+1)}}{2} \right) dh \text{ ....} \textit{Equation 4}$$

Where C= Reservoir capacity, A_i =Surface area at contour interval i, A_{A+i} =Surface area at the next contour level above contour level i
This method is more suitable where the contour interval, dh, is small.

Prismoidal Method

This assumes the capacity enclosed by two contour intervals to be representing a prism and therefore the volume can be calculated using the prismoidal formulae.
Capacity enclosed by two contours is given by the formulae below.

$$C = \sum_{i=1}^{n} \left\{ dh \left[A_i + \sqrt{A_i A_{(i+1)}} + A_{(i+1)} \right] / 3 \right\} \text{.........} \textit{Equation 5}$$

Where C, A and dh are as previously defined
The direct methods are quite laborious and time consuming hence the use of indirect methods.

2.4.2 Indirect Methods

Besides the mentioned methods above there also exist indirect methods used to estimate surface areas from topographical maps or satellite images, from which a power relationship between surface area and capacity of a reservoir is used to estimate reservoir capacity.

Meigh (1995) used 1:50 000 topographic maps to estimate surface areas of the small farm reservoirs on the study of finding the impact of small farm reservoirs on urban water supplies in Botswana. The study clearly stated that area estimated from the maps would be of poor measure of the actual area because the aerial photography on which the maps are based was unlikely to correspond to the times when the reservoirs are full, and because some of the reservoirs were so small that they may not be representative of the actual areas of the reservoirs.

A study was carried in Ghana by Liebe (2002) on the use of remote sensing data to estimate reservoir storage capacities for small reservoirs and had indicated that there exist relationships between areas, depth and volume for the small reservoirs. In the study a relationship was established to estimate small reservoir capacities using remotely sensed surface areas and storage volumes in savannah climates. The model uses GIS and remote sensing in estimation of area and volumes of reservoirs and such a model does not exist in Zimbabwe for small reservoirs.

2.4.3 Capacity Area Power Relationship

From the study by Meigh (1995) a power relationship between capacity of the reservoir and its surface area measured from topographical maps was obtained as:

$$C = 7.381 * Area^{1.251}$$ …*Equation 6*

(R^2=93.1%)

Where capacity is in thousand m^3 and area in hectares (ha)

The established power relationship by Liebe (2002) between capacity of the reservoir and its surface area measured from satellite images is summarized in the equation:

$$C = 0.00857 * Area^{1.4367}$$ ……….*Equation 9*

Where Capacity is in m^3 and Surface area in m^2

At high precision, the equation allows satellite based reservoir storage assessment and volume monitoring in the Upper East Region of Ghana. The relationship explained 97.5% of measured variance.

Mitchell (1976) did some work in establishing a general power relationship between capacity and area for 12 selected large reservoirs in Zimbabwe using data from detailed survey. The relationship was used in establishing yield estimates of the large reservoirs. The power relationship is given by the following equation obtained from log area/ log capacity linear regression:

$$C = 2.646 * Area^{1.5}$$ ………*Equation 7*

Where area is in ha and volume in $10^3 m^3$

Study by Mazvimavi *et al* (2004, unpublished) on assessment of water resources in Zimbabwe assumed that there exists a surface area-capacity power relationship for an average or medium reservoir that is given by

$$C = 0.770 * Area^{1.299} \text{ ………………}\textit{Equation 8}$$

Where A=surface area (ha) and C is the storage volume (m^3).

Knowledge of a power relationship for small reservoirs is not available in Zimbabwe. No attempt was made to apply surface areas derived from satellite images in storage capacity estimates from the work previously done as indicated by the relationships above.

According Sugunan (1997) from Fisheries Department, Zimbabwe, inventories on small reservoirs was compiled at the Agricultural Technical and Extension Services (AREX) under a Geographic Information System format. However, this information is not adequate and from the available data, approximately 826 small reservoirs were in Insiza District, with approximately 2500 being in the Mzingwane catchment as a whole (Sugunan, 1997) based on the assessment done. In addition, a similar database was being designed at the Aquaculture for Local Community Development Programme (ALCOM) of FAO in Harare. Even though these databases provide information regarding the name, location, capacity, surface area, type of ownership, dam use, rainfall, soil type, altitude, and other attributes of dams not all relevant data on each reservoir is available, for instance, capacity of 7609 small reservoirs was known, but their surface areas were available for only a few. In fact, not many people would be interested in surface areas of reservoirs but instead reservoir volumes that give a clear picture of amount of water stored. The following relationship obtained from work done from Eastern Province Zambia to estimate surface areas based on storage capacity was used to give total area estimate of small reservoirs:

$$A = 0.215 * Capacity^{0.7401} \text{ …}\textit{Equation 10}$$

Where Area is in m^2 and Capacity is in (1000) m^3

This was so because reservoirs were constructed for storing water and only their capacities were recorded in original database and surface areas were therefore estimated using the equation. In general, it can be clearly seen that the constants differ for the equations above because of different study areas and climatic conditions and methods used to estimate surface areas, that is, from topographical maps and/or field survey.

2.5 Remote Sensing and Geographic Information Systems applications in hydrological modeling

Hydrological models require a large amount of geographical and time series data. Models for simulating of water balance for an area take into account detailed physical and hydraulic relationships with respect to data availability, knowledge, computer capacity and available time. In the past the spatial reference of the time series data has been modeled in a simplified way by reference algorithms and statistical interpolation methods (Wolf-Schumann and Vallant, 1996). It is only recently that the time varying aspect of GIS data has been taken into consideration. A geographic information system is a system for turning large volumes of spatial data into useful information (Tomlinson, 1972). By contrast remote sensing is a powerful technique for the collection of multi-temporal data sets but there exist a gap between data collection and utilization. Many scholars feel that full potential of both techniques can only be achieved if they are integrated (Shelton and Estes, 1981).

For an understanding of the hydrology of areas with little available data, a better insight into the distribution of the physical characteristics of the catchments is needed. By image processing techniques, maps can be produced which depict some of the characteristics, notably the cover types such as areas with dense vegetation, water bodies and areas with bare soils or rock outcrops. Remote sensing could contribute to hydrologic information provided the matter is handled by hydrologists experienced in qualitative hydrological reasoning based on knowledge of the field conditions of a particular catchment (Shelton and Estes, 1981). Remote sensing techniques and more detailed climatologically and process models now available provide new possibilities for detailed modeling of small reservoirs in order to capture their surface areas for estimating their storage capacities to have a clear picture of available water resources.

Furthermore, recent advances in computer technology have provided a means to rapidly process large arrays of spectral data for remote sensing and to combine these data with other geographical information, such as topography (including slope classes and aspect), vegetation types, soil types and geology and/or water reservoirs (Isard, 1986). In addition, the development of GIS representations of model output provides an improved visualization of the hydrologic processes by combining several spatial characteristics such as inflows and out flows and small reservoirs capacities to evaluate cause and effect relations or correlations (Vieux, 1991). Thus, there are indications that there is room for improvement as far as research on small reservoirs is concerned and a need to establish a model equation to estimate reservoir storage capacities of small reservoirs using their remotely sensed surface areas.

3. MATERIALS AND METHODS

3.1 DESCRIPTION OF STUDY AREA

The study was conducted in the Mzingwane catchment, which forms part of the Limpopo Basin on the Zimbabwean side.

3.1.1 Limpopo River Basin

The Limpopo River forms part of the northern border of South Africa, and separating South Africa, Zimbabwe and Botswana before it enters into Mozambique and drains into the Indian Ocean. The basin is therefore shared between four countries, Figure *2*

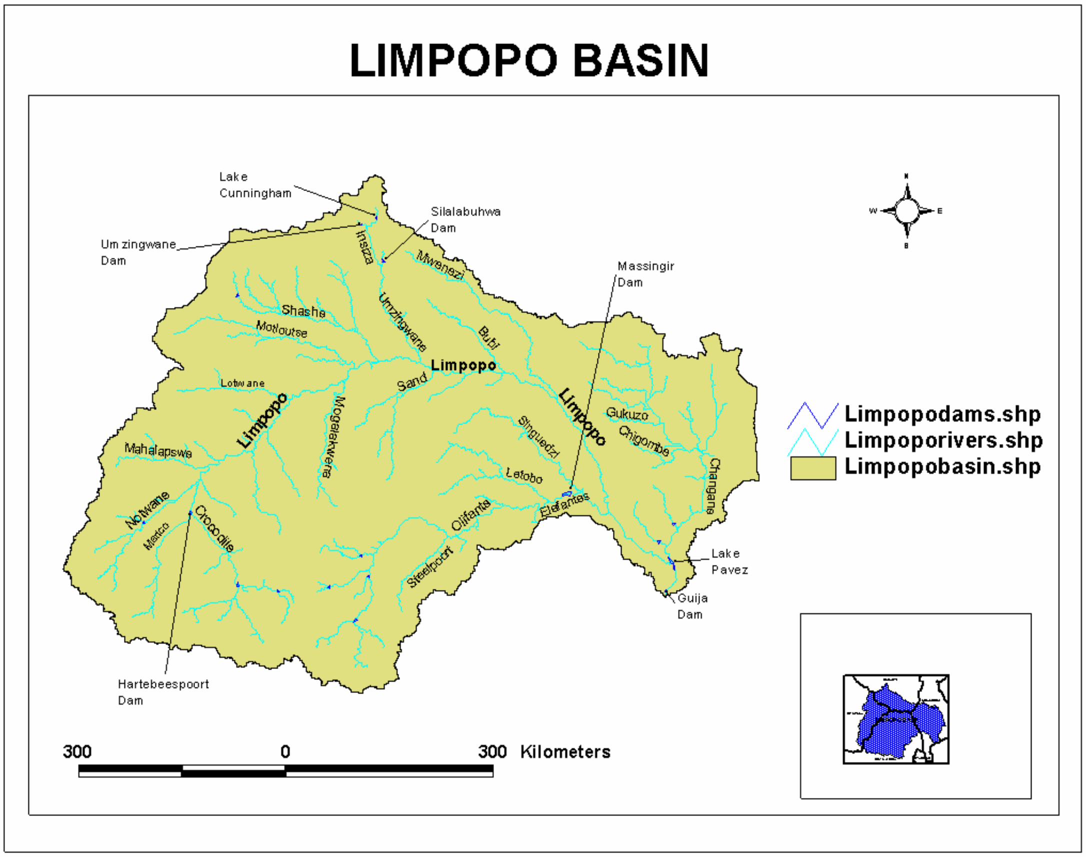


Figure 3.1: Map of Limpopo Basin

The Limpopo River Basin is demarcated by latitude 24^0S, longitude 25^0E and latitude 26^0S, longitude 34^0E. The annual runoff of the Limpopo is 5500 Mm^3, small in comparison to other major basins, but the river is important because of its strategic value for water to the four countries (Pallet, 1997). However, surface water resources produced (yielded) in the basin within Zimbabwe are estimated at 540 Mm^3/year, of which, 410 Mm^3/year drains to the Limpopo River at the Zimbabwe-South Africa border and 130 Mm^3/year enters Mozambique before flowing into the river (DSE, 2001). Only 76 Mm^3/ year is water considered as being potentially available for irrigation after other deductions like domestic, mining and industry. In addition, 3992 ha have been developed or planned for irrigation and suitable land for irrigation estimated to be 7000 ha (DSE, 2001). A short and intense rainy season in the Limpopo river basin, with highly unreliable rainfall leads to frequent droughts. Crop production is not secure. On major reaches of the Limpopo and many of its tributaries, the flow of water in the river in dry years can occur for 40 days or less. When the rivers do flow, river water can contain up to 30% sand and silt (Lawrence, 2000). Other issues limiting water resources development include difficulty in obtaining development capital, insufficient training and support services for small-scale farmers, political instability, land piracy in certain areas, and land mines. Some catchments (mainly in the southern regions) are highly developed. Over utilization of water resources and pollution arising from high-density urban settlements, mining and other industrial development are seen to have an impact on the social, economic, political and natural environments downstream (WRMS, 2000).

3.1.2 Mzingwane Catchment

The Mzingwane catchment, which forms part of the Limpopo River Basin is located in the semi-arid region of Zimbabwe, and is divided into four sub-catchments, namely, Shashe, Upper Mzingwane, Lower Mzingwane, and Mwenezi (Figure 3.2). The rivers flow to the south eastern direction into the river Limpopo as shown on the map below, carrying with them sediments. In certain parts of river courses, flow occurs only during the wet months, while during the dry months the riverbed is a sandy alluvial bed of considerable thickness and provides enormous storage of water. These alluvial formations serve as sources of water for rural communities.

While the temporal distribution of rainfall follows the general pattern of the Southern African region with wet months between November and March, the spatial distribution of rainfall is quite variable over the entire catchment. The annual rainfall ranges from 250mm in the south to 550mm in the north of the catchment, with average of about 350mm over the entire catchment. One feature of the aridity of the catchment is the annual evapotranspiration rates being higher than those of precipitation, so that there are long-term net fluxes of moisture from the catchment.

