UNIVERSITY OF ZIMBABWE

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

DEVELOPMENT AND TESTING OF AN ICT-BASED DECISION SUPPORT SYSTEM FOR EFFECTIVE MANAGEMENT OF SMALL RESERVOIRS: THE CASE OF GWANDA DISTRICT, ZIMBABWE

BAHAL'OKWIBALE MULENGERA

M.SC. THESIS IN IWRM

HARARE, JUNE 2011

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In collaboration with

DEVELOPMENT AND TESTING OF AN ICT-BASED DECISION SUPPORT SYSTEM FOR EFFECTIVE MANAGEMENT OF SMALL RESERVOIRS: THE CASE OF GWANDA DISTRICT, ZIMBABWE

By

BAHAL'OKWIBALE MULENGERA

Supervisors:

Dr EMMANUEL MANZUNGU
Dr JEAN-MARIE KILESHYE ONEMA
Mr COLLIN C. MABIZA

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Integrated Water Resources Management (IWRM) of the University of Zimbabwe

Harare, June 2011

DECLARATION

I, **Bahal'okwibale Mulengera**, hereby declare to the Senate of the University of Zimbabwe that this research report is my own work. It is being submitted for the degree of Master of Science in Integrated Water Resources Management (IWRM) of the University of Zimbabwe. It has not been submitted before for any degree of examination of any other University.

Date: ____________________

Signature: _____________________

The findings, interpretations and conclusions expressed in this study do neither reflect the views of the University of Zimbabwe, Department of Civil Engineering nor of the individual members of the MSc Examination Committee, nor of their respective employers.

ABSTRACT

Small reservoirs represent one of the most important sources of water for livelihoods in the Mzingwane catchment, which constitutes the entirety of the Limpopo basin in Zimbabwe, because of semi-arid conditions that prevail in the area. Despite the water reforms that, among other things, were meant to improve water-based livelihoods, little attention has been paid to systematic management of small reservoirs as illustrated by disparate and in some cases non-existing information. Recent developments in Information and Communication Technologies (ICTs) provide opportunities for identification and characterization of small reservoirs, which is critical to effective local water resource management. This is because non-ICT methods are worthwhile, but they are time and cost ineffective. The study therefore sought to develop and test an ICT-based tool for effective management of small reservoirs. The study built upon previous work that demonstrated the possibility of identifying small reservoirs and estimating their capacities using satellite images and GIS. The objective of this study was to integrate the output information – small reservoir location, capacity, river or subcatchment, reliability, and status – in decision making processes by using Gwanda district located in southwest Zimbabwe as a case study. The study focused on identifying and characterising small reservoirs, and building up a database of little physical requirements. Identification was done through GIS processing of Landsat TM 4-5 images of February-March and April-May 2009. Finding recent images of the period around September for the dry season period was a major limitation. Fields surveys were done for ground truthing and for further identification and characterisation (name, place, capacity, turbidity and chlorophyll-a validation) of the reservoirs. Documents reviews were carried out to explore the contents of the existing databases. A total of 256 small reservoirs were identified and their status characterised in the district. The distribution of the capacities among the three subcatchments (Shashe, Lower and Upper Mzingwane) was found to be proportional to their surface area coverage over the district. Capacities were found to vary widely from around 4,000 m^3 to over 650,000 m^3; with the majority of them being around 30,000 m^3. The total capacity in the district was estimated to 17 million m^3 from which ward 23, one of the 24 rural wards in the district, accounted for more than 40% of the total capacity. Reservoirs with capacities less than 52,222 m^3 were found susceptible to drying up in the dry season. Only 32% of the small reservoirs could reach the next rainy season. Seven reservoirs were characterised as highly turbid indicating a poor catchment protection, 79 moderately turbid, and 170 clear or less turbid. However, among the clear ones, 23 were characterised as affected by excessive floating vegetation probably due to nutrient leaching (mainly from fertilisers) in the catchment. A database was designed and integrated the results of the study with other attributes of some small reservoirs that were documented in organisations' records. Finally, a Decision Support System was built from the results in a web application interface to provide a basis for informed decision-making concerning small reservoirs, especially in relation to their capacities, locations, and status, via facilitated information query, update, and visualisation. The tool provides a basis for effective collaboration between local institutions (for both based on hydrological and administrative boundaries) and responsible decision-making that needs information in various areas. These areas include surface water resources assessment, ability of small reservoirs to reach the next rainy season, and interventions required in catchment to ensure the sustainability of a small reservoir. The study demonstrated the possibility to use ICTs in effective small reservoirs management as a resources and time-efficient way to continually acquire, and integrate information.

Keywords: Decision Support System, ICT, small reservoir, water resources management, Gwanda.

DEDICATION

To my late father Mulengera Kazungu,

for instructing me values of education for problem solving;

To my mother Nicole Mirindi,

my brother Ntaboba Mulengera, and my sister Solange Amani

for sacrifices you made for my best achievement;

To all my family members and friends,

for considering that we can only improve life on Earth,

not by one big solution, rather by solving people’s little problems;

To whoever understands that information is key

to responsible decision-making;

I dedicate this work.

Patrick-Moïse Bahal’okwibale Mulengera

ACKNOWLEDGEMENTS

I thank God for always providing me with the courage to overcome challenges when a weak mindset would have abandoned on the way. I also recognise the careful supervision of this work by Dr Emmanuel Manzungu who demonstrated humble lightning of the way research has to be strictly done. I express my gratitude to Dr Jean-Marie Kileshye Onema for being perspicacious all along the study undertaken. I thank Mr Collin C. Mabiza for facilitating the logistics provision when it was needed. It was for me a team of supervision that I felt well committed to the best of my achievement.

Special thanks should go to Professor Innocent Nhapi, Dr Hodson Makurira, Mr David Love, and Dr Jean-Marie Kileshye Onema for assisting my access to the project at the core of this study and that focuses on research for people's lives betterment.

I acknowledge the support of Mr P. Ndlovu for the assistance provided on tough, sometimes dangerous, ways on his motorbike during the fieldwork. I am grateful to Surveyor General, GIS Laboratory Staff of the Department of Geography and Environmental Sciences of the University of Zimbabwe, ZINWA in Harare, DDF, RDC, and Veterinary Department in Gwanda for providing me with the data I needed for the work.

The Staff members of the Department of Civil Engineering of the University of Zimbabwe are acknowledged for their critical views on this work that helped shape it better. My colleagues are also acknowledged for constructive remarks all along this programme.

Lastly, but not least, I thank WaterNet and the Challenge Programme on Water and Food for planning and funding such research. Water is a strategic resource in the SADC region and it was a pleasure for me to do a study that aims at influencing policy and development of people on the ground. Science will ever be worthy only if it solves people's little problems.

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ACRONYMS

AGRITEX	Agricultural Technical and Extension service
CD	Compact Disc
DDF	District Development Fund
DSS	Decision Support System
GDSS-SR v.1.0	Gwanda Decision Support System for Small Reservoirs, version 1.0
GIS	Geographic Information System
ICT	Information and Communication Technology
ID	Identifier
IWRM	Integrated Water Resources Management
LDS	Lutheran Development Services
NGO	Non-Governmental Organisation
RDC	Rural District Council
RVD	Relative Volume Difference
SADC	Southern African Development Community
TM	Thematic Mapper
UNCED	United Nations Conference on Environment and Development
WSSD	World Summit on Sustainable Development
ZINWA	Zimbabwe National Water Authority

1. INTRODUCTION

1.1. Background

Since the 1990s water resources management perspectives seem to have shifted from infrastructure-centred perspectives towards Integrated Water Resources Management (IWRM) despite the fact that water infrastructure development is important for livelihoods sustenance, poverty reduction (Hanjra and Gichuki, 2008) and economic development in general. The driver behind this seems to have been the global movement towards sustainable development (Allan, 2003), a fact that is echoed by the IWRM definition which aims at reconciling social, economic, and environmental aspects of water resources. IWRM has been defined as a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP-TAC, 2000). IWRM is based on the four Dublin principles that considerably contributed to the Chapter 18 on freshwater resources of the Agenda 21 recommendations adopted at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992 (GWP-TAC, 2000). The conference promoted sustainable development ideas based on the three pillars of environmental sustainability, economic efficiency, and social equity (Parson *et al.*, 1992). The four Dublin principles, namely that 1) fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment; 2) water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels; 3) women play a central part in the provision, management and safeguarding of water; 4) water has an economic value in all its competing uses and should be recognized as an economic good (GWP-TAC, 2000), have in the main provided guidance regarding the implementation of IWRM.

The international efforts at IWRM implementation, of which the World Summit on Sustainable Development held in Johannesburg in 2002 (WSSD, 2002) is yet another example, resulted in regional and national attempts at realigning and reshaping water policies and institutions in line with IWRM principles. A good example is the Southern African Development Community (SADC), a political and regional economic grouping to which all the southern African countries belong. SADC incorporated various aspects of IWRM in their regional policies, strategies and legal frameworks (SADC, 2000; SADC, 2005a; SADC, 2005b; SADC, 2006). Individual countries within SADC, such as Namibia, South Africa, Tanzania, and Zimbabwe, to cite a few, undertook national water reforms that took into account IWRM principles (Manzungu, 2004). However, local circumstances meant that the implementation was different in different countries. There was, however, across the board the use of pilot catchments as a means to gaining important lessons for IWRM implementation although the methodology differed (Manzungu, 2004) because of prevailing socio-political history and socio-economic circumstances (Swatuk, 2008). On one side was South Africa and Tanzania that took a longer, progressive way of IWRM implementation in order to build on acquired experience. On the other side were Zimbabwe and Namibia which adopted a quicker way in order to break the societal inequities. Zimbabwe established all the institutions after six months of legislation enactment (Manzungu, 2004). In the case of the Kuiseb basin of Namibia, the process involved all interested stakeholders and took one-and-a-half years for gathering the necessary information and formally establishing a committee (Botes *et al.*, 2003).

Water reforms in Zimbabwe that started in the mid 1990s and culminated with the promulgation of the 1998 Water Act (Zimbabwe, 1998a) and the Zimbabwe National Water Authority Act (Zimbabwe, 1998b) fundamentally changed the way water was managed. The reforms, which were informed by the need to redress the situation where a white minority population used practically all the developed water resources, were conflated with IWRM principles because of the global developments in the water resource management circles as pointed out earlier, and also because the water reforms were bankrolled by Western donors who insisted on the adoption of IWRM (Manzungu, 2001). The outcome of the reforms process was that: 1) all water became the property of the state, 2) priority date system of allocating water was replaced by a more equitable system, 3) water allocation was decentralised from the Water Court to popularly elected stakeholder bodies called catchment councils, 4) day to day water resource management became the responsibility of stakeholder bodies called sub-catchment councils (see chapter 2 for an in depth description), 5) water management was organised along hydrological instead of administrative boundaries and 6) water resource planning was the joint responsibility of the catchment council and the national water authority (Manzungu, 2001; Manzungu and Kujinga, 2002).

It can be said that the water reforms in Zimbabwe have not brought about effective water resource management in the country (Fatch *et al.*, 2010; Makurira and Mugumo, 2005; Marimbe and Manzungu, 2003). Issues relating to how stakeholder participation can be enhanced, how and whether local livelihoods benefit from the new water resource management regime, and whether the new institutions have the requisite capacity to carry out their functions still loom large. Research findings indicate that the 1990s IWRM-based water reforms overestimated the capacity of decentralised institutions to effectively study, plan, and monitor management aspects of water resources at the local level (Butterworth *et al.*, 2010; Chereni, 2007; Fatch *et al.*, 2010). There are also two other confounding factors. Firstly, as pointed out by Lautze *et al.* (2011) what management means in the context of IWRM was not made clear, which however is not unique to Zimbabwe. In this vein it is important to note that *management* in water resource management can be used in a broad or narrow sense (Mollinga, 2008). In the broad sense it is used as a generic term that includes water use, allocation, distribution, governance, regulation policy etc, while in its narrow sense it is used to distinguish it from water governance (Mollinga, 2008). Water governance consists of the processes and institutions by which decisions that affect water are made (Lautze *et al.*, 2011). In this study water management is used in the narrow sense although it is recognised that management may have implications for water governance and vice versa. Consequently water resources management in this thesis is understood as the application of structural and non-structural measures in order to be in command of natural and man-made water resources systems for the achievement of benefits for humans and the environment (Grigg, 1996). Secondly, water availability, be it in the form of adequate precipitation for rainfed crop production or adequate storage, determines the outcome of whatever management regime is adopted. In low precipitation areas such as the Limpopo river basin in Zimbabwe, which was the locus of this study, storage is important. In order to extend the availability of water to livelihoods over time, reservoirs are needed (WWAP, 2009).