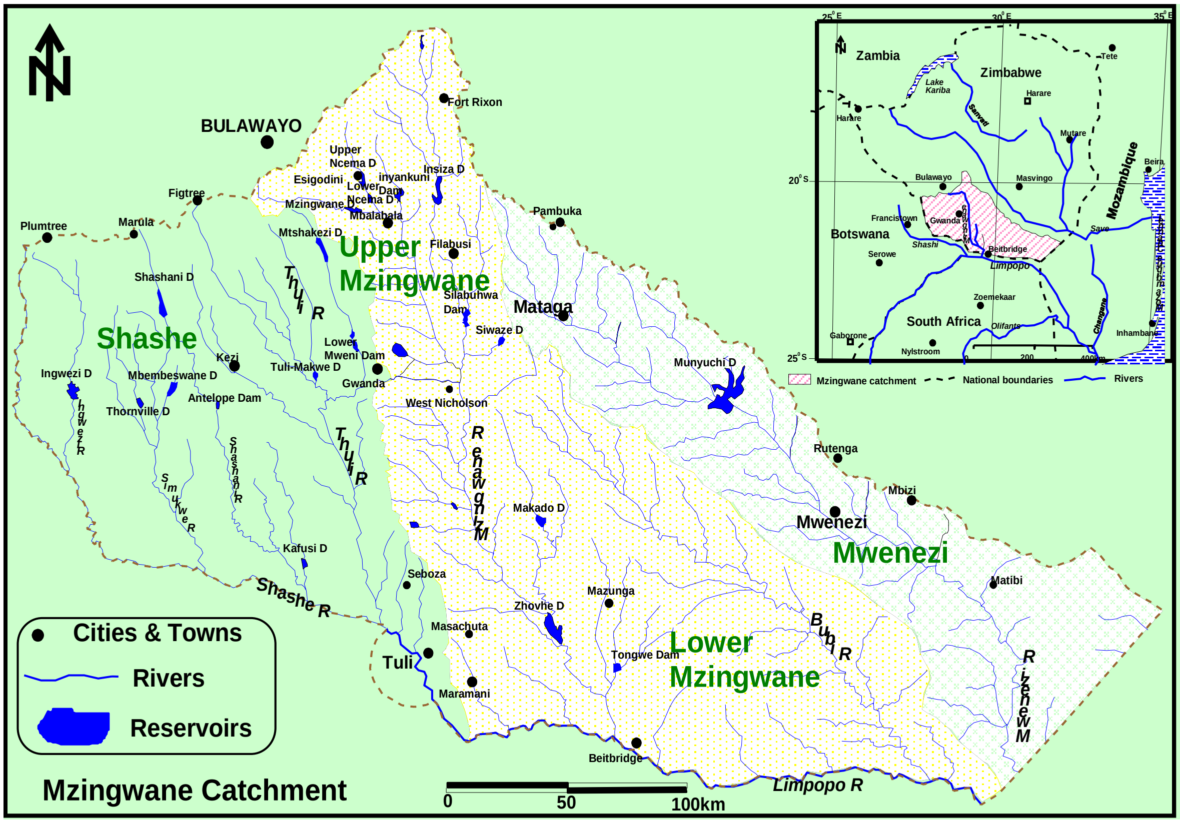


Figure 3.2: Mzingwane catchment map (Source, David Love, undated)

Most rivers are able to provide water only for short periods of time each year in the catchment. In addition, pollution of the available water in some catchments and competition for water in others create significant stress on the available water resources in Mzingwane catchment. Poverty is widespread and people are extremely vulnerable to the effects of drought or crop failure (WRMS, 2000). Little effort has been made to look at the importance of small reservoirs in the catchment.

3.2 RESERVOIR SURVEYS AND REMOTE SENSING FOR SURFACE AREAS AND STORAGE CAPACITIES

3.2.1 Criteria for reservoir selection

Before carrying out any reservoir survey it was necessary to have an insight of the characteristics of reservoirs. It is worth noting that for most small reservoirs, no data was available on their physical characteristics, but to model them it was necessary to have estimates at least of the following for each reservoir: the surface area and storage volume, the area/capacity relationship as the dam drawn down, and the abstractions. The critical component in dam survey was maximum volume of water which determines amount of water available at fully supply. Maximum volumes can be in two ways, firstly, that is in terms of 'relative maximum' that is defined by the highest level, reached in a given year, and secondly, in terms of 'full supply capacity' that is defined by the height of the spillway. Also the maximum capacities reached annually are defined as highest flood level reached when reservoirs are spilling. However, due to water losses and usage, the volume of reservoirs usually decreases from relative maximum, expected at the end of the rainy season. In general, influences of area and volume of reservoirs largely depend on:

- Inter-annual rainfall that accounts for relative maximum water levels
- Dam height and height of spillway
- Time of the year
- Withdrawals
- Storage reduction through evaporation, seepage and percolation
- Age of dam (siltation)
- Shape of the reservoir

The reservoir shape, dam wall height and length of throw back are characteristics that were used in determining the selection of 12 small reservoirs surveyed in this study, besides the issue of easy accessibility of reservoirs. The number of reservoirs surveyed was limited by the time of fieldwork for this research project.

3.2.2 Collection and processing of field data

In order to estimate the surface areas and volumes of reservoirs fieldwork was carried out in Insiza District, where 12 reservoirs were surveyed. The selected reservoirs were measured during the fieldwork from 8-20 February for the first six reservoirs and from 19-29 April 2005 for the other six reservoirs. The equipment used in the study includes the following, 1 boat, 1 GPS, Theodolite, 1 Stadia rod and rope, 1: 50000 maps, Tripod, Level, tape measure (50m), vehicle, and notebooks.

The dimensions of the reservoirs were surveyed by:

a) Shape and size of surface area were determined by walking around each reservoir with handheld GPS and use of a theodolite to locate (x, y) coordinates values at specified points, taking large number of points along the shoreline. See Figure 3.3.

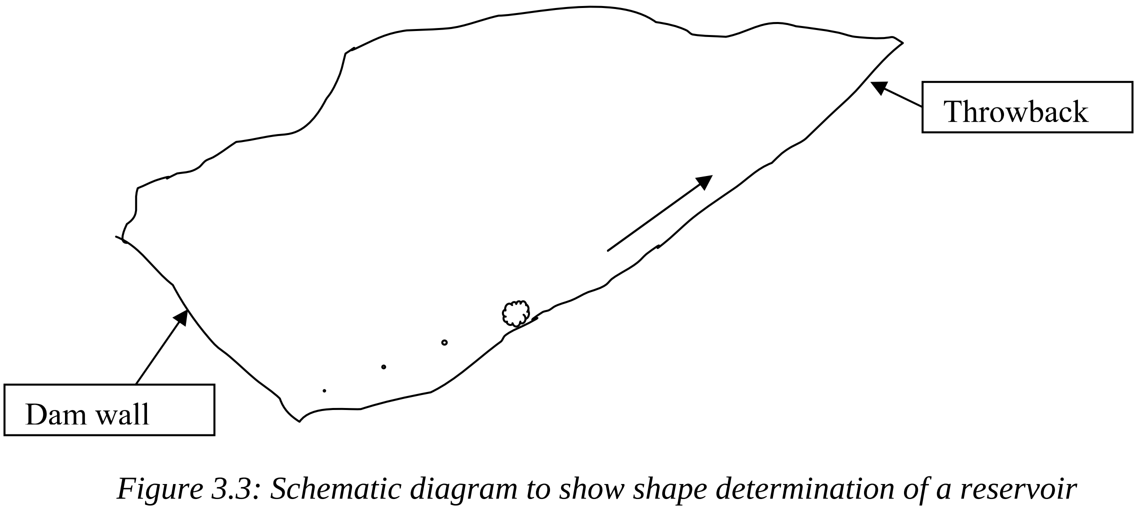


Figure 3.3: Schematic diagram to show shape determination of a reservoir

b) Depths were measured using telescopic stadia rod (5m) at say water level, spillway level and maximum flood level of the reservoir (see *photo 2*). Random points, at least 20m apart were made during measurements to allow creation of contours from which surface area was derived. Each measurement was accompanied with its GPS (error of <5m) coordinates and/or interpolated coordinates based on measurements from the theodolite to locate its position within the reservoir. For depths exceeding 5m a rope was used for extension.

c) Difference in height between actual water level and maximum storage capacity as defined by height of spillway in some cases was evaluated with a level mounted on tripod and telescopic stadia rod.

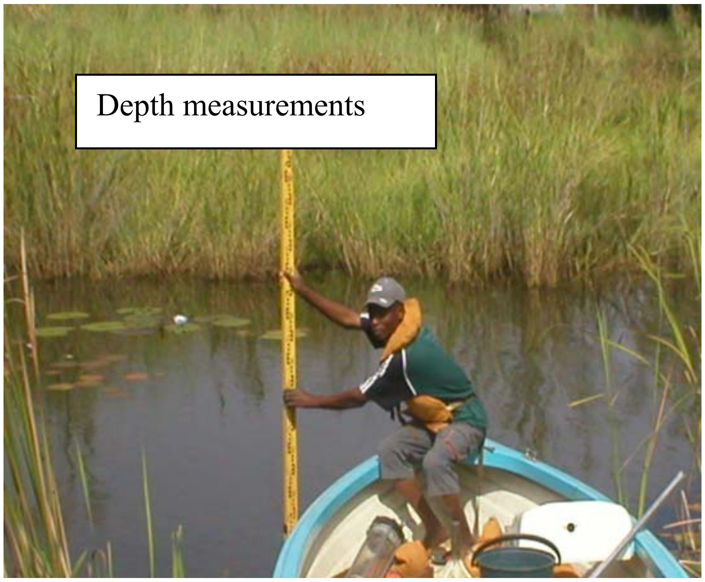


Photo 2: Photo showing depth being measured

In order to get an overview of actual and maximum levels, height differences were measured. A level mounted on a tripod was used in combination with the stadia rod. The lowest point along the dam wall generally defines the maximum level, which is dam spillway.

3.2.3 GIS Application

Arc View 3.2 GIS package with Spatial Analyst, plus Surface Areas and Ratios from elevation Grid extension (Appendix 1) was used, to automate surface area calculations and to provide surface area statistics. Interpolation was carried out using Spline interpolator that fits a minimum curvature surface through the input points. Spline fits a mathematical function to a specified number of nearest input points, while passing through the sample points. However, it is not appropriate if there are large changes in the surface within a short horizontal distance, because it can overshoot estimated values.

In order to establish the volume of the reservoir, the triangulated irregular network (TIN) model for the reservoir was calculated using Arc View with 3D analyst along with Surface tool for points. TIN is a surface model that splits up the surface into triangular elements. The very measured data was being used and honored directly as the model is used to model terrain.

The area and volume were obtained for different depths levels from full supply level to the level when the dam is emptied. A window in Figure 3.4 shows how the points were distributed in the reservoir after carrying out a survey. The points are represented by coordinates and are associated with depth of water measured.

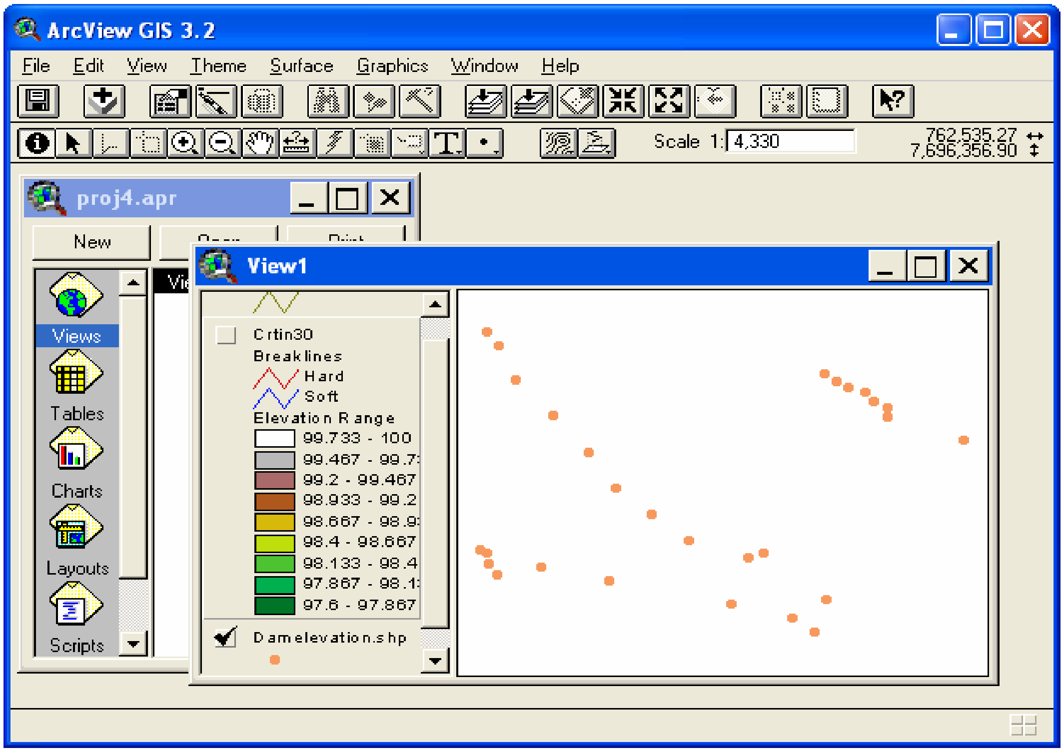


Figure 3.4: Distribution of measured points in a reservoir

Field data allowed the estimation of reservoir volumes by means of their remotely sensed surface areas. Each surveyed reservoir was modeled into a 3D model for further evaluation and visualization. Figure 3.5 shows different layers, representing water levels at different depths. Arrow 1 shows water level at the time of field measurement and arrow 2 shows the deepest point and that is where there is the dam wall for the reservoir. For all depth levels the changing extents of 'surface area', 'depth' and 'volume' were derived, thereby giving an insight into the flow regimes of each measured reservoir.

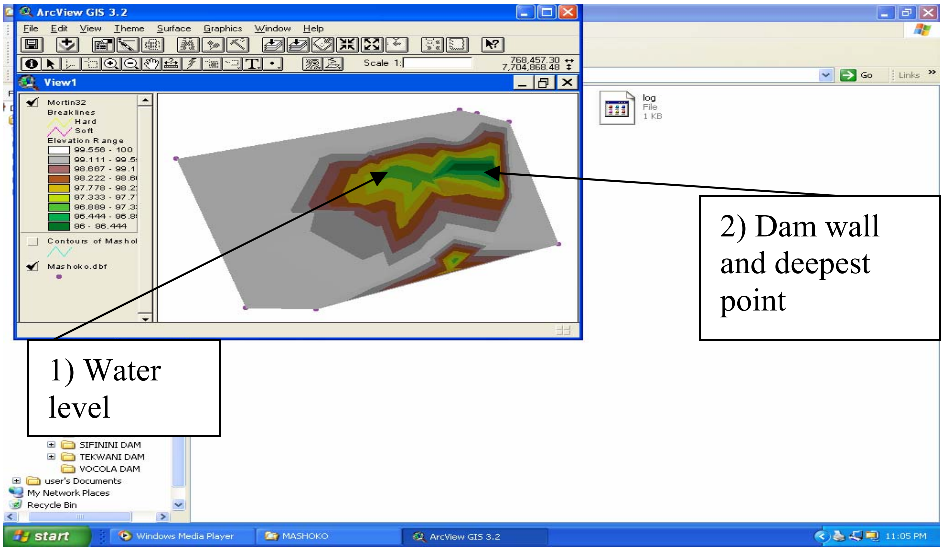


Figure 3.5: Water levels at different reduced levels

The field data was collected in a manner that was scheduled according to the acquisition of images. The reservoir surveys helped us to make an assessment of the quality of a method that can be used to derive the extent of small surface water bodies from images that will be discussed in the next section.

3.2.4 Use of Remote Sensing

3.2.4.1 Satellite images selection

In order to determine the maximum dimensions of reservoirs by means of remotely sensed data, which are represented by their largest surface area extent, the time of acquisition has to be as close as possible to the end of the rainy season, when reservoirs are filled to their maximum full supply capacity and losses (draft, seepage, evaporation) are still negligible (Liebe, 2002). However, in this study, the selection of images was based on images taken corresponding to the days of fieldwork so as to determine the storage capacity of reservoirs at the time of fieldwork. Months of February to April were regarded as suitable for the study when most reservoirs were approximately full to their maximum fully supplies capacity. This was not the case with all reservoirs studied, as most of the reservoirs were not spilling during the fieldwork. This was expected because it was below a normal rain season. The average rainfall was 9.7mm in January 2004 and in 2005 it decreased to 1.8mm during the same month and average evaporation rate was 7.6mm. No rainfall was received the following months till the end of rainy season in April in the area. The rate of evaporation was assumed constant and was considered less important for estimating capacities using surface areas obtained from satellite data, since the objective of the study was to find a relationship between surface area and capacity of a reservoir at any given time.

3.2.4.2 Water Detection with Landsat and reflectance of surface water bodies

Detection of water bodies is a concern that has been pursued since the first Landsat images become available in the 1970s (Liebe, 2002). The detection and delineation of open surface water bodies using optical systems like Landsat was best done with imagery from the infrared and visible part of the spectrum. The characteristic spectral reflectance curve for water shows a general reduction in reflectance with increasing wavelength, so that in the near infrared the reflectance of deep, clear water is virtually zero (Mather, 1999). The reflectance of soils and especially healthy vegetation are higher in these spectral bands and therefore stand in distinct contrast to water bodies. The visible bands (VIS) enhance the contrast between water and soils.

The figure 3.6 shows a typical spectral reflectance curves for dry bare soil, turbid and clear water.

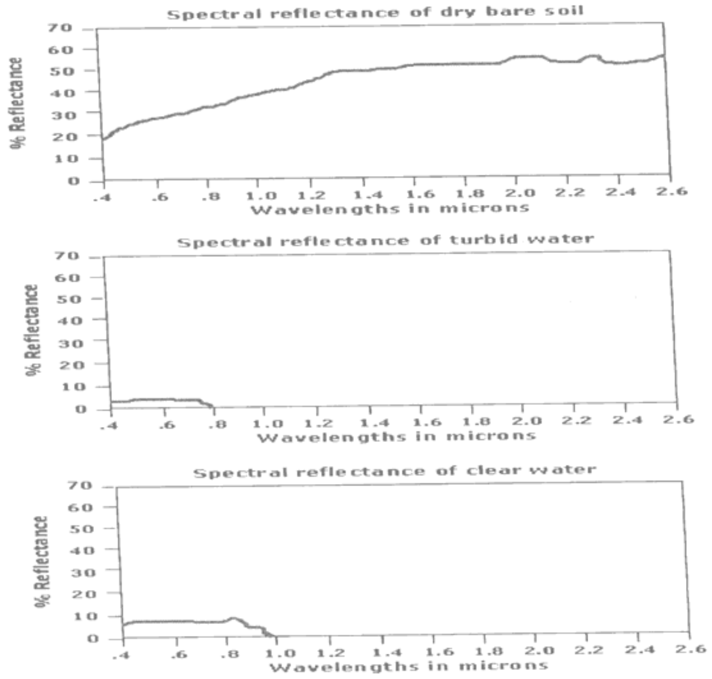


Figure 3.6: Reflectance curves (Schotanous, IWRM Lecture notes, 2004)

3.2.4.3 Pre-processing, classification and data extraction

The procedure used to estimate surface areas from satellite images follows acquisition of images (LANDSAT 5, bands 5, 4 and 2). Images were geo-registered and after pixel resizing to 30m x 30m resolution merged into one image strip. False colour composites with combination (Red, Green, and Blue) were created and the classification of images was performed using the maximum likelihood classifier. Using Red-Green-Blue channel, water bodies were depicted in colours ranging from blue to almost black. In order to recognise reservoirs on satellite image, the human mind makes use of several visual characteristics, such as shape, contiguity and the association with drainage (see Figure 3.7). The contiguous water pixels were grouped to clusters that resemble reservoirs, and given unique identifiers.

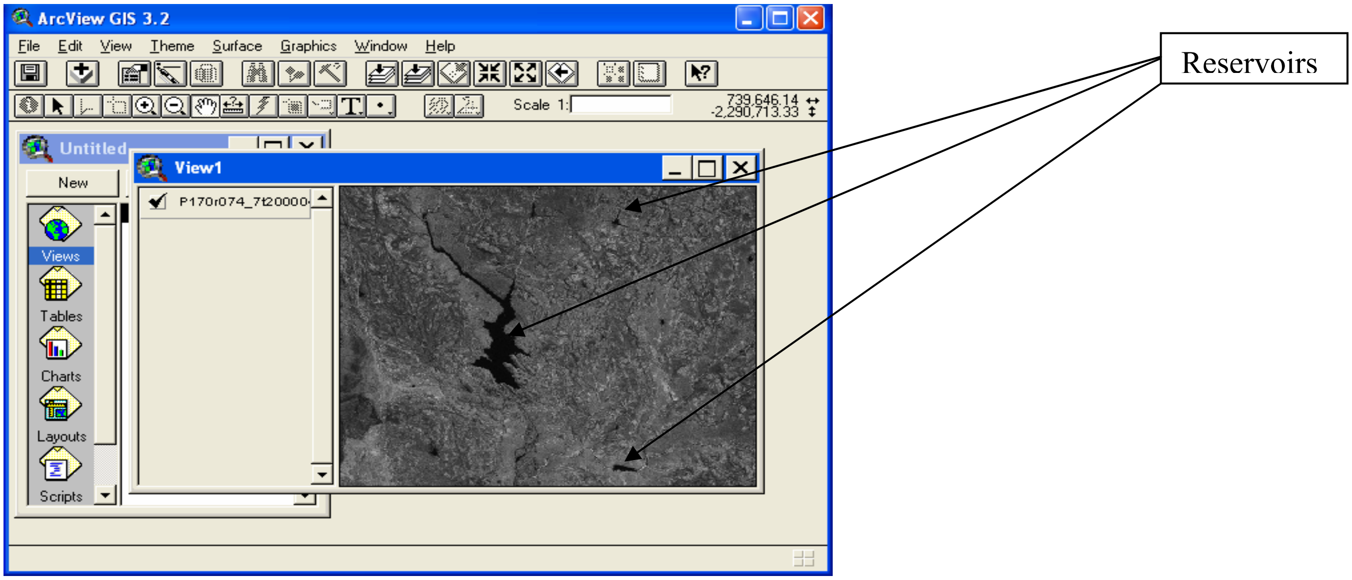


Figure 3.7: Reservoir identification from satellite image

From the above the general sequence of operations used was as follows:

-Image enhancement

a) Colour coding, the visualization of processed remote sensing product forms an essential link with spatial feature extraction and is used for judging errors in classification procedures

b) Filtering enhance image for visual interpretation

-Geometric corrections of the image using the map coordinate involve conversion of an input image into an output image with different geometry and possibly different resolution.

-Visual interpretation, image visualization plays an important role in the information extraction process because remote sensing projects use multispectral data and an understanding of how we perceive colour is important in this process.

Thus after identifying the selected reservoirs, they were counted in terms of their distribution in the study area and their surface areas were estimated. On screen digitizer for small reservoirs zooming in enabled clear visualization and the digitizing, using Arc view (Figure 3.8).

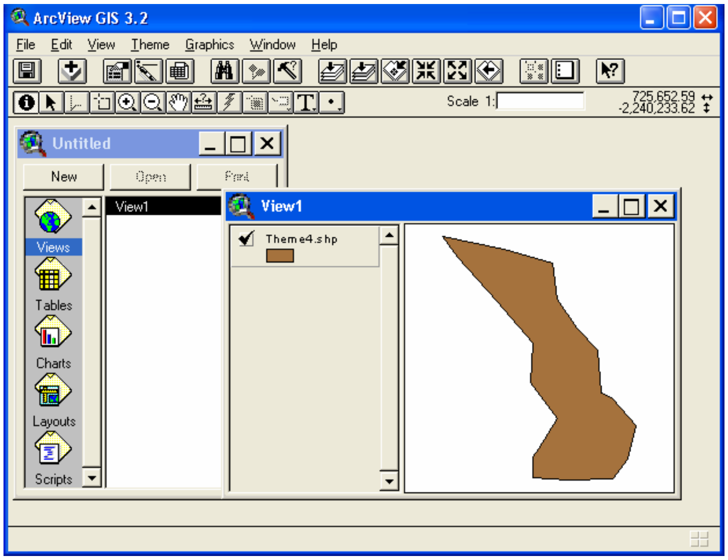


Figure 3.8: Window showing on screen digitizing of a reservoir

After digitizing the surface area was estimated by Avenue Script (see *appendix 2*). This was programmed to assist planners to quickly estimate areas and perimeters of geometric features. The assumption is that expected area estimated from the image would be a better measure of actual area as the selected images correspond to times when field work was done.

However, in order to make a comparison of surface area obtained from field and from that obtained from satellite, T-test and a measure for goodness of fit of the classification was used, called area determination based on Normalized Difference Area Index (NDAI) (Liebe, 2002). NDAI that weighs deviations can express the relation between the area measurements from the field data and the satellite image classification from -1 to 1. This study slightly modifies NDAI to PDAI (Percentage Difference Area Index) to have a clear picture of the deviations expressed as percentage of surface areas obtained from fieldwork. It is expressed as

$$PDAI = \left(Area_{field} - Area_{image} \Big/ Area_{field} \right) * 100 \; \ldots . \textit{Equation 11}$$

Values obtained ranges from –100% to 100% and reservoirs with values close to 0% have the best match between $Area_{satellite}$ and $Area_{field}$ while moving to both extremes stand for increasing deviations between surface areas. Negative values will resemble reservoirs where $Area_{satellite} > Area_{field}$ and positive values represent $Area_{satellite} < Area_{field.}$

3.3 Model Development

Thus, after reservoir surveys were carried out a model was developed to estimate reservoir storage capacities using surface area estimated from fieldwork. The model is in a form of an equation represented as

Storage Capacity=a*Area^{b} (model equation)

From this equation the constants a and b were obtained which are based on reservoir characteristics.

The following flow chart (figure 3.9) describes the steps to develop the Modelling equation of small reservoirs.