Depending on decision-makers' approach, a policy choice can be made between either developing centralised large reservoirs or distributed small reservoirs (Van der Zaag and Gupta, 2008). Small reservoirs are known to play an important role in the livelihoods of many rural livelihoods in the Limpopo basin (Manzungu *et al.*, 2009). However, the size categorization of dams and reservoirs varies from country to another. In Zimbabwe, small dams are defined as those having a dam wall of less than 8 meters and a storage capacity of less than one million cubic metres of water at full supply level (Kabell, 1986), or declared as small dam by the relevant authority (Zimbabwe, 1998a).

1.2. Problem statement

In Zimbabwe, the management of small reservoirs is problematic in three main respects. First the jurisdiction of the management of small reservoirs is not clear. Sometimes the management of small reservoirs is said to be the responsibility of local authorities (locally known as rural district councils), the Non-Governmental Organisations (NGOs) that constructed at least during their presence in the area, and the local communities to whom the small reservoir is donated or is located. Small reservoirs in previously white-owned farms added to the complexity as a consequence of the land reform programme that began in 2000. The second problem relates to the disparate and in some cases non-existing information (Sawunyama *et al.*, 2006; Senzanje and Chimbari, 2002). The third problem relates to the fact that there is virtually no technical capacity at the subcatchment council level where water management is located or at the local authority level where planning is undertaken. Thus despite the critical importance of small reservoirs to rural livelihoods for their multiple uses (Senzanje *et al.*, 2008), small reservoir management remains largely undeveloped.

This study sought to address this gap in the management of small reservoirs by exploring the possibility of using the now commonly available Information and Communication Technologies (ICT). The study focused on the management of small reservoirs in Gwanda District in the Matebeleland South Province of Zimbabwe, where their critical importance is illustrated by erratic rainfall. This was because small reservoirs are critical for rural livelihoods in arid and semi-arid areas for their multiple uses (Mati *et al.*, 2005), and improve livelihoods through income generation and food security (Katsi *et al.*, 2007). Small reservoirs are used for multiple purposes with a very high rank of over 70% for livestock watering (Senzanje *et al.*, 2008). However, small reservoirs generally face sustainability threats due to financial and management challenges (Machingambi and Manzungu, 2003; Smits *et al.*, 2010).

Nevertheless, scholars demonstrated that those decentralised institutions have faced critical challenges of capacity to function accordingly (Makurira and Mugumo, 2005; Manzungu, 2001; Manzungu and Kujinga, 2002; Tapela, 2002). To illustrate, Manzungu and Kujinga (2002) observed that the lack of required information on water resources in the case of Save catchment in Zimbabwe led to the incapacity to draw up a catchment outline plan. Altogether, small reservoirs management by decentralised institutions in Zimbabwe is not effective due to absent or disparate information.

1.3. Objectives

The general objective of the study was to develop an ICT-based Decision Support System for effective management of small reservoirs in Zimbabwe.

The specific objectives of the study were to:

- Identify small reservoirs in Gwanda District through the use of satellite images;
- Characterise the identified small reservoirs in terms of physico-chemical and socio-economic characteristics;
- Create small reservoirs database and maps that can be used to effectively manage small reservoirs in Gwanda district by the appropriate institutions; and
- Produce a Decision Support System that improves small reservoirs management in Gwanda district.

1.4. Limitations of the study

The study was limited by a number of factors. First, there was unavailability of full sets of satellite images of acceptable quality for a recent period around September, which could have enhanced capacity estimations for the dry period. Second, there was disharmony regarding the data obtained from the Veterinary and the Rural District Council offices. This limited the analysis at the village scale regarding the availability of water from small reservoirs for livelihoods use. Third, the data did not have any spatial locations and the reliable spatial data from Surveyor General is limited to the Ward level, which meant that the analysis was restricted to the ward level. Fourth, unfitting and sometimes missing grid references from the DDF records meant that it was not easy to integrate, the uses and names of some of the small reservoirs in the produced database from the secondary data that was available. Fourthly, Sawunyama *et al.* (2006)'s capacity-area relationship that was developed from 12 small reservoirs in nearby Insiza district was found to underestimate the small reservoirs capacities in Gwanda district.

1.5. Justification

Since the management of water resources - including their inventory, quantity and quality specifications – can only be effective if required information is available at the time and place as well as the format it is needed for decision making processes (Moriarty *et al.*, 2010), it follows that information on small reservoirs is a corner stone in the management of small reservoirs. This underlines the importance of what this study sought to do, namely gather, collate and process data, which can assist decentralised water resources managers to take informed decisions concerning small reservoirs.

1.6. Structure of the thesis

In addition to this introduction (Chapter 1), the thesis is organised on other four chapters. Chapter 2 reviews the literature on IWRM implementation challenges with a focus on Zimbabwe, as well as challenges relating to the management of small reservoirs. The information challenges and the tools to address those challenges, with a focus on Information and Communication Technologies (ICTs) and Decision Support Systems (DSS) are also outlined. Chapter 3 describes the materials and methods used while Chapter 4 presents the results obtained and their discussions. Finally, conclusions and recommendations from the work are provided (Chapter 5).

2. LITERATURE REVIEW

2.1. Overview of IWRM implementation challenges

IWRM is the currently pledged approach to effective water resources management. However, the approach has been globally criticised of being difficult to implement. According to Biswas (2004), IWRM's claims of integrating several aspects of water resource management at different levels across different institutions are not borne out in practice. For Global Water Partnership the integration is relative as perfect integration is unrealistic (GWP-TAC, 2000). Sellers and Lidstrom (2007) make the point that IWRM is very demanding in terms of its data requirements, especially at the local level (Butterworth *et al.*, 2010). In some cases politico-administrative rather hydrological units could be better management units (Cohen and Davidson, 2011; Fatch *et al.*, 2010; Manzungu, 2004). The assumption that decentralised institutions would have the required capacity has also been found to be incorrect (Manzungu and Kujinga, 2002; Moriarty *et al.*, 2010), as well as the assumption that all stakeholders have good will towards each other irrespective of the differential powers between and among them (Dube and Swatuk, 2002; Saravanan *et al.*, 2009; Swatuk, 2005; Swatuk, 2008; Van Koppen, 2003). Moriarty *et al.* (2010) also observed that some of the decentralised institutions lack reliable information, which could be of poor quality, outdated, non-existent, located in different institutions, and sometimes not in incompatible formats**.**

Emphasising the point that information on water resources is crucial for successful IWRM implementation, the GWP recommended the use of Information and Communication Systems as management instruments (GWP-TAC, 2000). In its 'Toolbox version 2', the GWP recommends Modelling and Decision Support Systems (DSS) in IWRM, which incorporates some aspects of Information and Communication Technologies (ICTs), as complementary tools for improved water resources management (GWP, 2011), as this ensures effective decision making (Jansky and Uitto, 2005; Koutsoyiannis *et al.*, 2003; Singh and Singh, 2004). ICTs also enable the collection and integration of biophysical and socio-economic data for better decision making processes, something which is difficult to achieve when non-ICT methods are employed (de Lange *et al.*, 2010). All this points to that water management institutions need to have capacity in different areas.

In Zimbabwe the new water management institutions have been found to lack capacity for a variety of reasons. For example Manzungu and Kujinga (2002) showed that in the Save catchment in eastern Zimbabwe that the new institution (catchment council) was keen to let the officials of the water management authority (ZINWA) produce the catchment outline plan because of capacity constraints and yet by law it was mandated to play an active role. This was because the new stakeholder institutions were not conceptualised as professional bodies with technical expertise but as stakeholder institutions that would 'participate in water issues.' As a consequence the new institutions tend to be (over)reliant on the state when it comes to technical aspects. The fact that catchment manager's office, that was part and parcel of the national water authority, acted as secretariat to the catchment councils, confirms this observation. The fact that ZINWA's mandate does not include small dams means that the management of small reservoirs does not get any technical input. It is, however, also important to underline the fact that since 2000s ZINWA lost also a lot of personnel, which was compounded by serious financial problems. As will be shown below the IWRM-related implementation challenges have also affected the management of small reservoirs. There are, however, unique problems that affect the management of small reservoirs.

2.2. Small reservoirs management challenges

The management of small reservoirs is a complex undertaking activity because it brings together issues relating to physical dimensions of the catchment, institutional coordination, and the acquisition of data and information to inform decision-making processes. This is further compounded by the fact that in many instances, especially in developing countries, we are talking about community management since these reservoirs are used by communities rather than individuals.

2.2.1 Taking account of physical dimensions of the catchment

Good management of small reservoirs starts in the catchment (also called watershed or drainage basin) which is defined as the area of land from which all precipitation flows to a single stream or set of streams (Encyclopaedia Britannica, 2010). The activities and protection measures in a catchment determine the quality of water downstream (Foster *et al.*, 2007; Monaghan *et al.*, 2009). Soil erosion in the catchment leads to very turbid inflows in reservoirs and consequently their faster siltation (Felfoul *et al.*, 2003; Lawrence *et al.*, 2004). Nutrients leaching, especially phosphorus contained in fertilisers (Pinto-Coelho *et al.*, 2005), causes eutrophication of downstream water bodies (Monaghan *et al.*, 2009). These issues are amplified by the runoff that occurs within a catchment (Valentin *et al.*, 2008) and this reduces the sustainability of small reservoirs and is especially true in the absence of control measures (Bossio and Geheb, 2008; Critchley *et al.*, 2007). Although catchment protection can be a challenge for planners and decision makers (Woolley and McGinnis, 1999), some least cost measures, that include reducing irrigation runoff, fencing, planting riparian margins, and reducing nutrients leakages, proved to be very efficient (Gordon *et al.*, 2009; Monaghan *et al.*, 2009). Beside the catchment management, there are specific measures required at the reservoir dam wall itself.

Dam wall maintenance is critical to the sustainability of a small reservoir. Consequently the owner of a dam should be able to indentify emergency situations threatening a dam and deploy effective response actions to prevent dam failure (DEC, 1987). In spite of rural communities' willingness to participate in the management and maintenance of water infrastructures (Machingambi and Manzungu, 2003), such infrastructures actually face avoidable failures that could not require more expensive skills or interventions than awareness raising, training, management committee and responsibilities establishment (Hoko and Hertle, 2006).

With specific reference to small dams, visual inspection of the wall is one of the most economical approaches to ensure the long life of a small dam. This can help less skilled individuals to gather important dam safety data such as the colour of the water, cracks and seepage in the wall, plant growth, ants and rodents holes, as well as livestock grazing on the wall. All these could be related to increased erosion and runoff, or rust expansion on metallic components (like pipes) in the dam wall (DEC, 1987). Visual observations can result either in immediate interventions that involve little training and costs from local community or direct reporting to specialized institutions (DEC, 1987). This calls for the necessary mechanisms to be in place since some degree of institutional coordination is needed.

A risk of failure evaluation tool[1] for small dams in the Limpopo river basin in Zimbabwe locally known as the Mzingwane catchment found that, despite being built according to the guidelines, most of the small dams were in bad physical state due to limited maintenance, lack of resources, and unclear roles (between the District Development Fund, Non-Governmental Organisations, local authorities and local communities) regarding the ownership and maintenance of the small dams (Mufute *et al.*, 2008). Pisanielloa *et al.* (2006) made a similar observation in Australia, where small dams were not looked after properly by the community despite the existence of improved design and policy.

2.2.2. Institutional challenges

In addition to the IWRM-related implementation management challenges that have been highlighted, management of small reservoirs is made complex by the fact that small reservoirs are community managed. Effective management involving the community requires adequate incentives, sufficient skills and resources, appropriate processes for water systems operations and maintenance, effective inter-organizational relationships, appropriate technology, and effective systems of monitoring, evaluation and feedback (Rondinelli, 1991).

Van der Zaag and Gupta (2008) noted that small reservoirs represent a decentralised model of water provision to communities for which the institutional system at the reservoir level might vary from one reservoir to another. Uniform management models for small reservoirs are thus likely to fail and need a strategic approach from the coordinating institutions. In Zimbabwe, the 1998 Water Act gives provision to the Zimbabwe National Water Authority (ZINWA), in

[1] Failure was defined as the inability of a dam to hold water due to breaching or siltation.

collaboration with the catchment council, for the approval to build small dams, their inspection, and the enforcement of defaulting requirements of small dams (Zimbabwe, 1998a; section 108). This presupposes that the ZINWA and the catchment council could control and coordinate the small dams' management. However, the role of coordinating institutions can only be effective if required information and documentation on small reservoirs is available where it is needed.