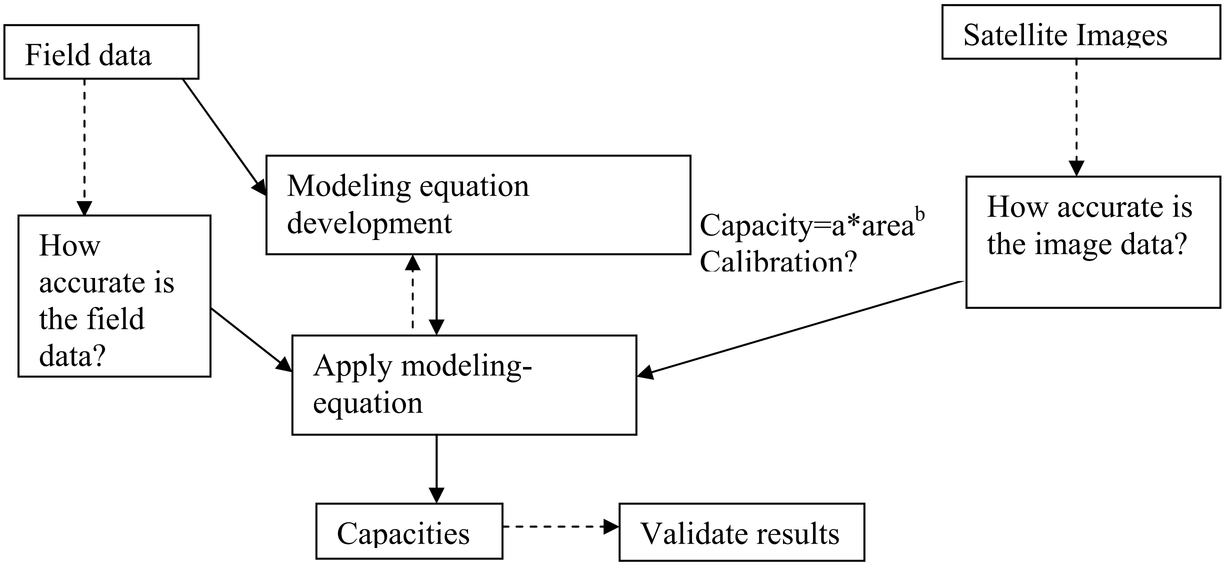


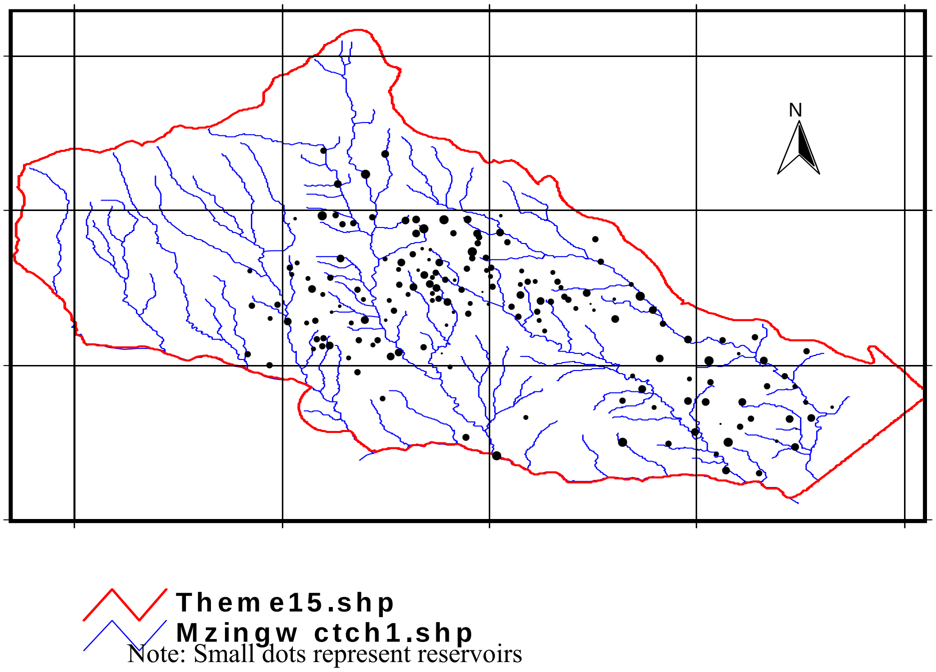
Figure 3.9: Model development flow chart

Thus all the necessary parameters were deduced and the model equation was developed for the basin.

4. RESULTS AND ANALYSIS

4.1 RESULTS

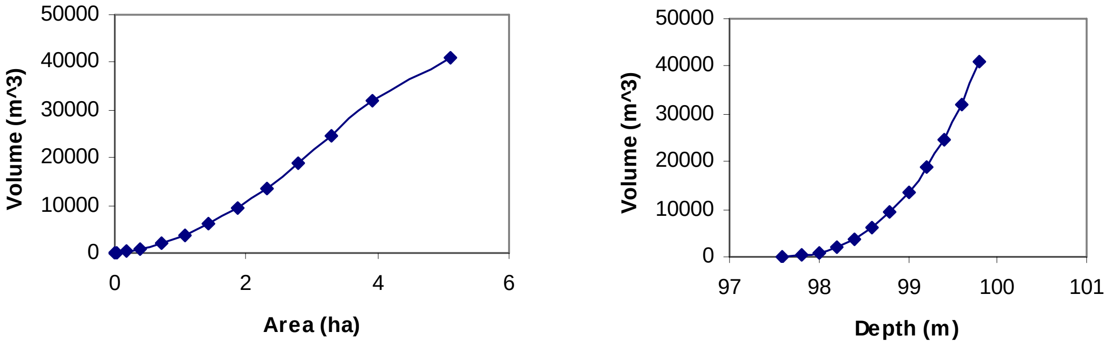
In the study, from the inventory carried out using satellite images 1000 small reservoirs were visually identified from Insiza District, which forms part of Mzingwane catchment (*Figure 4.1*) and the accuracy was based on comparison of test areas which had an error of <1%.



Note: Small dots represent reservoirs

Figure 4.1 Spatial distribution of small reservoirs in the Mzingwane catchment.

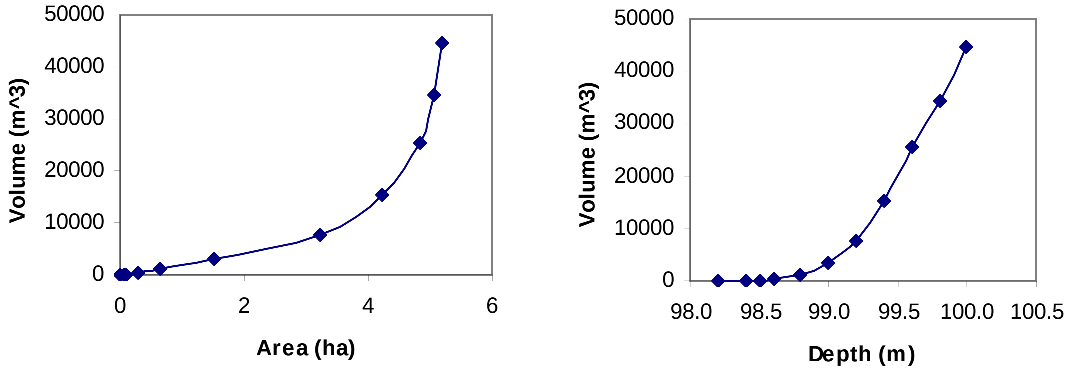
However, the main results on the data attained in the study are graphs and a set of equations to represent the relationship between three parameters' 'depth', surface area' and 'capacity/volume'. The graphs in Figure 4.2 show the representation of these parameters using the data obtained from the fieldwork. The graphs show relationships between, area, depth and storage volumes/capacities for studied reservoirs. In each case, a reservoir has its area-volume curve and depth-area curve. Thus given, the surface area of a reservoir, the storage volume can be estimated from the area-volume curve and likewise for each depth, storage volume of a reservoir can be estimated using depth-volume curve. The graphs showing area-volume and volume–depth relationships depict the general shapes expected for small reservoirs.



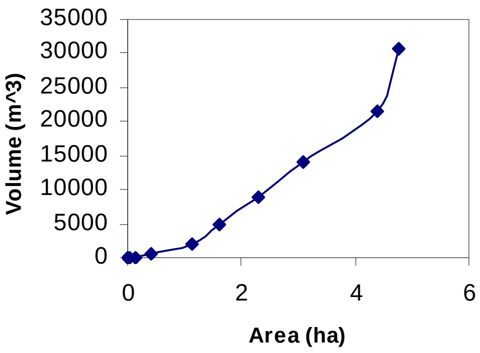
i) Area-volume curve

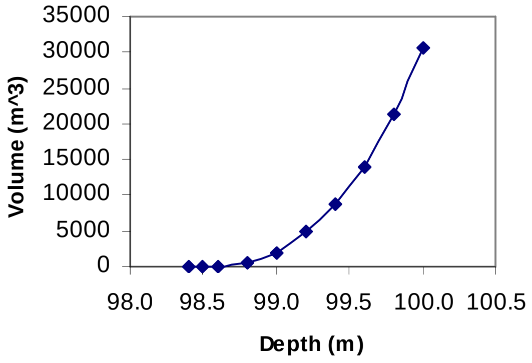
ii) Depth-volume curve

a) Relations for Avoca.

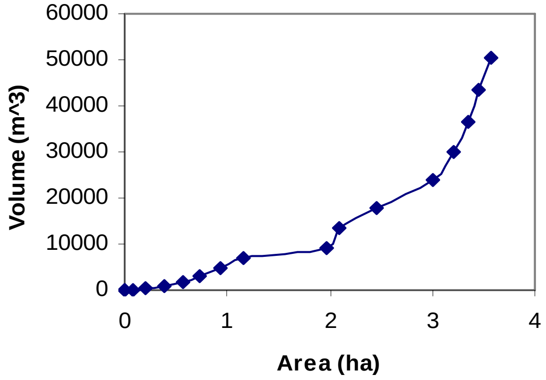


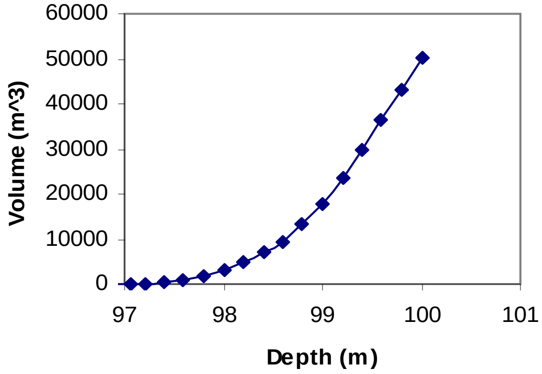
b) Relations for Sibasa



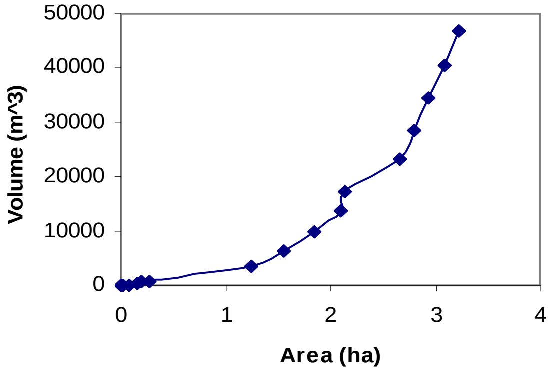


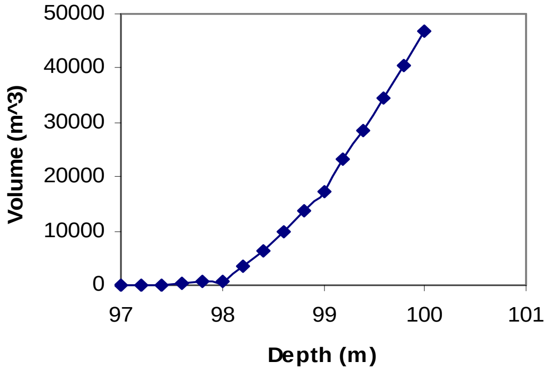
c) Relations for Bova



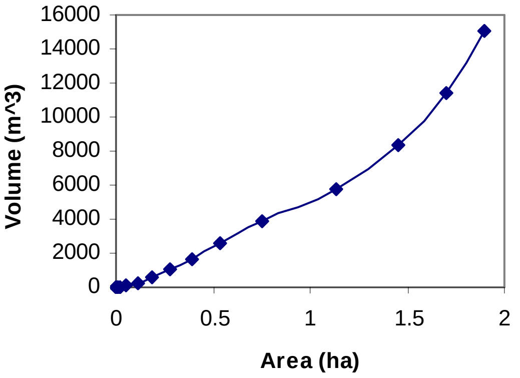


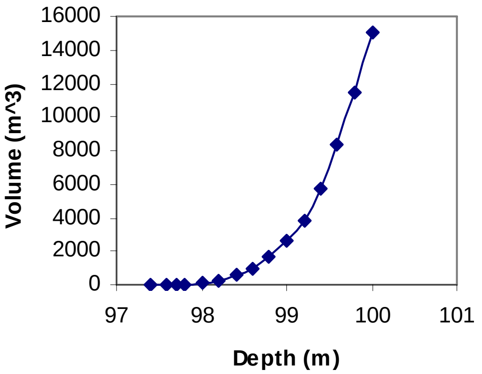
d) Relations for Sifinini



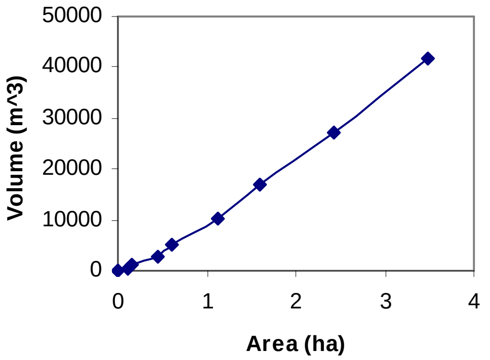


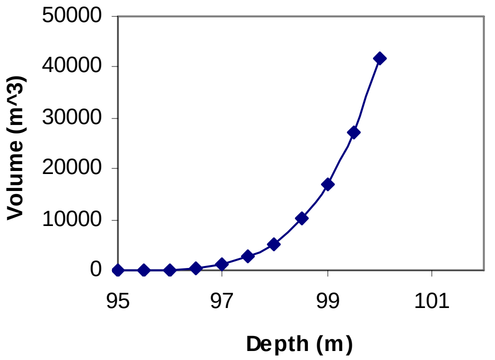
e) Relations for Dehwa



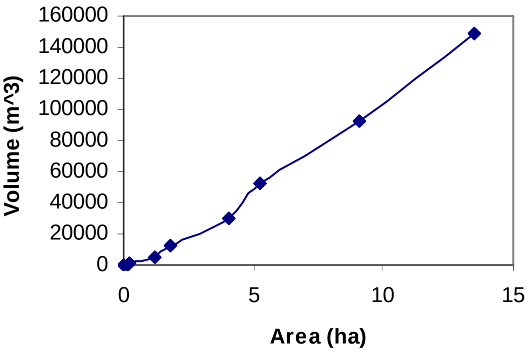


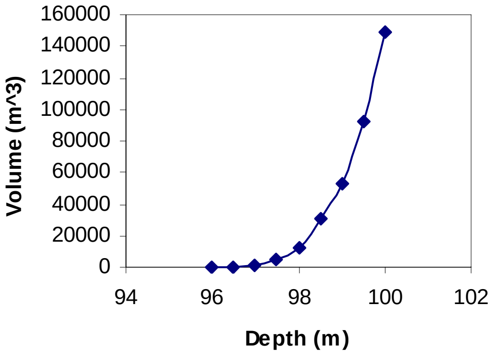
f) Relations for Tekwani



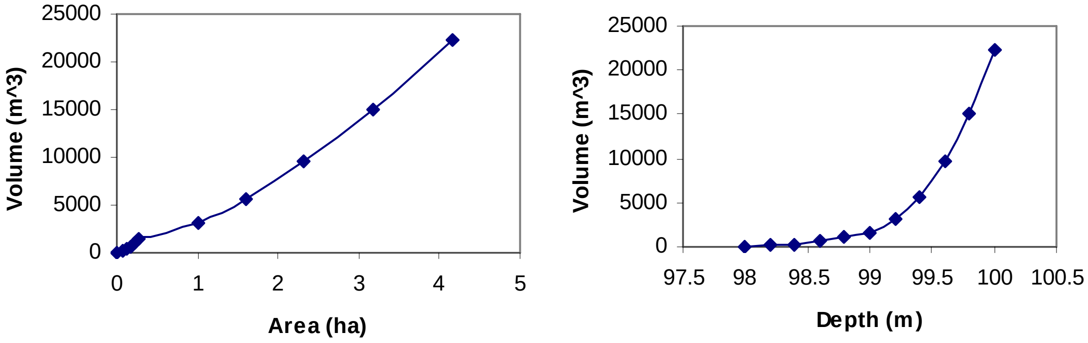


g) Relations for Manzamhlope

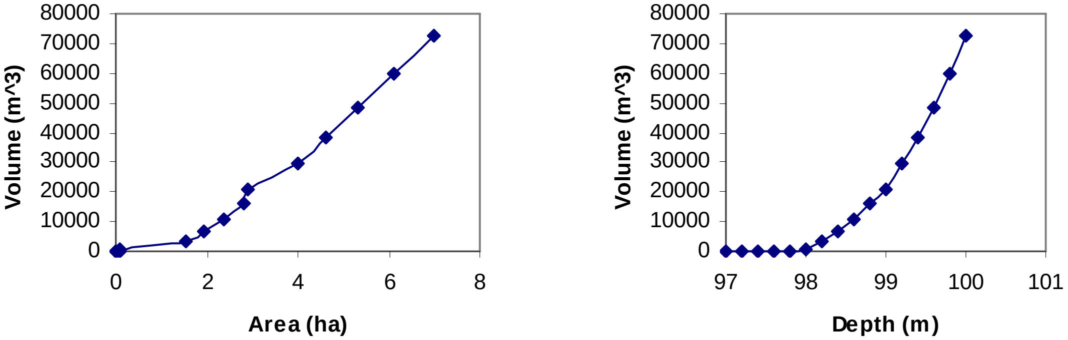




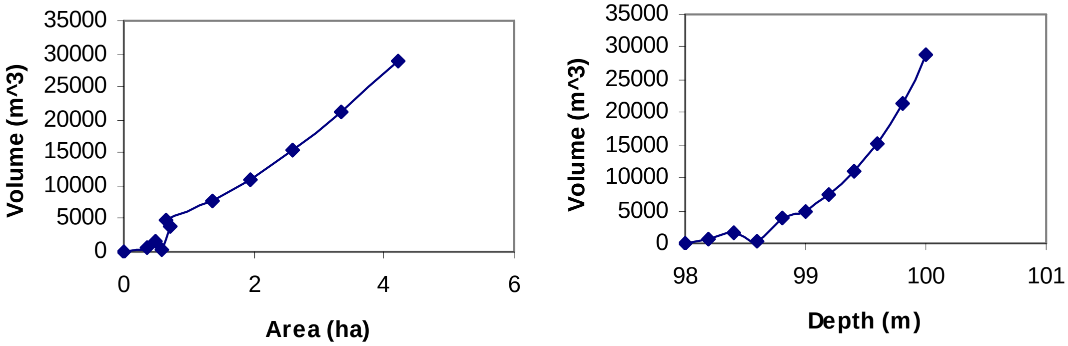
h) Relations for Mashoko



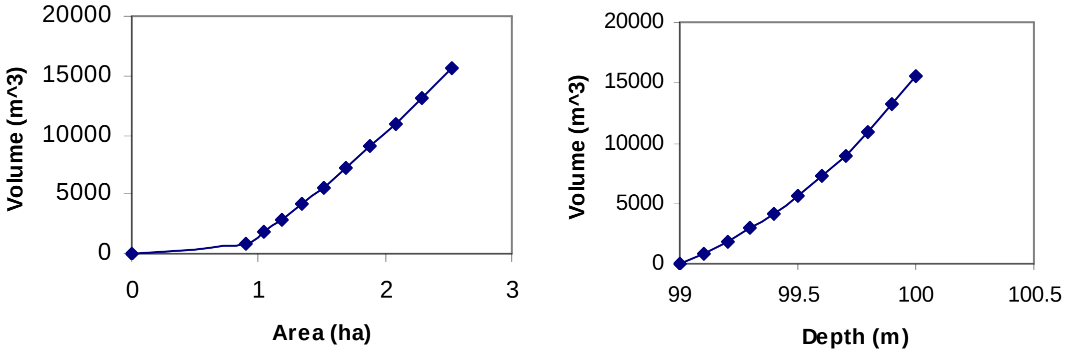
i) Relations for Mbondo



j) Relations for Ndlegu



k) Relations for Vocola

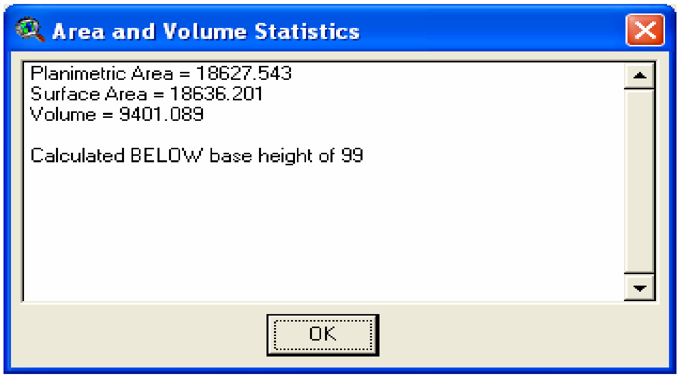


l) Relations for Masuto

Figure 4.2: Graphs showing interrelations between volume, area, depth for reservoirs surveyed

4.1.1 Model Calibration

Thus in order to establish the constants **a** and **b** for the model equation field data was used. For the area studied some generalized equations were obtained based on logarithmic plots, deduced from data that was obtained from the field. The window (Figure 4.3) shows the representation of the results as they appear after inputting field data into GIS file and convert it to Triangular Model and then estimate surface area and volume statistics of each reservoir (table *4.1*) which are then used to formulate logarithmic equations. In the stable as shown the level of water was measured from the sediment level hence results are showing storage volumes at the time of field survey.



```
Planimetric Area = 18627.543
Surface Area = 18636.201
Volume = 9401.089

Calculated BELOW base height of 99
```

Figure 4.3: Output results of volume and area statistics from field data

Table 4.1: Field survey data, Model equation development parameters for reservoirs

Measured from	**Reduced levels M**	**Surface area m^2**	**Surface area ha**	**Cumulative Volume (1000)m^3**	**log area M^2**	**log Volume m^3**
Sediment level	98.2	0	0	0		
	98.4	486.48	0.05	0.04	2.69	1.64
	98.5	1091.91	0.11	0.12	3.04	2.08
	98.6	2810.19	0.28	0.32	3.45	2.51
	98.8	6364.56	0.64	1.22	3.80	3.08
	99	15090.89	1.51	3.26	4.18	3.51
	99.2	32338.98	3.23	7.78	4.51	3.89
	99.4	42297.87	4.23	15.37	4.63	4.19
	99.6	48440.47	4.84	25.52	4.69	4.41
	99.8	50741.79	5.07	34.46	4.71	4.54
Full supply level	100	52051.95	5.21	44.77	4.72	4.65

4.2 REGRESSION ANALYSIS

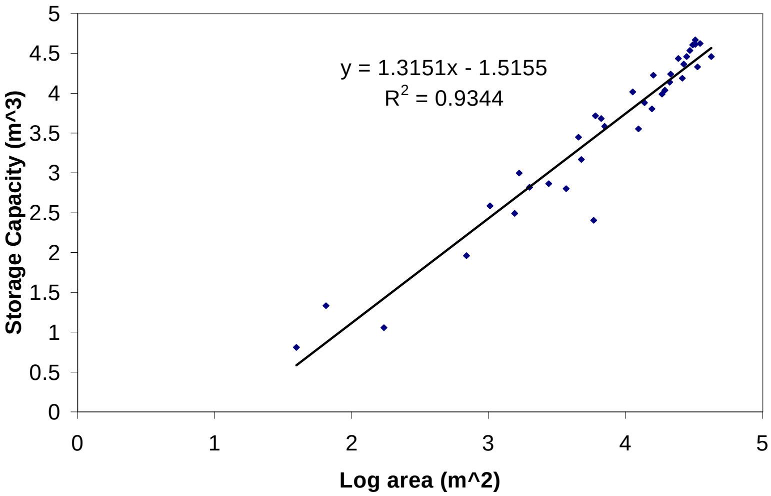
A method used for quantitative forecasting, ‘casual modeling’ was examined from which the basic premise is that the variable y (storage capacity) is influenced by an independent variable x (surface area). Thus, after the calculation of volume and area was made for each dam, regression analysis was carried out and a set of equations obtained (table 4.2). In addition, the plots on Figure 13 (log Area-log Volume plots) depict the basic principle for area-based estimation of small reservoir volumes. Focusing on log Area-log Volume correlation, a mean volume was sought for each area-step. This is achieved by averaging the volumes of corresponding area-steps in base 10 notations. The regression equations for log Area-log Volume has been categorized into two, depending on the general shape of the reservoir, and the length of throw back. The first category (Category 1) resembles oval shaped reservoirs with a fairly short throw back. On the other hand, the second category (Category 2) resembles triangular shaped reservoirs with a fairly long throw back. This data led to model development. The model is expressed as Storage Capacity=**a***Area$^{\mathbf{b}}$**.**

Table 4.2: Regression equations and the coefficient of determination (R^2) values for the studied small reservoirs