2.2.3. Information challenges

Moriarty *et al.* (2010) observed that some challenges affecting the effectiveness of water resources management by decentralised institutions are related to the lack of reliable information (either of poor quality or outdated) or to poor access to information (disparate information, distributed in different organisations records). This is a correct observation as far as the management of small reservoirs in Zimbabwe is concerned. To illustrate the point, Senzanje and Chimbari (2002) observed a critical discordance of number and attributes of small reservoirs that ZINWA holds in its national database and those known by provincial and local institutions. Thus the available records could hardly 'speak to each other' so as to deliver consistent information that could improve the small reservoirs management by decentralised institutions. As discussed below ICTs can help in this regard (Jansky and Uitto, 2005; Li, 1997).

ICT can be understood as the systematic application of a body of knowledge acquired through research, study, or instruction in a standardized system of codes exchange and interpretation using computer systems and electronics in order to solve a problem of human life or to improve a situation affecting that life (Encyclopaedia Britannica, 2010). Some examples of ICTs are mobile phone telecommunications, radio, television, internet, databases, remote sensing, and geographic information systems. An example of application of ICTs to small reservoirs was by Sawunyama *et al.* (2006) who estimated the capacities of reservoirs using remote sensing data and Geographic Information Systems (GIS). However, the study did not show how such information could be directly used by decentralized institutions in order to improve small reservoirs management. In this vein it can be observed that there are ICT tools, named Decision Support Systems (DSS), which can greatly assist in the decision making processes. A DSS is a computer based system that facilitates decision-makers to utilise data to solve unstructured problems (Pereira, 2002). Various types of DSS have been developed to date and are becoming easy to deploy given the opportunities offered by free software systems, increased computers capabilities and their lowered costs (Tian *et al.*, 2007).

In the context of this study we can say that ICTs provide an opportunity to develop a Decision Support System for small reservoirs. This will assist gathering data and generating related information that can be directly used by decentralised institutions involved in small reservoirs management in Gwanda district, which can make a contribution to the betterment of rural livelihoods dependant on small reservoirs.

2.3. Small reservoirs management: data requirements and acquisition tools

The success of ICTs in the decision making process depends on the availability of good data and also how it can be acquired. Data related to small dams' management cover a wide range of components which can be grouped into identification, safety, capacity, and uses. The following are some of the important features of the data that is required:

- Identification of a dam in terms of its location, owner, catchment area, date of completion (Zimbabwe, 1998a).
- Safety referring to its status, risk of failure (Mufute *et al.*, 2008), and the possible downstream impacts (DEC, 1987).
- Capacity of the dam which refers to its reservoir design capacity, and its actual capacity (Sawunyama *et al.*, 2006), which varies over time with sedimentation rates or runoff changes due to seasonal or climatic rainfall variations; and
- The uses of the dam which refer to the direct and indirect benefits derived through its existence (Katsi *et al.*, 2007).

In Zimbabwe, the Water Act states that the owners of small dams should submit to the Secretary, ZINWA and the catchment council approved plans and specifications by a civil engineer before and after commencement of the dam works, in conformity with adequacy and safety requirements (Zimbabwe, 1998a).

Different tools can be used to acquire data for effective management of small reservoirs and these include non-ICT and ICT methods. Several methods that do not depend on ICT have been used to acquire data on reservoirs. These are siltation and sediment loads assessments (Rossi *et al.*, 2009; Tan, 1996), archived documents reviews, fields' visits from point to point, and questionnaires for locations of reservoirs, bathymetric surveys for reservoirs capacities estimations (de Moustier, 1988), nutrients loads characterisation and quantification (Koelmans and Lijklema, 1996; Muvundja *et al.*, 2009), environmental impacts assessments (Naiman and Dudgeon, 2009). Although these methods are valid in their approaches and some of their benefits still irreplaceable to date, they are globally time consuming and resources intensive. These can be made more efficient if complemented by ICTs.

ICT consist of a range of tools and technologies that may include radio, television, mobile phone (CTA, 2011), or the Internet and its various applications, as well as non-networked decision support, remote sensing and geographical information systems (Jansky and Uitto, 2005). Recent developments in ICTs are providing opportunities to generate information in data scarce areas, especially in developing countries (Hayes and Rajao, 2011). In water resources management, a few applications can be identified for illustrative purposes:

- Use of remote sensing and geographic information systems for rainfall (Kileshye Onema and Taigbenu, 2009),
- Estimation of the location and capacities of reservoirs (Gupta and Banerji, 1985; Rakhmatullaev, 2010; Sawunyama et al., 2006),
- Assessing groundwater potential (Moyce et al., 2006),
- Characterisation of water quality and land use impacts on soil erosion and catchment (Bee, 2009a; Bee, 2009b; Frohn and Autrey, 2009; Frohn, 2006; Shinde et al., 2010),
- Geologic and soil mappings, natural disaster and environmental assessments (Lillesand et al., 2004), and
- Intelligent water metering for smarter cities (European Commission, 2010).

There are also other advantages. Today there are many open source softwares for which information encoding have been standardised to facilitate inter-operability of systems and adaptability to different users languages (OpenGIS, 1999). Another important application of ICTs superseding traditional methods relates to its increased capabilities to handle and organise data by using databases. These are powerful tools that, if well designed (Harrington, 2002), enable the efficient storage, and retrieval of data, avoiding redundancy (Teorey *et al.*, 2006). Databases vary in the form, conceptual framework, physical implementation requirements and applicability. The main types of databases are relational databases, object relational databases, and recently spatial databases (Ramakrishnan and Gehrke, 2003; Yeung and Hall, 2007).

As already highlighted the use of ICTs in the development and application of Decision Support Systems (DSS) is gaining importance, which has benefited from the development of computers capabilities and affordability since the 1970s (Tian *et al.*, 2007). The rationale of their use in management is not to replace the decision maker, rather to assist the latter take informed decisions from unstructured data (USEPA, 2000). This is a key characteristic that makes DSS suitable for the management of complex systems (Knieper *et al.*, 2010) like natural resources management and, particularly, integrated water resources management (IWRM). An example of DSS application to water management is the assistance in the creation of a water management plan in Athens (Koutsoyiannis *et al.*, 2003).

There are various types of DSS, with some of the most developed ones running in their background multicriteria analyses, artificial neural network (artificial intelligence), or modelling applications (Pereira, 2002). The timeline of DSS development indicates that from their generation in 1970s, they expanded in the forms of simple DSS to Group DSS (GDSS) that integrated networking capabilities and Intelligent DSS (IDSS) in 1980s, to Online Processing Analytical Processing (OLAP) and web-based DSS in the 1990s, to spatial DSS (Tian *et al.*, 2007; USEPA, 2000). Despite the variability in forms, the basic framework for the development of a DSS is, as presented below, a dynamic system for which contents are continually built as the DSS is used, enabling better decision-making processes (Fig 1):

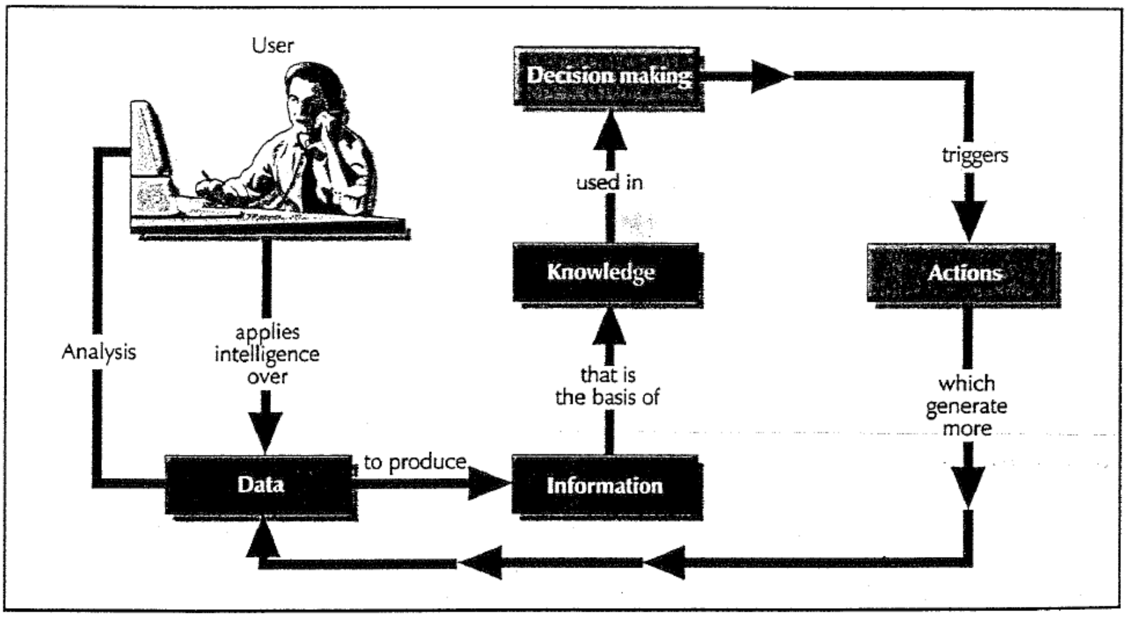


Figure 1.1. Framework for Decision Support System (Rob and Coronel, 2004)

2.4. Conclusion

In summary IWRM faces implementation challenges in most parts of the world. Some important causes of those challenges are the complexity involved in IWRM, the lack of management-ready information on water resources and the inappropriate or absence of strategic approach to address such challenges. Information acquisition and handling by decentralized institutions is a specific challenge for effective management of small reservoirs in Zimbabwe. Notwithstanding the recognised benefits and value of non-ICT methods, recent developments in Information and Communication Technologies (ICTs) provide opportunities that supersede the previous methods in terms of time and resources efficiency in the production of data that can be directly integrated in decision-making processes. ICTs integrate well with traditional methods and can be fed by the latter. The opportunities offered by ICTs are magnified by the development and application of Databases and Decision Support Systems (DSSs) that assist decision-makers to derive more information from unstructured data regarding complex systems. The properties that offer DSSs are thus valuable to IWRM decision-makers by assisting them take informed decisions, especially in the case of small reservoirs management in Zimbabwe which face challenges of scarce or disparate data.

3. MATERIALS AND METHODS

3.1. Description of the study area

3.1.1. Location and physical characteristics

The study was undertaken in Zimbabwe's Gwanda administrative district that is located in Matebeleland South province (Figure 3.1). The district covers approximately 11000 km^2. The altitude ranges from around 560 m in the southern part to greater than 1300 m in the northern part (Figure 3.2), and falls under Mzingwane catchment that constitutes the entire Limpopo river basin in Zimbabwe. The district is drained by two main rivers, namely the Tuli in the west and Mzingwane in the east. It falls under the hydrological zone B, which is one of the six hydrological zones in Zimbabwe and is characterised by the lowest mean annual runoff of 19 mm. It has the highest coefficient of variation (130%) in the whole country (Mtisi and Nicol, 2003; Mupangwa *et al.*, 2008; Zimbawe, 1983). Consequently, the streams are generally ephemeral. This underlines the importance of storage in the area. The rainy season ranges from November to March while the dry season starts from May to September. The soils types in Gwanda district (Figure 3.3) are not suitable for agriculture due to low potential of humus content unless fertilisers are used. The soils also require appropriate management in terms of erosion control. Due to the erratic rainfall, rainfed crop production is difficult. Crop production is not reliable unless done under irrigation, which emphasised the importance of storage facilities in the area. Livestock farming is also another livelihood strategy (PlanAfric, 2000).