	Dam	Equation logy=alogx+logb	R^2
category 1	Dehwa	1.5130x-2.3338	0.9847
	Manzamhlope	1.2624x-1.1062	0.9965
	Vocola	1.5764x-2.7572	0.7819
	Mashoko	1.2923x-1.4405	0.9895
	Ave	**1.3151x-1.5155**	**0.9344**
category 2	Ndlegu	1.2872x-1.4894	0.9858
	Masuto	2.6652-7.4603	0.9663
	Mbondo	1.1585x-1.0375	0.9651
	Sifinini	1.5746x-2.6172	0.9946
	Ave	**1.3479x-1.7716**	**0.9614**
summarised equation		**1.3272x-1.6367**	**0.9455**
Validation of model	Sibasa(cat 1)	1.4134x-2.2601	0.9825
	Avoca(cat 1)	1.5543x-2.668	0.9990
	Tekwani(cat 2)	1.3937x-1.8233	0.9991
	Bova(cat 2)	1.4758x-2.5221	0.9929

Note: From the table the average R^2 value for all the reservoirs is 0.95 (95%), Cat 1- category 1 and Cat 2- category 2

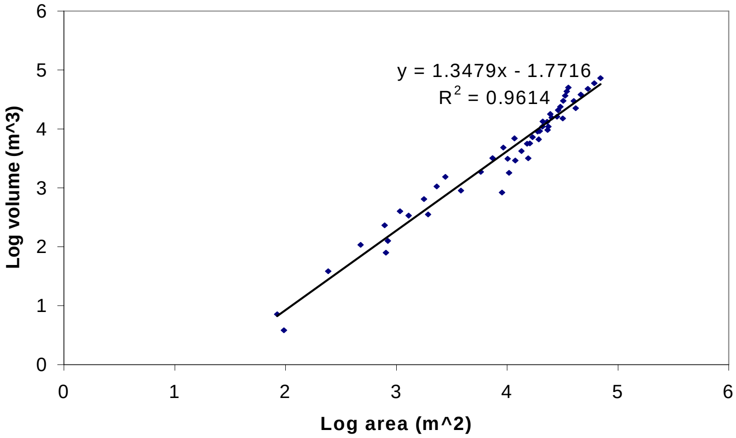
From the regression equations regression lines were established for each category of reservoirs, see Figure 4.4. The regression line gives a formula from which, knowing surface areas of reservoirs by remote sensing, the storage capacity for each reservoir is estimated. The coefficient of determination, shows the amount of ‘explained variation’ that is the percentage variation in the y-values (in this case storage volume) that can be accounted for by x-values (surface areas).



(a) For Category 1 reservoirs

$$C = 0.0305 * Area^{1.3151} \text{........} \textit{Equation 12}$$

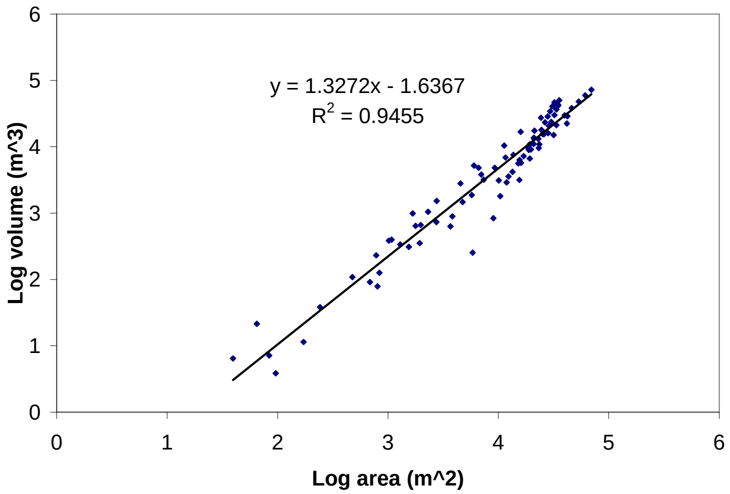
R^2=0.9344



(b) For Category 2 reservoirs

$$C = 0.01692 * Area^{1.3479} \text{...........} \textit{Equation 13}$$

R^2=0.9614



(c) Summarized equation for small reservoirs

Figure 4.4: Log area-log volume relationships for different reservoir categories

However, the assumed general characteristics of the reservoirs in terms of their size, maximum depths, geology and topography led to one general equation to be used to estimate reservoir volumes based on their remotely sensed surface areas.

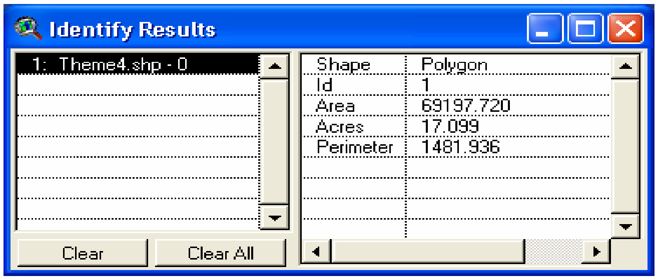
The best-fit equation (*figure 4.4c*) obtained for small reservoirs surveyed is

$$C = 0.0231 * Area^{1.3272} \quad \ldots Equation\ 14$$

(R^2=94.6%)

Where Storage Capacity is in m^3 and Surface area is in m^2

The surface area results obtained from satellite images are displayed in the format shown (figure 4.5) after running the script in Arc view 3 D analyst and the full set of results for all reservoirs are shown later.



1: Theme4.shp - 0

Shape	Polygon
Id	1
Area	69197.720
Acres	17.099
Perimeter	1481.936

Figure 4.5: Surface area result from satellite data

The model was validated using four reservoirs in the catchment. The model results using category equations and summarized equations are presented in table 4.3.

Table 4.3: Summarized results
of using model equations

Dam	Area field(m^2)	Area image (m^2)	Actual Volume(m^3)	Volume-category eqns	Volume-summarized eqn	Volume-image
Sibasa	15090	18616	7782.00	9547.58	8114.25	10722.24
Avoca	51170	52224	40873.49	47569.14	41029.62	42155.04
Tekwani	7562	6884	3852.00	2860.32	3243.54	2863.35
Bova	22955	19596	8766.00	12776.94	14159.52	11477.75

The table 4.3 shows the estimated storage volumes of four small reservoirs using category equations and the summarized equation as well as the storage volumes estimated using remotely sensed surface areas.

The model results are also graphically presented on Figure 4.6, after applying the summarized equation.

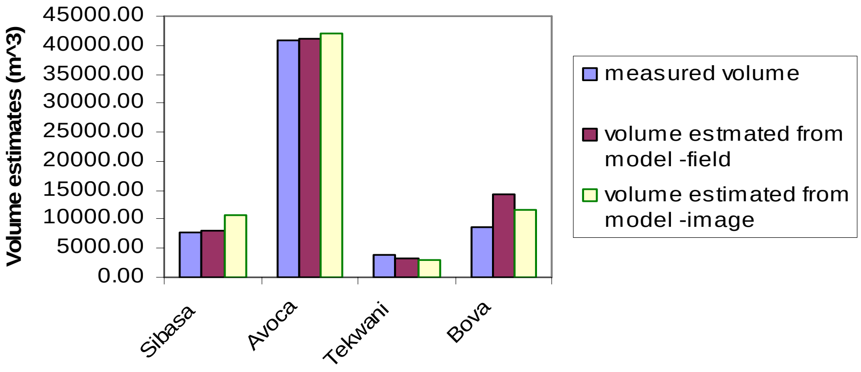


Figure 4.6: Model Validation results

However, the data on the surface areas obtained from both field survey and remote sensing was statistically compared and Percentage Difference Area Index was calculated to find if there is any significant difference in the surface areas. The analysis of the data obtained was mainly to investigate the relationship between surface areas obtained from the field to that estimated from remote sensing data. From t-test distribution (Appendix 3) it was found out that there was no significant difference at (t (5)= -0.966, p=0.378), two-tailed at 95 per cent confidence interval, between surface area obtained from field survey and that from image data. The minus sign is immaterial, reflecting merely the order of the two means in the numerator of the formula used to calculate t, so its value may be given as 0.966. Moreover, from Pearson Correlation at 95% confidence interval ($p<0.05$) it shows that surface areas are correlated meaning that the surface areas are similar. In addition, table 4.4 shows the percentage deviations (% error) in the data obtained using difference area index (PDAI), which weights deviations and can express the relation between the area measurements from the field data and the satellite image classification.

Table 4.4: Surface Areas obtained from Field Data and Satellite Images

Dams	**Area image (m^2)**	**Area Field (m^2)**	**Volume field (m^3)**	**Volume image (m^3)**	**% error**
Sibasa	18616	15090	8114	10722	-23.37
Dehwa	25213	26516	17146	16037	4.91
Avoca	52224	51171	41031	42155	-2.06
Manzamhlope	22253	24284	15258	13588	8.36
Vocola	16495	19297	11246	9132	14.52
Mashoko	88824	90543	87504	85306	1.90
Tekwani	6884	7562	3244	2863	8.97
Bova	19596	22955	14160	11478	14.63
Sifinini	19585	19730	11582	11469	0.73
Ndlegu	55719	53387	43405	45940	-4.37
Masuto	19934	20859	12470	11741	4.43
Mbondo	30408	31747	21775	20564	4.22
Note:negative sign indicates area field<area image					

The results are comparable; with error close to 0% giving better match between remotely sensed surface areas and areas obtained from field work.

The graph (figure 4.7) shows the differences in storage capacities that were obtained based on field data and that from satellite data?

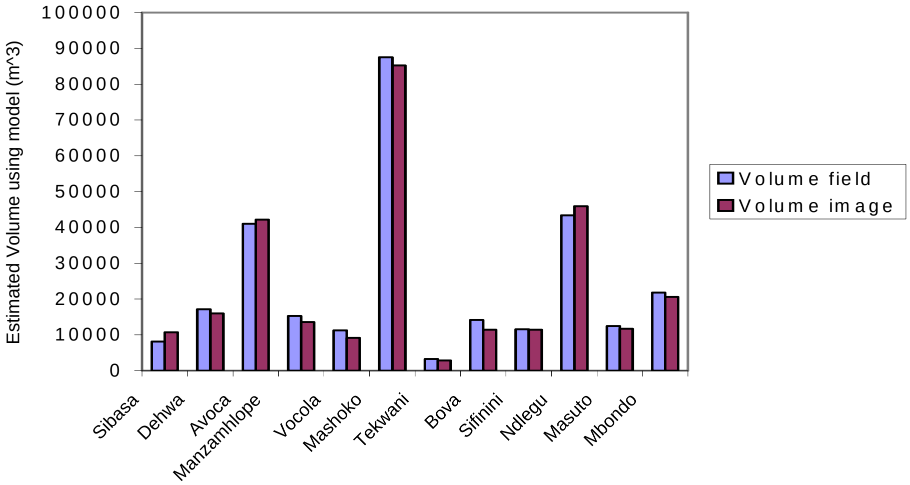


Figure 4.7: Volume estimates for reservoirs using model

4.3 Management of reservoir storage volumes

Satellite images can be used to evaluate water levels changes of small reservoirs over time say after a year. In this case we evaluated Sibasa reservoir to see the changes, which took place in storage capacities over years as a result of various activities carried out around the reservoir and most importantly livestock watering. Since the capacity is a function of surface area, we presented the expected changes in surface areas as picked by remote sensing for Sibasa reservoir. The choice of images used was based on rainfall data for Filabusi that is fairly uniform over those years in Insiza District (Figure 4.8). The vertical bars show the rainfall distribution for each rainfall season and the trend line gives a general pattern of rainfall. The rainfall season 1991/92 had the lowest rainfall and 1990/00 had the highest rainfall.

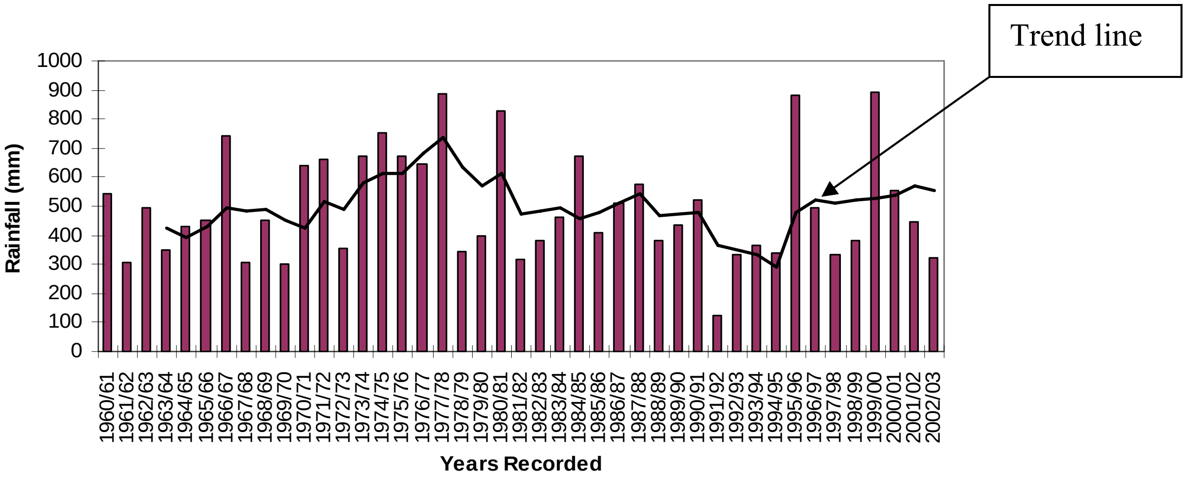


Figure 4.8: Rainfall distribution over years

Figure 4.9 shows surface areas and corresponding reservoir storage capacities obtained for the month of April in 1991, 2000 and 2003 and February 2005 for Sibasa reservoir. Importantly are the highest estimated capacities in year 1991 regardless of its low rainfall and year 2000.

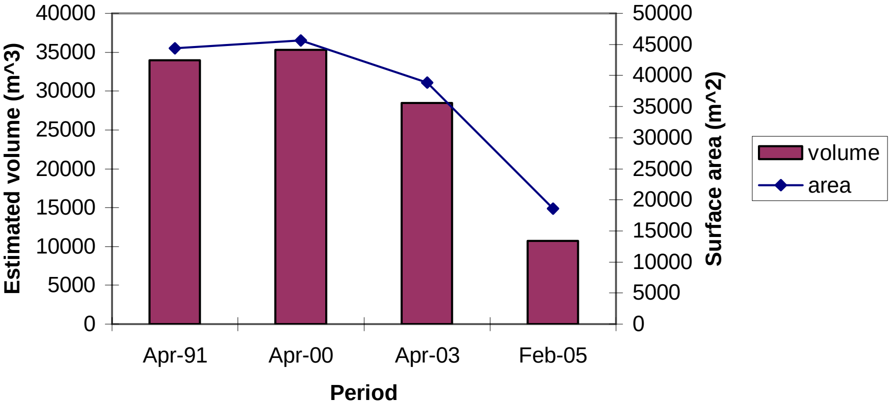


Figure 4.9: Remotely sensed surface areas and estimated volumes for Sibasa dam for four selected years

5. DISCUSSION OF RESULTS

Water has been described as the most valuable of Zimbabwe's natural resources (WRMS, 2000). It is undoubtedly the most vital and hence the need for effective water resources planning and management. The inventory of small reservoirs in Insiza District that forms part of Mzingwane catchment was done from remote sensing data and there was little labour and less cost incurred on counting all small reservoirs in the district, AS image interpretation was used for that purpose.

The estimated number of small reservoirs is 1000 in Insiza District where the study was conducted as depicted from satellite image for the month February 2005, based on findings of this study thereby addressing objective one of the study. The small reservoirs are quite evenly distributed in the entire catchment. However, from literature 826 small reservoirs were identified in the district and over 2500 small reservoirs were found in the catchment (Sugunan, FAO 1997) and this includes reservoirs in both communal lands and resettlement areas. However, in the same study, 7838 small reservoirs with capacity <1 million cubic meters were found in Zimbabwe. Thus updating database of small reservoirs really requires a very comprehensive method, which is less expensive, and remote sensing is such a tool.

5.1 Capacity- area relationships

The storage capacity-surface area relationships for the twelve small reservoirs were established from log volume-log area curves using regression analysis. The general shapes of the curves represent the expected curves for small reservoirs as indicated by designs common for small reservoirs (Lawrence, and Lo Cascio, 2004). This is so because reservoirs, in particular, vary considerably in their shape, depth and nature. Three equations were obtained, that is for category 1 reservoirs, with fairly short throwback and oval shaped, and category 2 reservoirs, which resembles triangular shape, with fairly long throwback and a generalized equation for all small reservoirs based on general characteristics of all small reservoirs in terms of their size, purpose and their general dam wall height among others. It was found out that all the equations had a high value of coefficient of determination (R^2) above 93% (table 4.2) but the difference in R^2 of two categories was explained by the different characteristics of reservoirs other than their general shapes, and length of throwback. However, from results in table 4.3, summarized equation give better estimate of storage capacity as compared to category equations, which result in the use of summarized equation which might mean shape and throwback has no influence on storage capacity predictions. This compares well with the coefficient of determination obtained by Meigh (1995) on the analysis for small farm dams in Botswana where they establish a relationship between capacity and surface areas, (equation 6). The difference of the work done by Meigh (1995) with this study is that remotely sensed surface areas are being used to estimate storage capacities of reservoirs whilst Meigh used areas estimated from topographical maps, hence the difference in constants for the equation. Thus, from the regression analysis carried out in this study for the generalized equation, 94.6 % of the variation in the storage capacities of small reservoirs in the Limpopo Basin is due to their surface areas, with about 5.4 % being due to other factors that influence capacities which includes evaporation, dam shape and water abstractions. It is mostly the surface areas and evaporation rates that are a determinant factor in volume of water at any given time hence the use of one equation rather than several equations to estimate the capacities.

The fairly strong relationship, $C = 0.0231 * Area^{1.3272}$ results from topography, which is generally assumed uniform over the entire catchment, with most reservoirs assumed to be lying in similar relatively broad, flat valleys. This has a major influence in determining the area and volume of water in the reservoirs. The soils were identified as sand clays, which are a good characteristic of storing water. The equation gives a better estimate of storage volumes with increasing surfaces areas, *Figure 4.6*, for instance Avoca dam as compared to other reservoirs but with a deviation of approximately average value of less than 10 % due to irregularities in reservoir characteristics. Thus, the larger the reservoir surface area is, the more robust its volume estimate with the above equation is. The equation matches closely with the one obtained by Liebe (2002) in Ghana for estimating storage volumes for small reservoirs, that is,

$C = 0.00857 * Area^{1.4367}$ but the constants differ because of different study areas and climatic conditions.

5.2 Comparison of storage volumes calculated from the model using surface areas obtained from fieldwork and imagery.

The t-test and Pearson correlation analysis at 95% confidence interval indicates that the variances of the two surface areas (field area and image area) are not significantly different ($p<0.05$), which gives closely similar volume estimates and this is the case because the time of fieldwork corresponds to the dates when image used was taken. Thus the hypothesis that there is a relationship between remotely sensed surface areas and small reservoir storage capacities is proven. This will then enable the established relation; $C = 0.0231 * Area^{1.3272}$ to be used to estimate the capacities of reservoirs using remotely sensed surface areas. Thus, from the comparison of remotely sensed surface areas and surface areas obtained from field survey (table 4.4) errors ranging from –23.4% to 14.5% for all surveyed reservoirs were obtained. The error of –23% for Sibasa reservoir was maybe due to high reflectance of vegetation cover around the shores of the reservoir since there was aquatic vegetation around the reservoir during period the image was taken. Thus some areas covered with water might have been classified as vegetation. Cater (1980) discusses the similar problem of estimating areas by counting pixels in Landsat imagery in which perimeter cells with mixed spectral signature occur. On the other hand, during classification, shallow water areas covered by floating vegetation are classified as wetlands but where aquatic vegetation is submerged the area is classified as water, which might have also contributed to the error. The other thing might be the spatial resolution (30m) used, given that some reservoirs are small, give rise to errors in imagery data and thus the study suggest better spatial resolution (10m) should be used to detect small reservoirs. The method is quite easy to use though it requires better visual understanding of satellite images.

However, from the findings obtained by Lawrence, Care Zimbabwe Report (2000), small reservoir volumes estimated from simple calculation used in Zimbabwe

($C = (D * W * T)/6$) in most cases results in an under prediction of storage volumes (With an average discrepancy of under prediction of 53% for surveyed dams). It was seen that on average the USAID relationship over-predicts small reservoir volumes by 36%, the 1/6-rule under-predicts reservoir volumes by 43% while the Nelson and the Fowler relationships performed quite well, with an average under-prediction of 10% to 15% (Lawrence and Lo Cascio, 2004). Thus the results from the remote sensing data obtained from this study compares closely with Nelson and Fowler relationships as the estimated capacities deviates by 10%. Thus, the methodology of use of remotely sensed data attained in this study for small reservoirs is applicable given such variations in predictions of reservoir storage volumes.

5.2 Reservoir management

There was evidence of small reservoirs being used by communities or farmer groups to retain water for dry season irrigation. For instance Sibasa reservoir was wholly owned and managed by the community with the chief as the leader. It was found out that at the time of field survey the reservoir was only used for fishing and livestock watering.

The variations in storage capacities of Sibasa reservoir over the four years were due to rainfall variations and the different uses over those years depending on whether it was a drought year or not. The rainfall for the year 1991 was below normal and that for year 2000 was at an average of 550mm, which is the general, rainfall for the whole catchment. Thus remotely sensed surface areas for these years were used to estimate the reservoir capacities to define the importance of satellite data in reservoir management. In the year 2003, there was a gradual decrease of rainfall total to 350mm, which is almost the same as the total rainfall for the year 2005. Because of amount of rainfall received over that period, estimated surface area is small in year 2005 and thus its storage volume is low as compared with other years.

Taking a closer look at storage capacities for different annual rainfall figures for 1991/92 and 1999/00 seasons, it can be deduced that low rainfall does not necessarily mean low storage capacities as in the case of 1991/92 season when there was adequate water stored in the reservoir from previous rainfall (1998/99). However, the high rainfall and storage capacity in season 1999/00 was due to elnino and heavy floods in that year. This information is essential with regards to management of the small reservoirs, and storage capacities. Thus with time, based on the time of image acquisition and considering rainfall, abstractions and siltation, storage capacities will vary, hence the necessity of using satellite data to manage water levels in the reservoirs. Thus a clear picture of what a reservoir can hold at any given time will be deduced. Moreover, decision on allocation of water in larger reservoirs based on variation of small reservoirs can be made possible. If small reservoirs have lager storage capacities say by April than water in larger reservoirs, then water in large reservoirs can be allocated to say winter wheat as people will have adequate for primary uses and vegetable watering. On the other hand, if small reservoirs are almost empty by April, water in large reservoirs is allocated to vegetable watering, thereby substituting for primary purposes. In addition, most of the reservoirs were used to capture water for dry season irrigation of gardens among other uses in the community. With the capacities known, planners and water managers will quickly make decisions on how to utilize and manage the available water given the various competing uses. Thus from the results in this study reservoir storage capacities of small reservoirs can be estimated using remotely sensed surface areas.

Thus GIS and remote sensing was used in this study because of its capability to store and retrieve hydrological data required for planning reservoir development and able to analyze and quantify water stored in small reservoirs. However, the general estimate of the volume of water in this study using GIS procedure was based on the simple relationship based on depth, width and throwback (In this case depth is the maximum water depth at the dam when water level is at the spillway crest level). Instead of measuring all the parameters, GIS procedure makes use of the coordinates and the reduced levels to calculate the storage volumes in a manner that represent a basin being emptied over time. This process allows evaluation of storage changes in water levels over time to be estimated.

6. CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSIONS

From the inventory and digital maps produced for the study area in question, remote sensing may be a suitable means to detect small reservoirs and accurately measure their surface areas. A method is developed to estimate physical characteristics of small reservoirs using only remotely sensed surface areas. This means the majority of small reservoirs, for which detailed information is lacking, can be included in the modeling equation without the need to carry out extensive field surveys. Model equation established in this study provides a tool to quantify water available in small reservoirs and hence enabling planners to have a clear picture of water resource system in the river basin. From the general trend shown on remotely sensed surface areas obtained for Sibasa dam for the three years we can conclude that the use of satellite images and the obtained small reservoir capacities have a significant effect in water resources planning and management in the basin. The pertinent question the government must address is this: how can an effective water resources management help alleviate poverty and ensure that the poor are the beneficiaries rather than the victims of bad water management decisions and policies?

6.2 RECOMMENDATIONS

The model equation (equation 14) should be used to estimate small reservoir storage capacities of small reservoirs in Limpopo River Basin given that it explained 94.6% of measured variance.

However, equation does not apply to very deep valley cross-sections, which for example assume a rectangular section and also the period the equation will be useful needs further research.

The applicability of the relationship to other catchments should be looked at in future as well as carrying out a hydrological modeling to investigate the impacts of small reservoirs in water resources available in the basin.

However, lacking in this study is the assessment of sediment yield, because of its complexity due to temporal and spatial variability of the bulk densities in the reservoir storage.

We can recommend further study on assessment of evaporation rates and sediment yield in small reservoirs as this has a significant effect in water levels.

On the other hand, water managers will in case of flooding are able to predict the likelihood of floods and hence putting in place remedial actions to ensure the community is not at risk.

However, it is worth noting that the need for good information on the existing distribution of small reservoirs is perhaps questionable given that the future development has shown a trend from a large number of small reservoirs to a smaller number of large reservoirs.