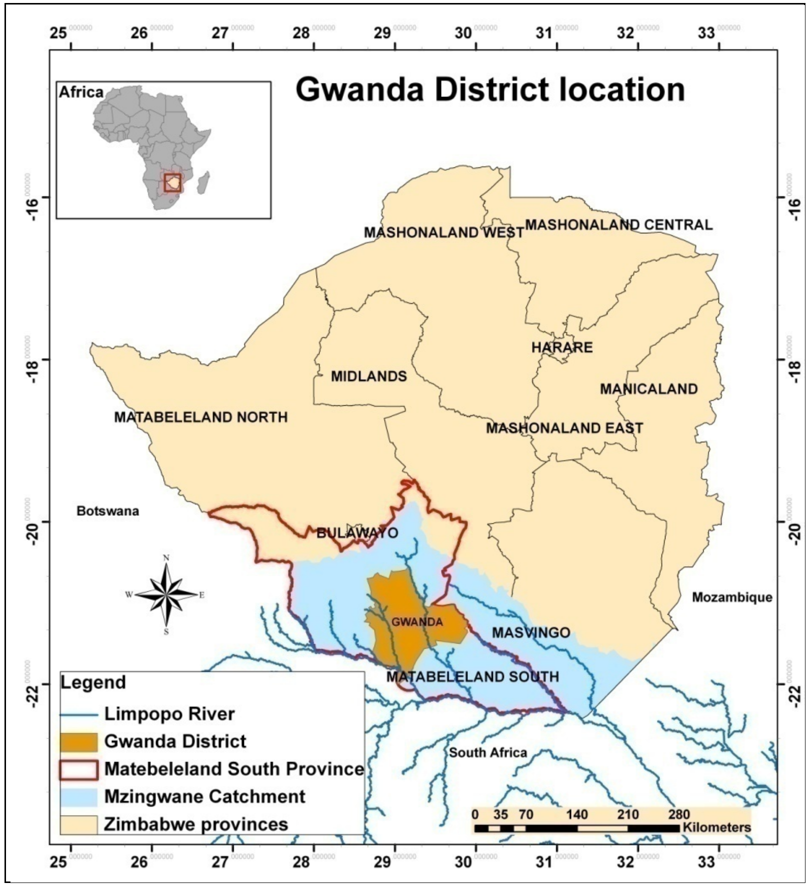


Figure 3. 1. Location map of Gwanda district

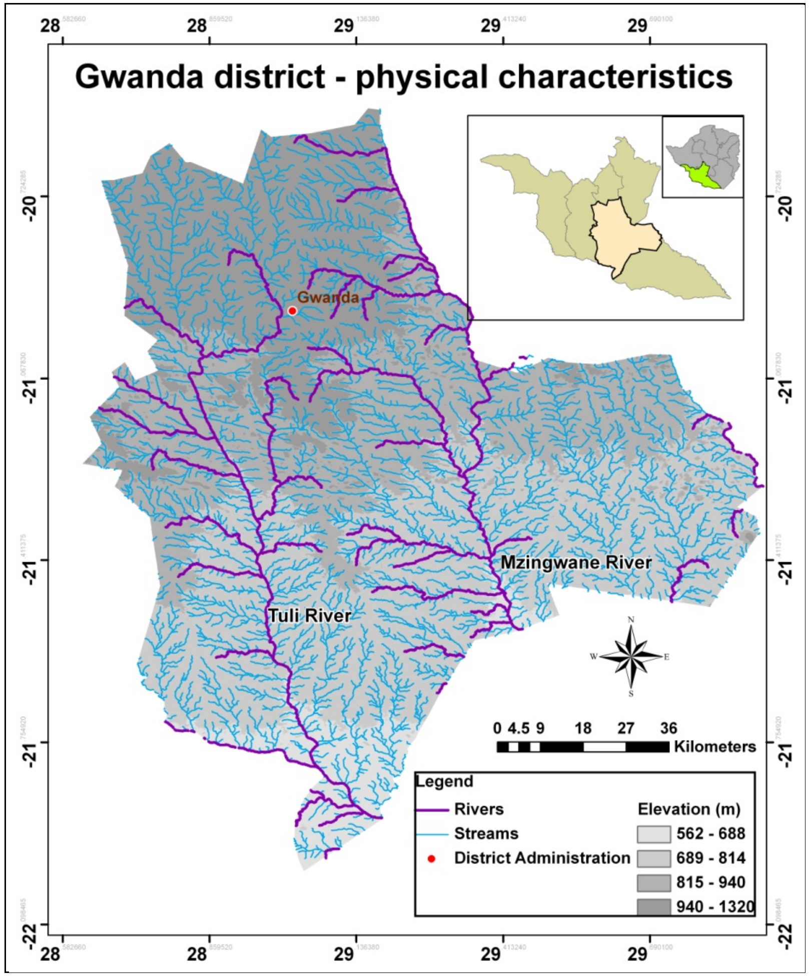


Figure 3. 2. Physical characteristics of Gwanda district

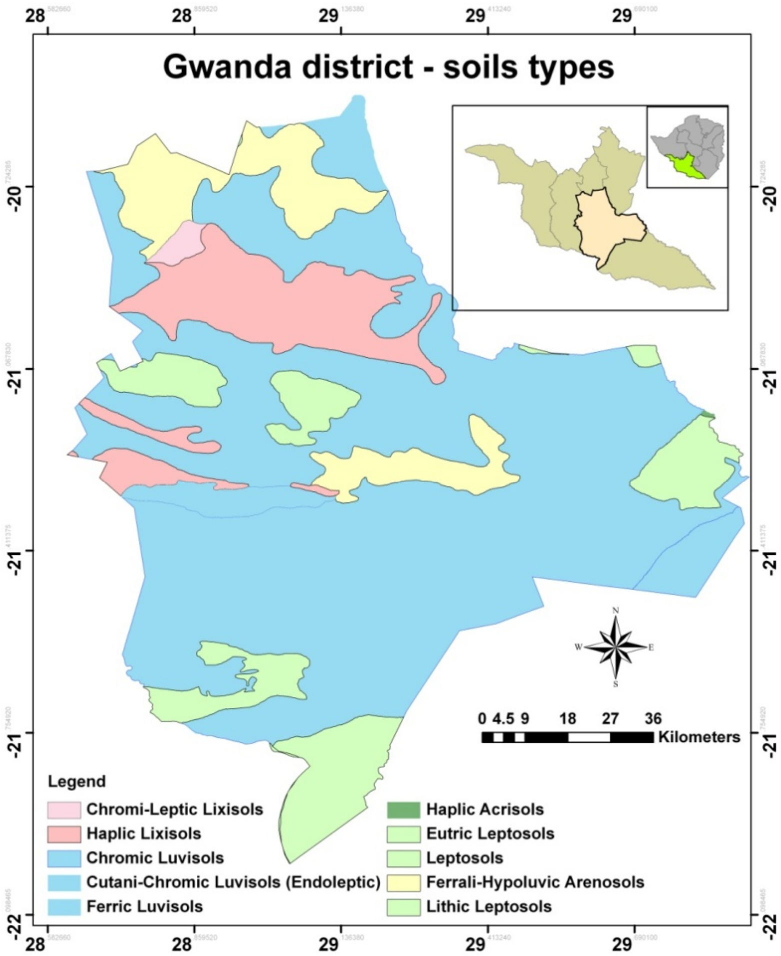


Figure 3.3. Soils types in Gwanda

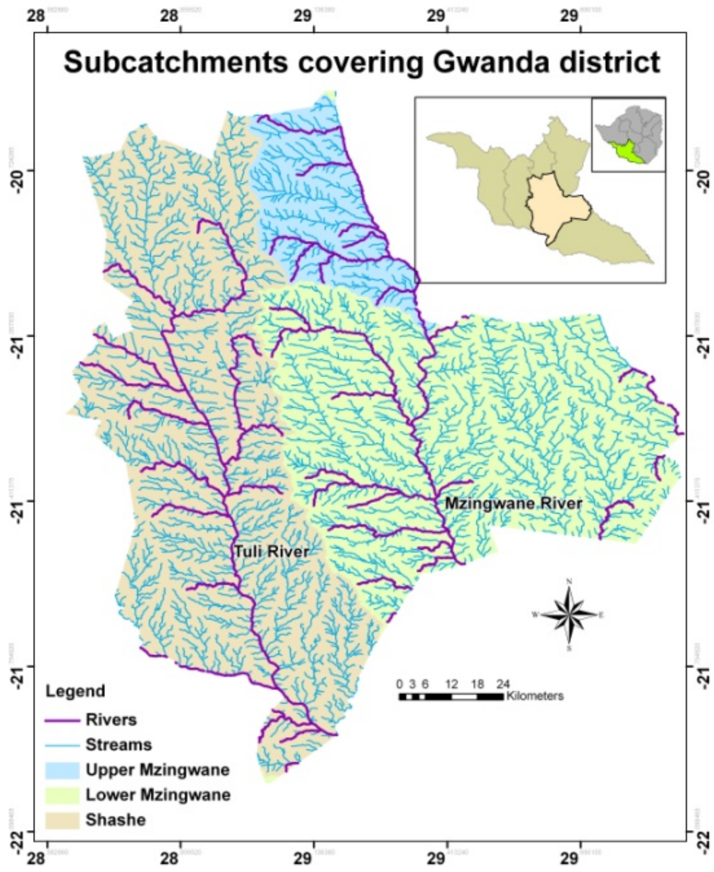


Figure 3.4. Subcatchments covering Gwanda district

3.1.2. Socio-economic characteristics

The human population in Gwanda district was estimated to be 133,167 (CSO, 2002), and estimated to 150,000 in 2010 (UN, 2010) . The settlements are spread far much apart from each other. The main source of income is cattle production, generally practised for subsistence. There is some privately-owned large scale commercial farming in the southern part of the district. The general population is relatively poor (PlanAfric, 2000). The rural population is characterised by an illiteracy level of around 18% and a Human Development Index (HDI) of 0.60 (FAO, accessed 1st June 2011). There is also high rate of unemployment in the district (UN, 2010).

3.1.3. Water related institutions

There are several institutions involved in water resources management in Gwanda district. These can be grouped in three categories; Non-governmental organisations (NGOs), local authority, and catchment and subcatchment councils. The local NGOs – namely the Lutheran Development Services (LDS), Dabane Trust, World Vision, and Telamanzi – are involved in the development of small reservoirs for communities, and in some cases their rehabilitation.

The institutions that are dedicated to water management include ZINWA, Mzingwane Catchment council and its three subcatchment councils, namely Shashe, Upper and Lower Mzingwane (Figure 3.4). ZINWA is not much concerned with the management of small reservoirs but with the management of medium to large reservoirs for commercial purposes. It, however, provides technical assistance to the other institutions of the same area.

The Gwanda Rural District Council (RDC), among other things, coordinates water development in the communal areas. The Water Division of the District Development Fund (DDF) drills boreholes and also provides training in the operation and maintenance of the same. The Department of Agricultural Technical and Extension service (AGRITEX) provides agricultural extension.

3.2. Data collection and processing

Several sources of data were used in this study: topographic maps, digital elevation models, satellite images and ground, livestock and human populations' data.

Maps and Elevation Models

Topographic maps and shapefiles for Administrative areas, major rivers names of Zimbabwe were acquired from the Surveyor General of Zimbabwe and the Department of Geography, at the University of Zimbabwe. These data were necessary to extract the boundaries of the district, its wards boundaries and some rivers' names where available. The area boundaries were then used to get other data by using overlay operations on the online mapping resources. Soils map of the scale 1:25000000, classified in the World Reference Base (WRB) format and published in January 2003, were acquired from the FAO website: http://www.fao.org/ag/agl/agll/wrb /soilres.stm#down. Digital Elevation models were downloaded from the ASTER website of Japan: http://www.gdem.aster.ersdac.or.jp/outline.jsp and used for extracting streams and delineating catchments.

Satellite images

There is a variety of satellites for Earth observation. These can be grouped into (Lillesand *et al.*, 2004):

- Landsat Satellite Program: have comprised seven missions (Landsat-1 to -7) and have used five types of sensors (Return Beam Vidicon- RBV – which is 80 and 30 meters of spatial resolution, Multispectral Scanner – MSS - which is 79 or 82 and 240 meters of spatial resolution, Thematic Mapper – TM - which is 30 and 120 meters of spatial resolution, Enhanced Thematic Mapper –ETM – which is 15, 30 or 120 meters of spatial resolution, and Enhanced Thematic Mapper Plus – ETM+ - which is 15 and 30 or 60 which is meters of spatial resolution). The Landsat -1 and -2 have seven bands, grouped into 3 RBV bands and 3 MSS bands. The Landsat -3 and -4 have a spatial resolution of 80 meters, 3 RBV bands and 3 MSS bands.

- SPOT Satellite Program,
- Indian remote Sensing (IRS),
- Advanced Earth Observing Satellite (ADEOS),
- Advanced Visible and Near Infrared Radiometer (AVNIR),
- Ocean Color and Temperature Sensor (OCTS), Advanced Land Imager (ALI)
- High Resolution Systems: IKONOS (1 and 4 meters of spatial resolution), EROS-A/QuickBird (1.8, 0.61 and 2.40 meters of spatial resolution), Orb-View-3 (1 and 4 meters of spatial resolution), EROS-B1 (0.82 and 3.48 meters of spatial resolution),

Hyperspectral Satellite Systems: Hyperion instrument (EO-1; 70 spectral bands, 30 meters of spatial resolution), Naval EarthMap Observer (NEMO, 200 spectral bands, 30 or 60 meters of spatial resolution).

To classify the land cover in Gwanda district, satellite images from Landsat TM 4-5 sensor were chosen for their free availability, multiple spectral bands (that is good for various features properties analysis), acceptable quality (i.e. with no stripes) and spatial resolution of 30m – for its bands 1, 2, 3, 4, 5 used in this study – that is an acceptable minimum size to identify small reservoirs. Using the district shapefile, the satellite images were downloaded from the USGS website http://glovis.usgs.gov.

In order to select the satellite images that were suitable for the study, the following criteria were used:

- images that cover the geographic location of Gwanda district and were preferably cloud-free;
- the most recent period of satellite acquisition in order to identify small reservoirs, including the most recently developed ones; and

- two sets of images of the same year that could be respectively representative of the rainy period and dry seasons in order to be able to characterize their capacities regarding the two seasons.

For this study, satellite images of February-March 2009 were downloaded in order to characterise the end of the rainy season. There was, however, a challenge finding recent images of around September that could be used to determine dry season capacity effectively. The best alternatives were images of around May 2009. In the appendices are found more details on these images metadata and the coverage of the district (Appendices A.1 and A.2).

Ground data

Ground validation of measurements were carried out to measure and validate physico-chemical parameters that were determined based on remotely sensed images and GIS. Small reservoirs depths were also measured for a sample of small reservoirs in order to estimate capacities. Small reservoirs inventory of 2006 from the DDF were also used for comparison purposes or completing the names of small reservoirs for which grid references matched spatial coordinates of the identified small reservoirs through this study. Dams design capacities and grid references obtained from ZINWA database were obtained for the three subcatchments that cover the district and beyond. Human and livestock data were respectively acquired from the Rural District council and the Veterinary Department of Gwanda in order to characterise the use of small reservoirs. Uses of some small reservoirs were acquired from LDS.

Data processing and software

The obtained data were processed using various types of software. ILWIS 3.0 (Integrated Land and Water Information System, version 3.0) was used to process the satellite images, run the features classification, extract river systems and delineate catchments. Microsoft Excel 2007 was used in some more complex mathematical and statistical analyses of the data. Microsoft Access 2007 was used to connect the tables following the normalised schema logically designed before converting them into Structured Query Language (SQL) data format. This format, which was handled in PostgreSQL (a free software for database management), was chosen because of its widespread enabling the interoperability of data and applications without being constrained to a certain commercial standard that is the weakness of Microsoft Access. The data handled in PostgreSQL was then used to build a Decision Support System in a web interface under Java technology using the free software Wavemaker 6.0

3.3. Methodological approach

3.3.1. Overview of the approach

The methodological approach used in the study, illustrated by the Figure 3.5, consisted of:

1) classifying remotely-sensed images in different features and validating them on the ground in order to extract information about water bodies,

2) identifying and characterising small reservoirs by estimating the wet and dry season capacity, turbidity and chlorophyll-a indices from satellite images and validating with ground measurements where possible,

3) integrating the derived information with documented data of published maps as well as data from local institutions involved in small reservoirs use and management in a database, and

4) designing a decision support system that facilitates analysis, handling, updating, and editing of acquired data.

The first step was carried out from January to February and partly in April 2011, the second was carried out partly in February and April, the third step was carried out between March and April while the fourth was carried out from April to May 2011.

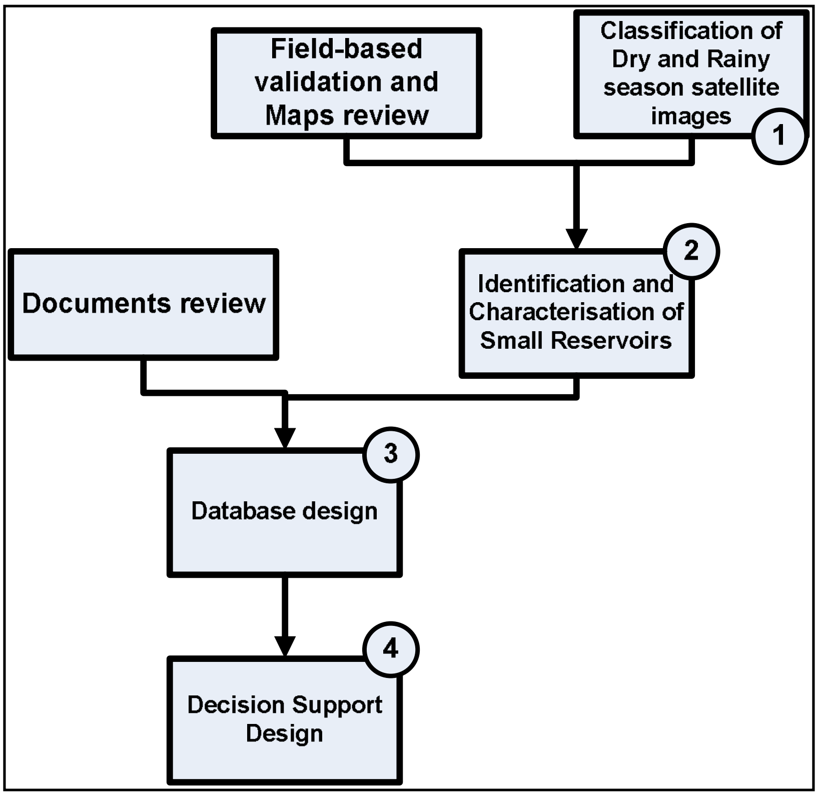


Figure 3.5. Methodological approach to the Study

3.3.2. Satellite images classification

In order to obtain individual bands fully covering the district per defined period, the satellite images tiles were merged per spectaral band and per period, geocoded to the georeference of the district – created using its boundaries coordinates – using the nearest neighbour resampling method. A supervised classification was then run based on pseudo-natural colour composite (bands 5, 4, 3 for channels Red, Green, Blue) with a 2% histogram stretching for visualisation enhancement and using the minimum distance to mean algorithm. Six classes of features were sampled based on their specific spectral reflectances that could be distinctly separated on the pseudo-natural colour composite (Figures 3.6 and 3.7). These were clear or deep water, shallow or turbid water, forests and shrubs, healthy vegetation, white soil/sand, brown soil/clay. Ground validation was then carried out to validate the classification by using the coordinates of the water bodies classified and picking the coordinates of other features around the water bodies visited.

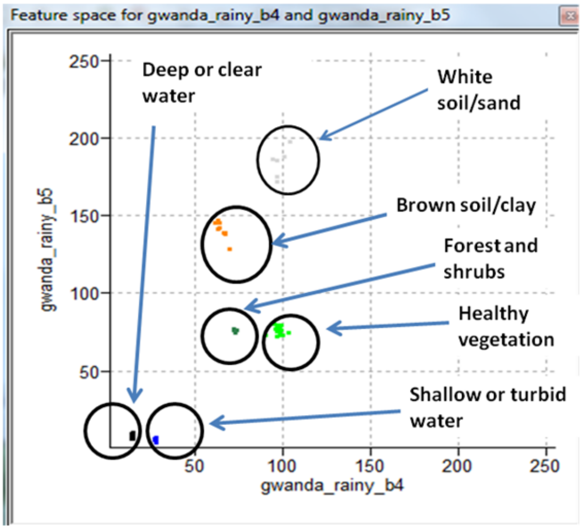


Figure 3.6. Features separation based on Landsat TM 4-5 bands 4 and 5

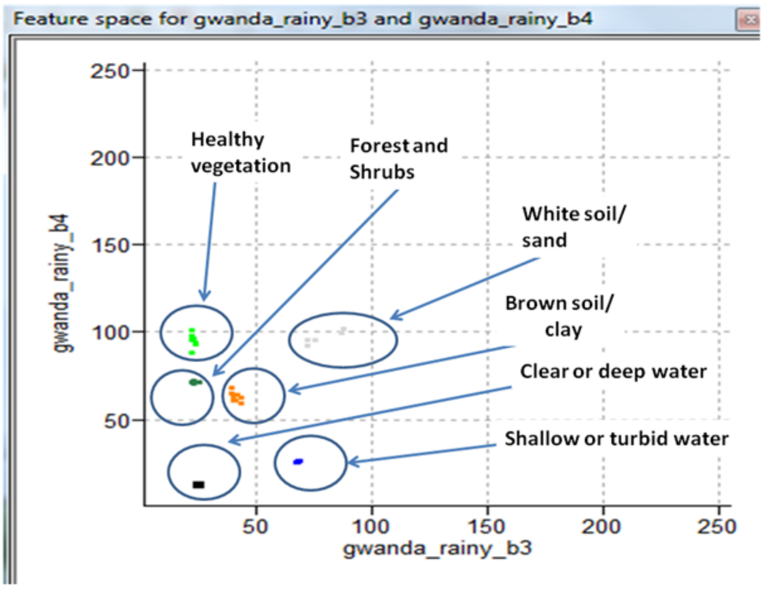


Figure 3.7. Features separation based on Landsat TM 4-5 bands 4 and 3

3.3.3. Small reservoirs identification and characterisation

Identification and Location

From the six classes in the classified images, the two classes of water (clear or deep water, shallow or turbid water) were merged into one class of "water bodies". The capacity-area relationship developed by Sawunyama *et al.* (2006) for which the R^2 was 95% was used to determine the size limit in terms of surface area between small and larger reservoirs as defined (in volume terms) in Zimbabwe (Kabell, 1986; Zimbabwe, 1998a). The reservoirs polygons were formed based on the contiguity of pixels using an automated 8-pixel connection method (that connects in horizontal, vertical, and diagonal pixels) and assigning such connected pixels a unique identifier. To that unique identifier was associated the location coordinates of the point at the center of the polygon. The surface areas were calculated based on the pixels numbers that formed each polygon and the pixel size of the images used that was 30m. To eliminate residual waters, a threshold of 2 pixels was set to classify negligible water bodies and a masking raster map was created for residual waters that could exceed 2 pixels in main channels of large rivers, namely Tuli and Mzingwane rivers (Appendix A.3)

Physico-chemical assessment

In order to characterize the physico-chemical parameters, the extracted small reservoirs surface areas were used to extract the areas having the same coordinates from Landsat TM 4-5 bands 1, 2, 3, 4. Turbidity (the measure of light scattering in water due to suspended matter) and chlorophyll-a (substance responsible for the pigment of algal plants, which gives a good indication of algal biomass in water) were chosen to characterise the small reservoirs status. The rationale behind this choice was that these two parameters have optical measurements that make them usable in remote sensing in the form of indices, and indicate well the status of the catchment of the reservoir in relation to soil erosion and nutrients loads. However, since the turbidity may indicate the bottom reflectance of a shallow reservoir (Bustamante *et al.*, 2009), it was necessary to determine a critical turbidity index. Scheffer *et al.* (2001) observed that the actual turbidity of a reservoir increases in the same way the actual chlorophyll-a concentration increases. However, the turbidity becomes critical when it starts increasing without increase in vegetation due to light obstruction, reduced oxygen concentration, and relatively increased temperature. The turbidity (independent parameter) and chlorophyll-a (dependant parameter) indices used in this study were developed and validated by Frohn and Autrey (2009) and further use of the approach was done by Bee (2009a; 2009b) using multiple Landsat bands ratios, based on the following considerations:

- Blue light is scattered by water molecules (the reason why water appears blue),
- pure water bodies absorbs, with negligible scattering, the majority of radiations,
- as the water becomes more turbid and the amount of sediments in the water increases, the peak reflectance is shifted toward the longer wavelengths in the visible spectrum (green and red energy),
- algal biomass strongly absorbs in the red and reflects in the green (due to the chlorophyll) and near infra-red (due to cell wall reflectance)

Turbidity and chlorophyll-a indices were then characterized as conversely evolving parameters (if one of the indices increases, the other one should decrease) as follows:

Turbidity Index = (Green Reflectance + Red Reflectance)/(Blue Reflectance) (*Equation 1*)

Chlorophyll-a Index = (Green Reflectance + Near-IR Reflectance)/(Red Reflectance) (*Equation 2*)

Or in terms of Landsat TM bands:

Landsat Turbidity Index = (Band2 + Band3)/ (Band1) *(Equation 3)*

Landsat Chlorophyll-a Index = (Band 2 + Band 4)/(Band 3) *(Equation 4)*

Frohn and Autrey (2009) found a correlation between the turbidity index and the actual turbidity to be 0.879, which was said to be good enough to state with certainty that the index reflects the same parameter as actual values measured.