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8.0 APPENDICES

APPENDIX 1: Procedure for calculating surface areas and volumes of small reservoirs using Geographical Information Systems.

```
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	FirstRootClassName:  "Project"
	Roots:  2
	Version:	32
	Title:   "3D Scene1-Viewer1"
	Resizable:	1
	AlwaysOnTop:		1
	HasTitleBar:   1
	Activate:	"Viewer.Activate"
	Close:  "Viewer.Close"
	Open:  "Viewer.Open"
	ServerOpened:"Viewer.ServerOpened"
	ServerClosed: "Viewer.ServerClosed"
	DefaultButton:503
)

(PointZ.42
	x:	10.19531196997232
	y:	-141.21216393254994
	m:	NaN
	z:	536.08923308336909
)

(PointZ.43
	x:	173.97545000000000
	y:	173.97545000000000
	m:	NaN
)

(Vector.44
	dx:	0.38437620503408
	dy:	0.73971496406315
	dz:	0.55233749188758
)


(GTheme.70
	Name: "Surface from Sibastheme3.shp"
	Source:	71
	Flags:  0x06
	Legend:	75
```

```
	Threshold:	148
	View:	6
	GSet:	149
	LegEditScript:	"View.EditLegend"
)

)

(BShSym.78
	Color:	79
	Outline:	1
	OutlineColor:	80
	OutlineWidth:	0.10000000000000
	BgColor:	81
)

(TClr.79
	Red:	0xaf4f
	Green:	0xfeff
	Blue:	0xe6b4
)

(TClr.80
)

(TClr.81
	Red:	0xffff
	Green:	0xffff
	Blue:	0xffff
)

(BShSym.82
	Color:	83
	Outline:	1
	OutlineColor:	84
	OutlineWidth:	0.10000000000000
	BgColor:	85
)

(TClr.83
	Red:	0x973d
	Green:	0xfeff
	Blue:	0x9668
	Name:	"Contour interval sibasa.dbf"
	Source:	199
	Flags:	0x06
```

```
	Legend:		216
	Threshold:	248
	View:	6
	GSet:	249
	LegEditScript:	"View.EditLegend"
	TxPos:	250
	SnapTolCursor:		1
)

(XYSrc.199
	Name:	200
	FTab:	208
	XField:		210
	YField:		211
)

(XYName.200
	Name:	"contour interval sibasa.dbf"
	OwnerClass:	"XYSrc"
	VTab:	201
	XField:		203
	YField:		204
)

(VTab.201
	Name:	"contour interval sibasa.dbf"
	BTab:	202
	Fields:	203
	Fields:	204
	Fields:	205
	SelBits:		207
)

(dBASE.202
	Name:	"contour interval sibasa.dbf"
	Fields:	203
	Fields:	204
	Fields:	205
	FileName:	206
)

(Field.203
	Name:	"N1"
	Btab:	202
	Alias:	"N1"
	Visible:		1
```

```
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	Order:	-1
	Pixels:	59
)

(Field.204
	Name:	"N2"
	Btab:	202
	Alias:	"N2"
	Visible:		1
	Type:	9
	Order:	-1
	Pixels:	59
)

(Field.205
	Name:	"N3"
	Btab:	202
	Alias:	"N3"
	Visible:		1
	Type:	9
	Order:	-1
	Pixels:	59
)

(FN.206
	Path:	"c:/contour interval sibasa.dbf"
)

(Bitmap.207
	NumBits:		33

)

(FTab.208
	Name:	"contour interval sibasa.dbf"
	BTab:	209
	Fields:	214
	Fields:	210
	Fields:	211
	Fields:	212
	SelBits:		215
	FSrc:	199
)

(dBASE.209
```
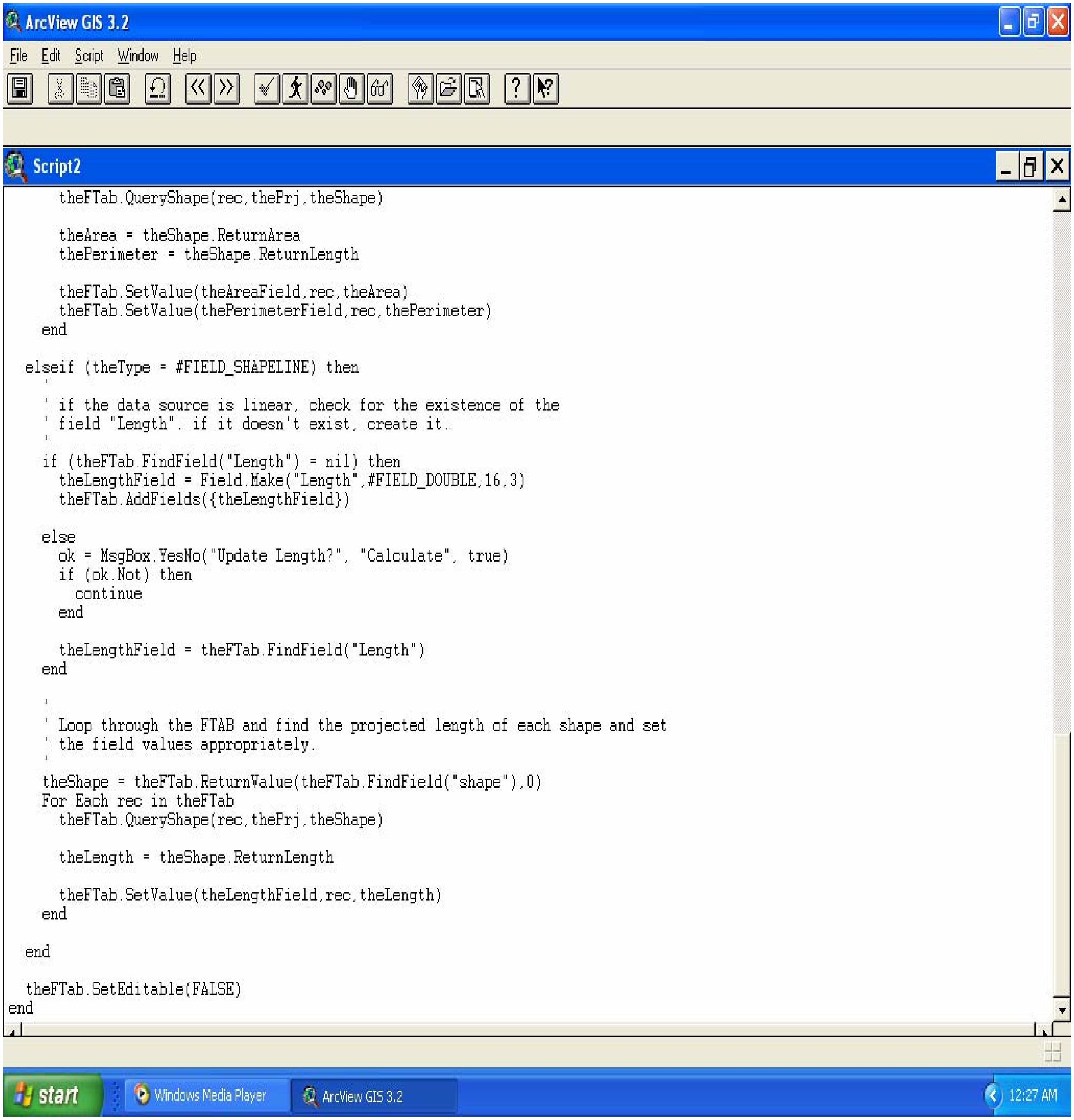

```
	Name: "contour interval sibasa.dbf"
	Fields: 210
	Fields: 211
	Fields: 212
	FileName:	213
)

(Field.210
	Name: "N1"
	Btab:	209
	Alias:	"N1"
	Visible:		1
	Type:	9
	Order: -1
	Pixels: 59
)

(Field.211
	Name: "N2"
	Btab:	209
	Alias:	"N2"
	Visible:		1
	Type:	9
	Order: -1
	Pixels: 59
)

(Field.212
	Name: "N3"
	Btab:	209
	Alias:	"N3"
	Visible:		1
	Type:	9
	Order: -1
	Pixels: 59
)

(FN.213
	Path:	"c:/contour interval sibasa.dbf"
)

(Field.214
	Name: "Shape"
	Alias:	"Shape"
	Visible:		1
	Type:	17
```

```
        Order:  -1
)

 (ToolMenu.1619
        Disabled:       1
        Help:   "Contour//Creates a contour based on a point you define in a view"
        HelpTopic:      "Contour_Tool@surface.hlp"
        Update:         "Spatial.ContourToolUpdate"
        Icon:   1620
        Cursor:         "Cursors.Bullseye"
        Apply: "Spatial.ContourTool"
        Child:  1621
        Child:  1622
        Child:  1624
)

(AVIcon.1620
        Name: "Contour"
        Res:    "Icons.Contour"

)

(Tool.1621
        InternalName: "Surface"
        Disabled:       1
        Help:   "Contour//Creates a contour based on a point you define in a view"
        HelpTopic:      "Contour_Tool@surface.hlp"
        Update:         "Spatial.ContourToolUpdate"
        Icon:   1620
        Cursor:         "Cursors.Bullseye"
        Apply: "Spatial.ContourTool"
)

(Tool.1622
        InternalName: "3d"
        Disabled:       1
        Help:   "Line of Sight//Calculates line of sight based on the active grid or tin
theme"
        HelpTopic:      "Line_Of_Sight_Tool@threed.hlp"
        Update:         "3D.LineOfSightToolUpdate"
        Icon:   1623
        Cursor:         "Cursors.CrossHair"
        Apply: "3D.LineOfSightTool"
        Click:  "3D.LineOfSightToolClick"
)
```

```
(AVIcon.1623
	Name:	"LineOfSight1"
	Res:	"SIcons.LineOfSight1"

)

(Tool.1624
	InternalName:	"3d"
	Disabled:	1
	Help:	"Steepest Path//Calculates the steepest downhill path from a specified
point on the active tin theme"
	HelpTopic:	"Steepest_Path_Tool@threed.hlp"
	Update:	"3D.SteepestPathToolUpdate"
	Icon:	1625
	Cursor:	"Cursors.Bullseye"
	Apply:	"3D.SteepestPathTool"
)

(AVIcon.1625
	Name:	"SteepPath"
	Res:	"SIcons.SteepPath"

)

(ToolMenu.1626
	InternalName:	"3d"
	Disabled:	1
	Help:	"Interpolate Line//Interpolates a line from the active grid or tin theme"
	HelpTopic:	"Interpolate_Draw_Tool@threed.hlp"
	Update:	"3D.InterpolateLineToolUpdate"
	Icon:	1627
	Cursor:	"Cursors.CrossHair"
	Apply:	"3D.InterpolateLineTool"
	Child:	1628
	Child:	1629
	Child:	1631
)

(AVIcon.1627
	Name:	"InterpolateLine"
	Res:	"SIcons.InterpolateLine"

)

(Tool.1628
	Disabled:	1
```

```
	Help:	"Interpolate Line//Interpolates a line from the active grid or tin theme"
	HelpTopic:	"Interpolate_Draw_Tool@threed.hlp"
	Update:		"3D.InterpolateLineToolUpdate"
	Icon:	1627
	Cursor:		"Cursors.CrossHair"
	Apply: "3D.InterpolateLineTool"
)

(Tool.1629
	Disabled:	1
	Help:	"Interpolate Point//Interpolates a spot height using the active grid or tin
theme"
	HelpTopic:	"Interpolate_Draw_Tool@threed.hlp"
	Update:		"3D.InterpolatePointToolUpdate"
	Icon:	1630
	Cursor:		"Cursors.CrossHair"
	Apply: "3D.InterpolatePointTool"
)

(AVIcon.1630
	Name: "InterpolatePoint"
	Res:	"SIcons.InterpolatePoint"

)

(Tool.1631
	Disabled:	1
	Help:	"Interpolate Polygon//Interpolates a polygon boundary from the active
grid or tin theme"
	HelpTopic:	"Interpolate_Draw_Tool@threed.hlp"
	Update:		"3D.InterpolatePolygonToolUpdate"
	Icon:	1632
	Cursor:		"Cursors.CrossHair"
	Apply: "3D.InterpolatePolygonTool"
)

(AVIcon.1632
	Name: "InterpolatePolygon"
	Res:	"SIcons.InterpolatePolygon"

)

(AVIcon.1633
	Name: "Icon"
	Res:	"View.Icon
```

APPENDIX 2 : GIS window to show a macro to calculate surface area of reservoirs from images



```
      theFTab.QueryShape(rec,thePrj,theShape)

      theArea = theShape.ReturnArea
      thePerimeter = theShape.ReturnLength

      theFTab.SetValue(theAreaField,rec,theArea)
      theFTab.SetValue(thePerimeterField,rec,thePerimeter)
    end

  elseif (theType = #FIELD_SHAPELINE) then
    '
    ' if the data source is linear, check for the existence of the
    ' field "Length". if it doesn't exist, create it.
    '
    if (theFTab.FindField("Length") = nil) then
      theLengthField = Field.Make("Length",#FIELD_DOUBLE,16,3)
      theFTab.AddFields({theLengthField})

    else
      ok = MsgBox.YesNo("Update Length?", "Calculate", true)
      if (ok.Not) then
        continue
      end

      theLengthField = theFTab.FindField("Length")
    end

    '
    ' Loop through the FTAB and find the projected length of each shape and set
    ' the field values appropriately.
    '
    theShape = theFTab.ReturnValue(theFTab.FindField("shape"),0)
    For Each rec in theFTab
      theFTab.QueryShape(rec,thePrj,theShape)

      theLength = theShape.ReturnLength

      theFTab.SetValue(theLengthField,rec,theLength)
    end

  end

  theFTab.SetEditable(FALSE)
end
```

APPENDIX 3: Statistical Analysis

T-Test

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	AREAIM	31312.58	12	23046.2562	6652.8811
	AREAFIEL	31928.42	12	22848.9989	6595.9378

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	AREAIM & AREAFIEL	12	.996	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	AREAIM - AREAFIEL	-615.8333	2033.1295	586.9139	-1907.62	675.9555	-1.049	11	.317