Since these computations are done per pixel, an average of the obtained values for all the pixels of a reservoir was calculated in the case of small reservoirs in Gwanda district. The critical turbidity index was then determined statistically by finding in the distribution of turbidity indices the point where the relationship between turbidity index and chlorophyll-a index changes its trend. All the small reservoirs above the critical turbidity were thus categorised as turbid, from which two classes (highly turbid and moderately turbid) were derived based on the absolute error. All the reservoirs with lower values were classified as "clear or less turbid". Similarly, considering that chlorophyll-a index is a dependant variable of turbidity index, statistically finding the critical chlorophyll-a index that indicates a change in relationship when chlorophyll-a increases was an indicator that the remotely sensed feature is predominantly vegetation than water. Such features were then validated using higher resolution images visualisation of Google Earth and ground truthed for some of them, and eliminated from the captured features of clear or deep waters. After elimination of vegetation features, a second critical index was determined similarly for the remaining water bodies. The second critical index allowed categorising the small reservoirs according to whether they were expected to manifest excessive floating vegetation or not. To appreciate the performance of determined turbidity indices, correlations were determined between the later and ground measurements of turbidity. In order to appreciate the performance of determined chlorophyll-a indices, firstly, the critical index was used as a proxy to validate the excessive vegetation development on the reservoir, secondly, field-based visual observations of vegetation development were encoded numerically (Table 3.1) and correlated to the chlorophyll-a indices.

Table 3.1. Encoding of field-based visual observation of vegetation development

Visual observation	Encoding of visual observation
no floating vegetation	1
sparse floating vegetation	2
dense floating vegetation	3

Combining the findings from the categorisation based on the two parameters (chlorophyll-a and turbidity indices), all the identified small reservoirs were grouped in four types, namely (1) “highly turbid”, (2) “moderately turbid”, (3) “clear water and no floating vegetation”, and (4) “clear water but excessive floating vegetation”.

In terms of decision-making, only the first and last types of reservoir would require immediate attention to ensure their sustainability. In fact, while the reservoirs of type (1) and (4) are respectively consequences of poor erosion control and excessive nutrients loads (generally leaching fertilisers from the catchment), the reservoirs of type (2) represent an ordinary status that includes the bottom soil reflectance of shallow ones, and the reservoirs of type (3) represent the best status.

Small reservoirs and livelihoods

To characterise the importance of small reservoirs to livelihoods in this study, a comparison was made between human population distribution and small reservoirs capacity distribution per ward using the Pearson correlation test, which is a statistically recommended test to find relationship between two sets of variables. Similar comparison was done between livestock population distribution per ward and capacity distribution per ward. The direct relationship between the compared variables was deduced from the strength of the Pearson correlation value.

Capacities estimations

To estimate the small reservoirs capacities, the capacity-area relationship, developed by Sawunyama *et al.* (2006) on 12 small reservoirs in Insiza district and recommended for Mzingwane catchment, was applied using the remotely sensed surface areas for small reservoirs in the wet period and dry period:

$$\mathbf{C_1=0.023*A^{1.33} \quad (R^2 = 0.95)} \quad \textit{(Equation 5)}$$

(Where C_1 = estimated capacity and A = remotely sensed surface area).

To validate the above formula for Gwanda district, a parallel approach, which considers a small reservoir like a pyramid and does not underestimate capacities (Sawunyama, 2005), was used based on remotely sensed surface areas and field measurements of reservoirs highest depths as illustrated in Figure 3.8. An average depth measured in the field from reservoirs was used and the capacity was estimated using the volume formula for a pyramid:

$$\mathbf{C_2 = (A * D)/3} \qquad \textit{(Equation 6)}$$

(where C_2 = estimated capacity, A = remotely sensed area of the small reservoir; D = average depth of the small reservoirs).

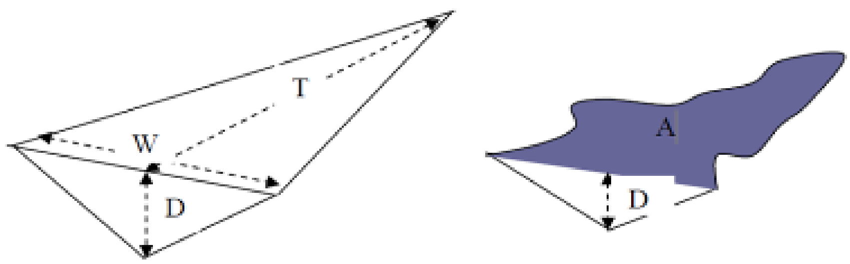


Figure 3. 8. Pyramidal model for reservoir's capacity estimation (Sawunyama, 2005)

To chose between the two approaches, a statistical comparison of closeness of figures obtained to the design capacities values in local institutions records by the two approaches was applied for small reservoirs that had design capacities in reviewed documents, by using the relative volume difference (RVD) in percentage and the standard error (σest.):

$$\mathbf{RVD = 100 * [\Sigma (C_{estimated} - C_{reference}) / \Sigma C_{refernce}]} \qquad \textit{(Equation 7)}$$

$$\mathbf{\sigma est. = sqrt \{ \Sigma [(C_{estimated} - C_{reference})^2]/(N-2)\}} \qquad \textit{(Equation 8)}$$

Where $C_{estimated}$ is the estimated capacity and $C_{reference}$ is the Capacity of reference that is documented for the selected small reservoir. Since the wet period images were used, it was expected that the better approach is the one which provides figures closer to the capacities of reference (value of RVD or σ_{est}.closer to 0).

Moreover, a comparison between surface areas changes of all the identified small reservoirs from the two sets of satellite images (wet season and dry season) was done to characterize the small reservoirs that dry before next rains. By correlation, a trend and a threshold were determined in this study to characterize the small reservoirs that could or not reach the next rainy season.

3.3.4. Database design

From the small reservoirs identification and characterisation as previously described, the attributes of each reservoir to which an ID was allocated (location, estimated capacity, water quality parameters, and drying trends), were extracted in specific tables (entities) for the database design. Documents reviews of human and livestock data, documents review of local water institutions for reservoirs names, uses, spatial analysis of maps for streams names and subcatchments associations, and data collected via interviews to informants on uses, committee existence and specific role in small reservoir management were carried out. All the data generated was integrated in a database.

The database was designed in respect to the established rules, starting by the database requirements analysis, the conceptual data modelling, the setting of functional dependencies (relationships), and, finally, the normalization of the entities and relationships (Harrington, 2002; Ramakrishnan and Gehrke, 2003; Teorey *et al.*, 2006). Figure 3.9 shows the final structure of the database after the whole process of its design (see Appendix A.4 for the related metadata).

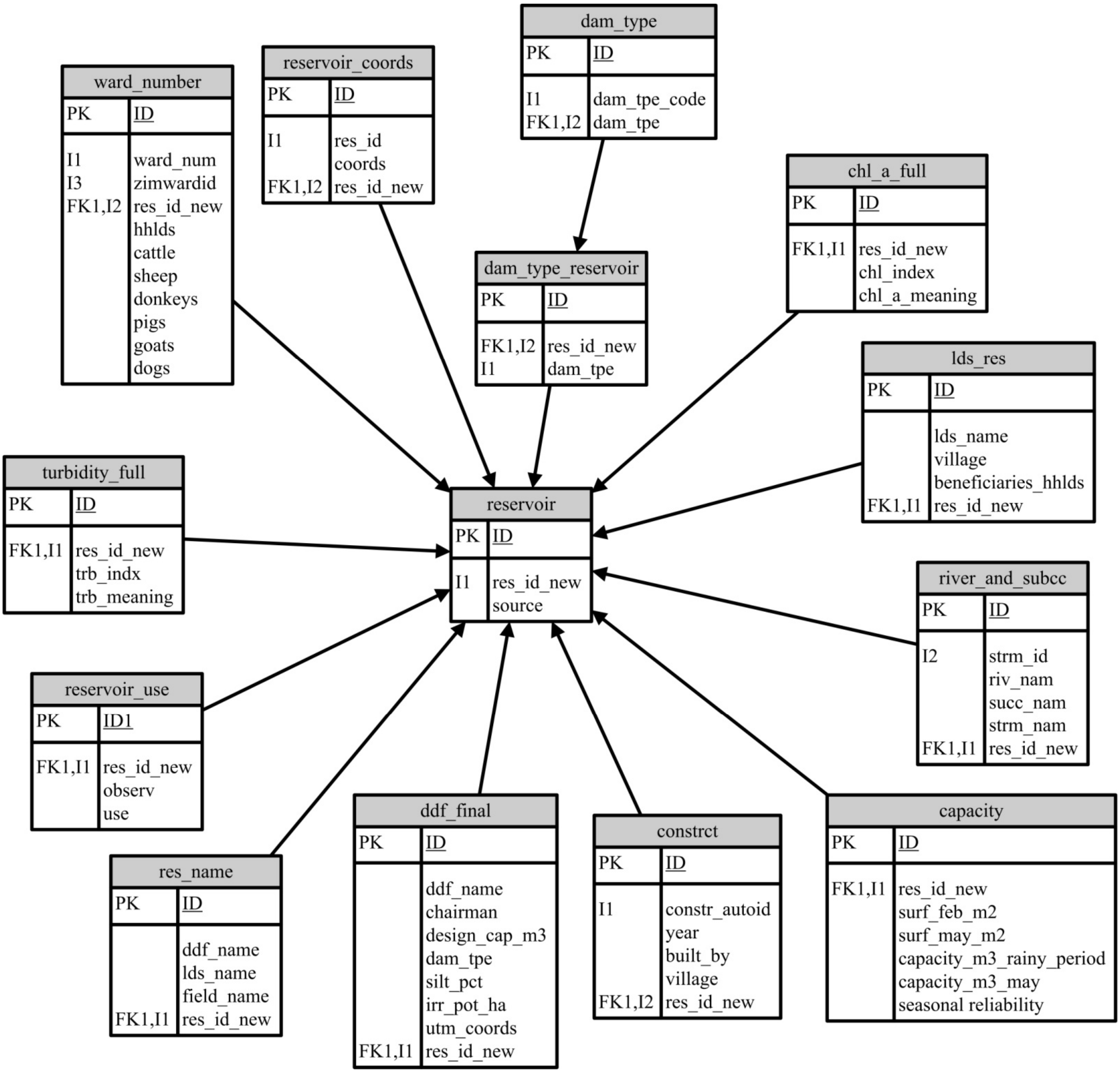


Figure 3.9. Structure of the designed database

Requirements analysis

Requirements analysis concerns establishing what individuals that are part of the system need to do with the database (Harrington, 2002). The guiding consideration in the design of the database was the lack of or disparate information that affects effective management of small reservoirs. The database thus needed to provide small reservoir data in terms of location coordinates, capacity (for both dry and wet period), associated river and subcatchment, ward in which it is found, its status in terms of turbidity and chlorophyll-a. The turbidity was categorised to indicate, in case it is high, that erosion control measures are required upstream. Similarly, the chlorophyll-a was categorised to indicate that nutrients loads in the catchment require appropriate management. The designed database had to provide such information for each small reservoir. Additionally, the database had to give, for some of the small reservoirs, data like its name, associated stream name, use, beneficiary, history (construction period); and of course the opportunity to update the data. All these groups of data were developed in tables and constituted the entities of the database (Figure 3.9).

Conceptual data modelling

The conceptual data modelling, which consists of representing how the data entities are represented in the real world (Teorey *et al.*, 2006), was based on the database requirements stated above. The conceptual data modelling was completed through the enterprise rules, which specified how the data entities were related in the real world. These relationships were either multiple, single, or mixed, and constituted the “enterprise rules” for the small reservoirs database.

Enterprise rules

The enterprise rules for small reservoirs database were established on the basis of stating how many elements of a given entity were related to how many elements of another entity of the database and whether such relationships were obligatory or not. The enterprise rules were established according to the database design principles (Harrington, 2002; Teorey *et al.*, 2006) that consider the way entities are naturally related in reality. To avoid duplication of data records and improve the general efficiency of the database, the entities and relationships were normalised.

Normalisation of entities and relationships

The normalisations of entities and relationships was about removing redundancy and improving its consistency as well as the efficiency of the database in information retrieval and manipulation following the established guidelines (Ramakrishnan and Gehrke, 2003). After the normalisation process, the database was implemented physically.

Physical design and Implementation

The physical design of the small reservoirs database is about establishing how the database can be accessed and manipulated (Teorey *et al.*, 2006). For the small reservoirs database, it was established to lock some of the entities – like reservoir location coordinates, associated ward or subcatchment – from being edited by the user in order to preserve the integrity of the data. The database was implemented in Microsoft Access. However, considering the need of interoperability, its SQL version was derived. This SQL version of the small reservoirs database was implemented in PostgreSQL, which is a free database management system that served as the basis of building the Decision Support System.

3.3.5. Decision Support System (DSS) design

There are five main aspects considered in the design of the DSS: the requirements analysis, the data store component, the data filtering tool, the end-user query tool, and the end-user presentation tool (Yeung and Hall, 2007).

Requirements analysis

The requirements of the small reservoirs Decision Support System was determined as easy to manipulate, to update and delete information, to retrieve information. While it is not set to replace the decision maker (Tian *et al.*, 2007), it was designed to be a user friendly system that could facilitate decentralised institutions involved in small reservoirs management to take informed decisions. For that, it had to filter the way its information could be presented.

Data store component

The data store component of the DSS is constituted of all the data from the small reservoirs database. However, to improve the efficiency of information retrieval, the entities and relationships were "denormalised" (Teorey *et al.*, 2006), an operation which is reverse to normalisation and results in data stored in one table.

Data filtering tool

The small reservoirs DSS, named GDSS-SR v.1.0, was designed to present information in thematic views. These views were set in terms of reservoir location (coordinates system, ward), river system and subcatchemt, status (turbidity class and chlorophyll-a class, with an explanation on what meaning these classes provide), capacity (for both dry and rainy period, and the ability to reach the next rains).

End-user query tool

The end-user query tool was designed as a textual search system inside the specified filtered views pre-established by the data filtering tool. The retrieved information was also designed to be editable, unless part of the physically enforced data like location or ward, and updatable. Then the retrieved information is displayed.

End-user presentation

The presentation to the end-user was designed in a web interface, for its interoperability despite the operating system of the user and its facility of manipulation from the user point of view since it only requires him to know how to type in keywords and to use a computer mouse.

4. RESULTS AND DISCUSSION

4.1. Classification of land cover

4.1.1. Selected images for classification

The characteristics of the four tiles of satellite images for both sets that were necessary to classify land cover in the district are presented in Table 4.1.

Table 4.1. Coverage of the district by selected Landsat TM 4-5 images

Percentage of Gwanda area covered		First set			Second set			Days difference
		Satellite acquisition date	Percentage of clouds	Sun elevation	Satellite acquisition date	Percentage of clouds	Sun elevation	
Tile 1	6.45	2009-03-23	0.03	49.7	2009-04-24	0	43.8	32
Tile 2	93.38	2009-03-23	0.04	48.8	2009-05-26	0	36.7	64
Tile 3	0.12	2010-02-13	0	54.8	2010-05-04	0.03	41.2	80
Tile 4	0.05	2010-02-13	0	55.1	2010-05-04	0	42.4	80
Total	100							

Table 4.1 shows that:

the images had very little to no clouds coverage,
all the district area was covered by recent images and Tile 2 covered the largest portion (around 93%) of the district (see Appendix A.1 for overlay representation of the district on the tiles and Appendix A.2 for the tiles specific metadata),
sun elevations were generally low and particularly lower in the second set of images than in the first set.

This means that:

the selected images met the acceptable coverage criteria for the identification of small reservoirs;
the Tile 2 was the most determinant in the classification of land cover, and
an increase in shadowed areas was expected from the period of the first set to the period of the second set of images due to acute topographic variation and lowered sun elevations. The effect of low sun elevation and acute topography that creates shadows and biases the classification of features of low reflectance such as water was illustrated by earlier studies (Piacentini, 1983; Srestha and Zinck, 2001).

4.1.2. Classification of land cover for the first and second set of images

With an overall accuracy of 93.44 % for the first set of images and an overall accuracy of 91.58 % for the second, the confusion matrices (Appendices B.1 and B.2) suggest a good confidence level in the obtained classification.

The classification of satellite images in the six classes identified is presented in Table 4.2 for both wet and dry period.

Table 4.2. Classification of land cover for wet and dry periods

<table>
<tr><th colspan="2" rowspan="2">Feature Class</th><th colspan="2">First set of images</th><th colspan="2">Second set of images</th></tr>
<tr><th>Surface area percentage</th><th>grouped percentage</th><th>Surface area percentage</th><th>grouped percentage</th></tr>
<tr><td>1</td><td>forests and shrubs</td><td>77.86</td><td rowspan="2">79.55 vegetation</td><td>31.68</td><td rowspan="2">31.70 vegetation</td></tr>
<tr><td>2</td><td>healthy vegetation</td><td>1.69</td><td>0.02</td></tr>
<tr><td>3</td><td>white soil/sand</td><td>18.77</td><td rowspan="2">19.94 bare soil</td><td>6.19</td><td rowspan="2">67.77 bare soil</td></tr>
<tr><td>4</td><td>brown soil/clay</td><td>1.17</td><td>61.58</td></tr>
<tr><td>5</td><td>clear or deep water</td><td>0.31</td><td rowspan="2">0.43 water</td><td>0.45</td><td rowspan="2">0.51 water</td></tr>
<tr><td>6</td><td>shallow or turbid water</td><td>0.12</td><td>0.06</td></tr>
<tr><td></td><td>undefined areas</td><td>0.08</td><td>0.08 undefined</td><td>0.02</td><td>0.02 undefined</td></tr>
<tr><td></td><td>total</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
</table>

Table 4.2 shows that there was a change in major features between the respective periods of two sets. This was characterised by:

- a reduction in vegetation from around 80% in February-March to around 32% in May 2009.
- an increase in bare soil from around 20% in February-March to around 68% in May 2009.

While there was a 50% decrease in the class “shallow or turbid water”, the increase in the grouped percentage of “water” was not conclusive because it was due to “clear or deep water” class that reflects as black as shadows which were expected to increase because of lowered sun elevations as discussed above (heading 4.1.1).

Therefore, as far as the land cover change is concerned, the first and second sets of images can be considered representing respectively the wet and the dry period.

4.2. Small reservoirs identification and characterisation

4.2.1. Preliminary number of small reservoirs

Using the classes specified above, the number of identified reservoirs in Gwanda district was obtained and their respective sizes (Table 4.3).

Table 4.3. Sizes categories of identified reservoirs in the district

Category of reservoir	Criteria	Number of reservoirs in category
Medium to large reservoirs	More than 614 pixels	7
Small reservoirs	More than 2 and at most 614 pixels	473
Negligible reservoirs	1 or 2 pixels	359
Total		839

The categories shown in Table 4.3 were confirmed by the number of medium to large dams owned by ZINWA in Gwanda district that are exactly seven. However, as negligible, some very small reservoirs might have been filtered.

The 473 identified small reservoirs in Table 4.3 still contain confusion of "clear or deep water" with shadows due to low sun elevation and topography variation. This was filtered using physico-chemical parameters of small reservoirs.

4.2.2. Physico-chemical characterisation

Two types of analyses were undertaken to characterise the small reservoirs; firstly, the *determination* of the phycico-chemical parameters, then their *validation*.

Determination of physico-chemical characteristics

For the identified 473 small reservoirs, their turbidity indices (which are averages of their constituting pixels) are summarised in terms of frequencies as shown in Figure 4.1 while Figure 4.2 shows their chlorophyll-a indices distribution.

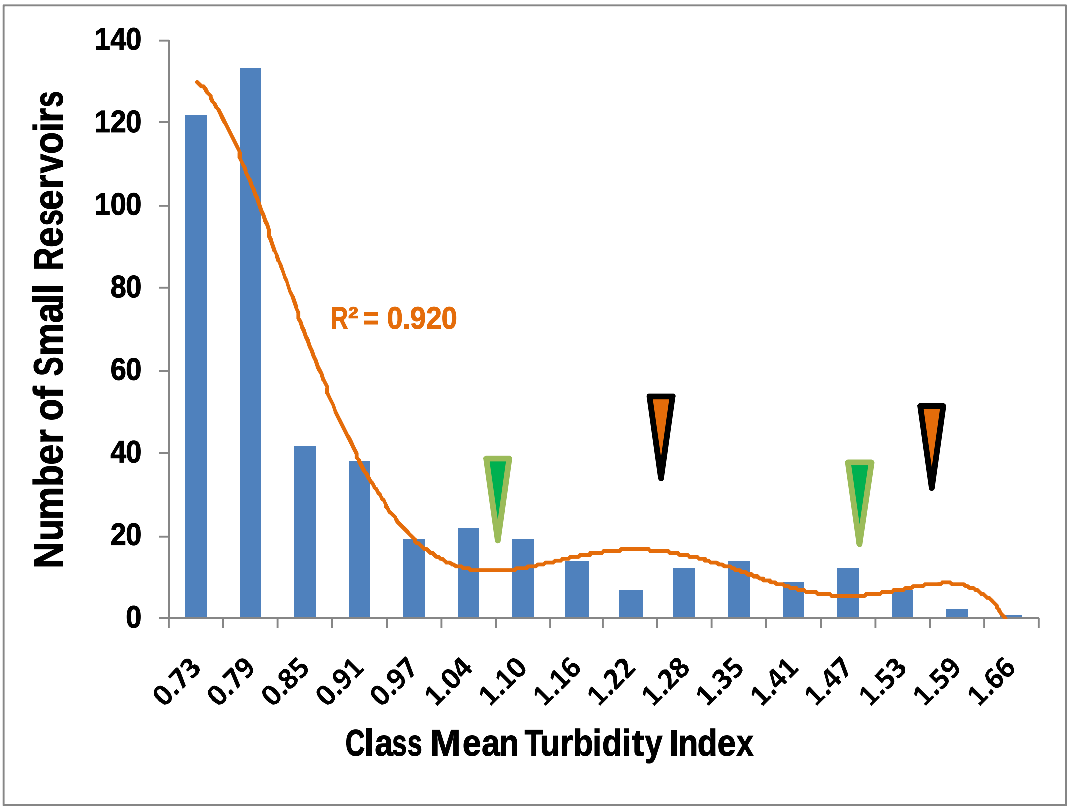


Figure 4.1. Frequency of turbidity indices

Figure 4.1 shows that the turbidity indices of the small reservoirs are very much skewed to the right, the median being 0.795, and there is a lot of variability of the turbidity index. The trend of the distribution can be subdivided into three narrow distributions separated by their minima, indicated by the green triangles on the best-fitting trendline curve. The red triangles indicate the maxima of these distributions and thus the points where the characteristics within the distribution start changing.

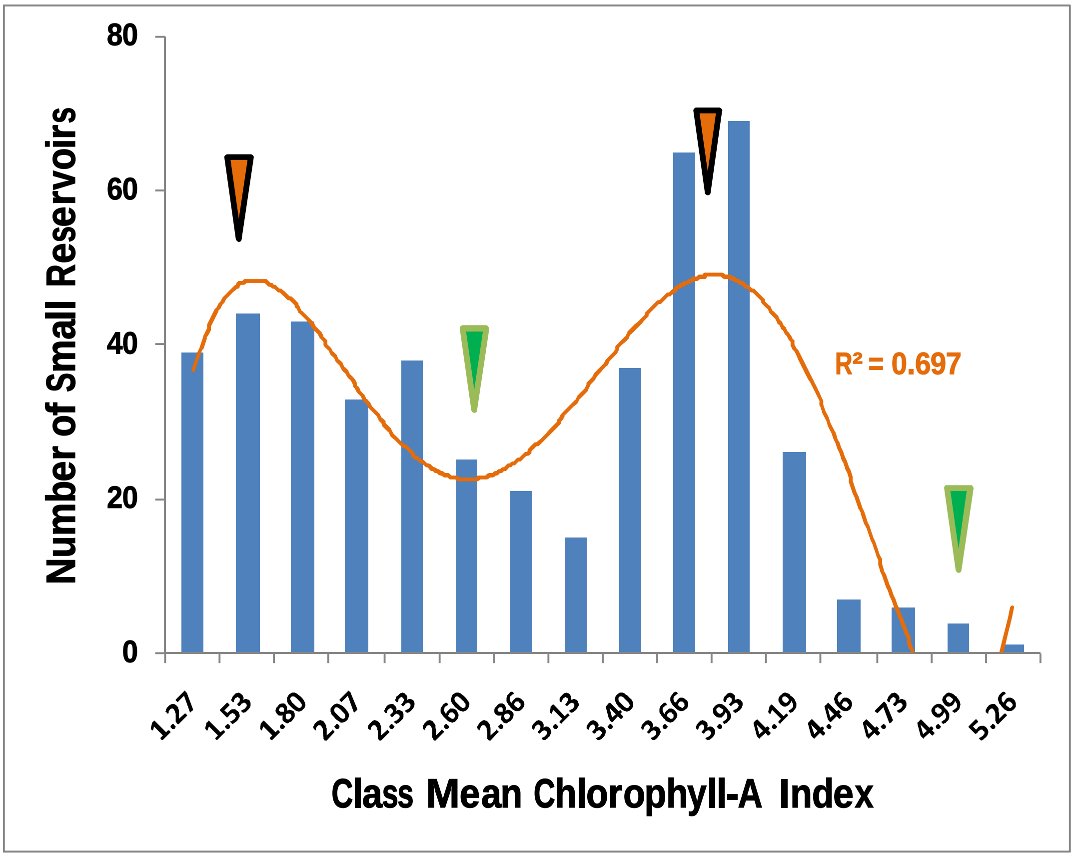


Figure 4.2. Frequency of chlorophyll-a indices

Figure 4.2 shows that the small reservoirs have variable chlorophyll-a indices. With the median being 2.91, the small reservoirs could be categorised in two main distributions separated by their minima indicated by the green triangles. The red triangles indicate the distributions maxima, meaning the points where the characteristics within the distributions start changing.

Altogether, Figures 4.1 and 4.2 show that the small reservoirs can be categorised in three main classes of turbidity indices and two main classes of chlorophyll-a indices. To characterise the classes separation succinctly, Scheffer *et al.* (2001) demonstrated that the critical turbidity can be determined when turbidity starts increasing without increase in chlorophyll-a, and the critical chlorophyll-a represents when the vegetation starts to increase without increase in turbidity. In other words, finding the critical indices of the two parameters is achieved by finding the point where their relationships change the trend.

Figure 4.3 shows the relationship between turbidity and chlorophyll-a indices for the 473 small reservoirs. This was used to find the critical turbidity.

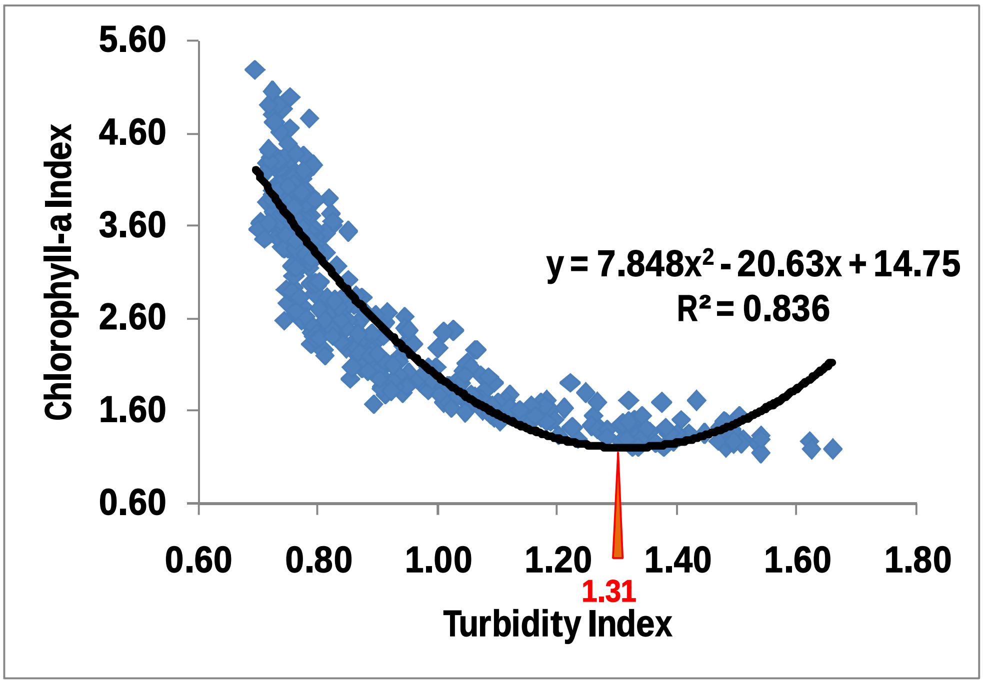


Figure 4.3. Determination of the critical turbidity index

Figure 4.3 shows the change in relationship between turbidity index and chlorophyll-a index in a second degree trendline equation. The Pearson correlation was -0.843, indicating an inverse relationship between the two indices. Using this equation (with its R^2=0.836), the point of change in the trend was determined by calculating the value for which the following derivative was null. In this order:

(dy/dx) = 0,

Thus: 7.848*2*x – 20.63 = 0

Consequently: **x = 1.31** was the turbidity index from which the turbidity of the reservoir had to be considered as critical. Translating the confidence margin of 83.6% into an absolute error of the actual critical turbidity index that was 1.31, it results that the critical turbidity was **1.31 (±0.215)**, which resulted in the interval **[1.095, 1.525]** and corresponds to the distribution between the two minima (green triangles) on the Figure 4.1.

From this we can deduce the following:

- any small reservoir with a turbidity index greater than or equal to 1.525 is highly turbid; this corresponds to the distribution on the right of the right green triangle of Figure 4.1 and 7 small reservoirs correspond to this criteria;
- any small reservoir with a turbidity index greater than or equal to 1.095 (left green triangle on the Figure 4.1) but lesser than 1.525 is to be considered as moderately turbid (the distribution in the middle on Figure 4.1). A total of 79 reservoirs correspond to this criteria; this category is not a critical category and includes the reservoirs for which the bottom soil reflectance was captured;
- any small reservoir with a turbidity index of less that 1.095 is considered as less turbid or clear water. However, this category includes shadows due to low sun elevations and variant topography, discussed earlier (heading 4.1), that will be filtered with the chlorophyll-a analysis .

Figure 4.4 was used to determine the critical chlorophyll-a index.

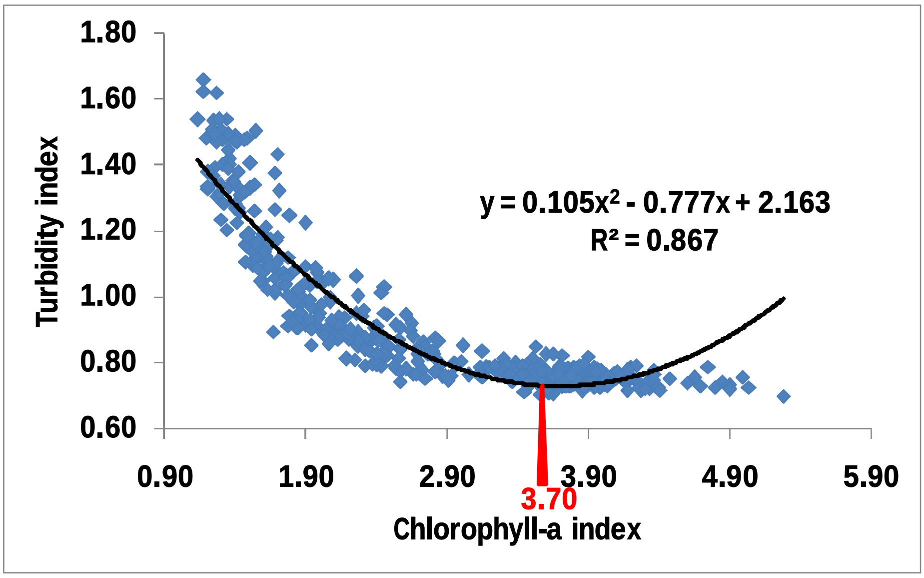


Figure 4.4. Determination of the first critical Chlorophyll-a index

From the trendline's equation (confidence level of 86.7%), the point of change in chlorophyll-a index (more of vegetation than water) is calculated as the point of inflexion of this second order equation, using derivatives:

(dy/dx) = 0,

Thus: 0.105*2*x – 0.777 = 0

Consequently: **x = 3.70** is the chlorophyll-a index from which the algal biomass concentration increases without increase in turbidity. Therefore, this represents more biomass than water. Considering the confidence margin of 86.7%, the actual critical chlorophyll-a index is **3.70** ± **0.493**, so it should be in the interval **[3.207, 4.193]** and corresponds to the distribution between the two minima (green triangles on Figure 4.2).

The following observations can be drawn:

any "small reservoir" with a chlorophyll-a index greater than or equal to 3.207 can be considered to be more of vegetation than water reservoir (a total of 217 features picked as "small reservoirs water" that are associated to shadows due to topography and low sun elevation correspond to this criteria), and

any small reservoir with a chlorophyll-a index lesser than 3.207 is a true water reservoir, containing more water than vegetation (256 reservoirs correspond to this criteria).

However, within the 256 small reservoirs, for the chlorophyll-a index lesser than 3.207, there are still two pics of distributions (Figure 4.2) on the left side of this value, indicating change in chlorophyll-a category. So, using a similar relationship between turbidity and chlorophyll-a (Figure 4.5), the second critical chlorophyll-a index was determined for the 256 small reservoirs.

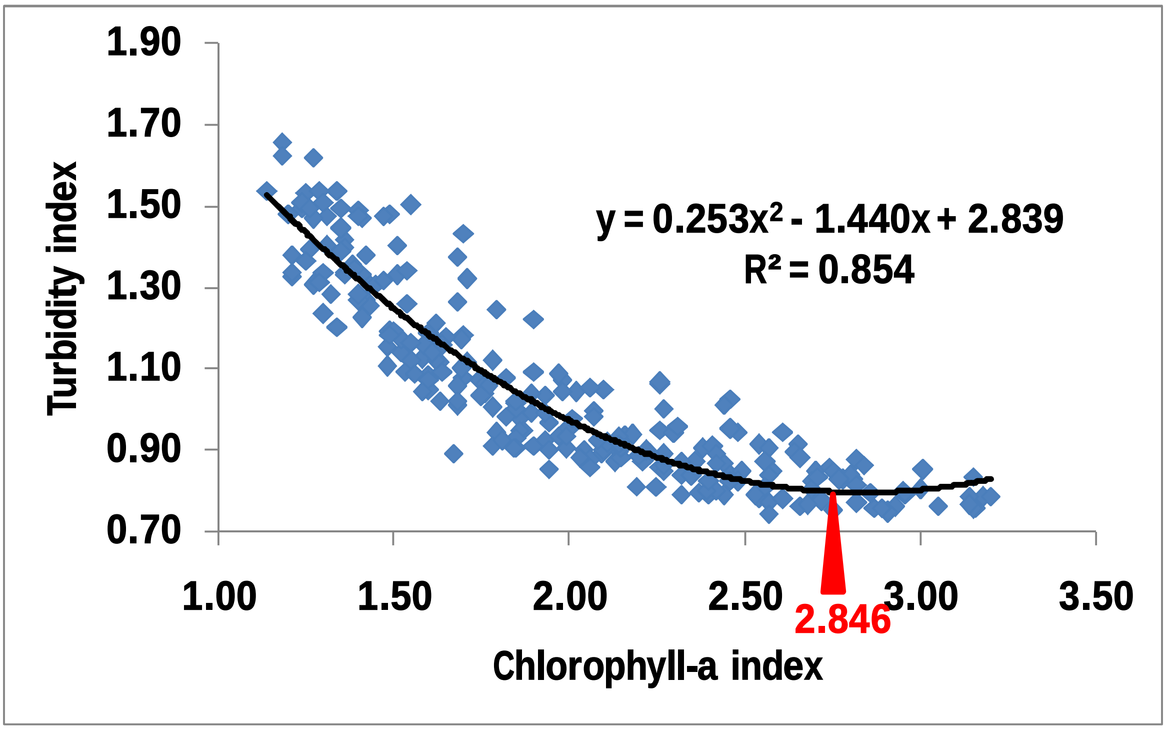


Figure 4.5. Determination of the second critical chlorophyll-a index

Like previously, the first derivative of the trendline equation of Figure 4.5 was used to determine the second critical chlorophyll-a index and was found to be **2.846.** In this order, at 85.4% confidence level, any small reservoir characterized by a chlorophyll-a index greater or equal to 2.846 is susceptible to develop dense floating vegetation on its surface due to excessive nutrients loads (23 of the 256 small reservoirs were concerned in this category). Conversely, any small reservoir for which the chlorophyll-a index is lesser than this threshold, is categorized as a reservoir with no vegetation spreading, meaning it has no excessive nutrients loads (233 of the 256 small reservoirs were found in this category).

Validation of physico-chemical characteristics

To further validate the above results on turbidity and chlorophyll-a indices, the following findings were considered.

False small reservoirs representing more of vegetation than water bodies: from the 217 qualified as shadows instead of clear water, a total of 11 sampled randomly were validated at 100% as shadows (that were confused with clear water) due to hills where vegetation was growing, using Google Earth finer resolution images, as illustrated by the Figure 4.6.

Figure 4.6. Shadow caused by topography variation and low sun elevation

This shadow, which was initially picked as “clear water” in the classification, was eliminated because of its chlorophyll-a index that was 3.45 and therefore beyond the threshold of 3.207

calculated. This also confirmed the impact of low sun elevation increasing shadows behind acute topography change as pre-discussed in heading 4.1.

From the 256 small reservoirs that remained after elimination of shadows, 27 were visited and none of them was found not to be a small reservoir, therefore the identification was done at 100%.

To validate the performance of turbidity indices, ground measurements of turbidity were carried out on 10 small reservoirs covering the 3 categories of turbidity (6 small reservoirs moderately turbid, 2 highly turbid, and 2 clear or less turbid), and the measured turbidity values were correlated to the calculated turbidity indices (Figure 4.7).

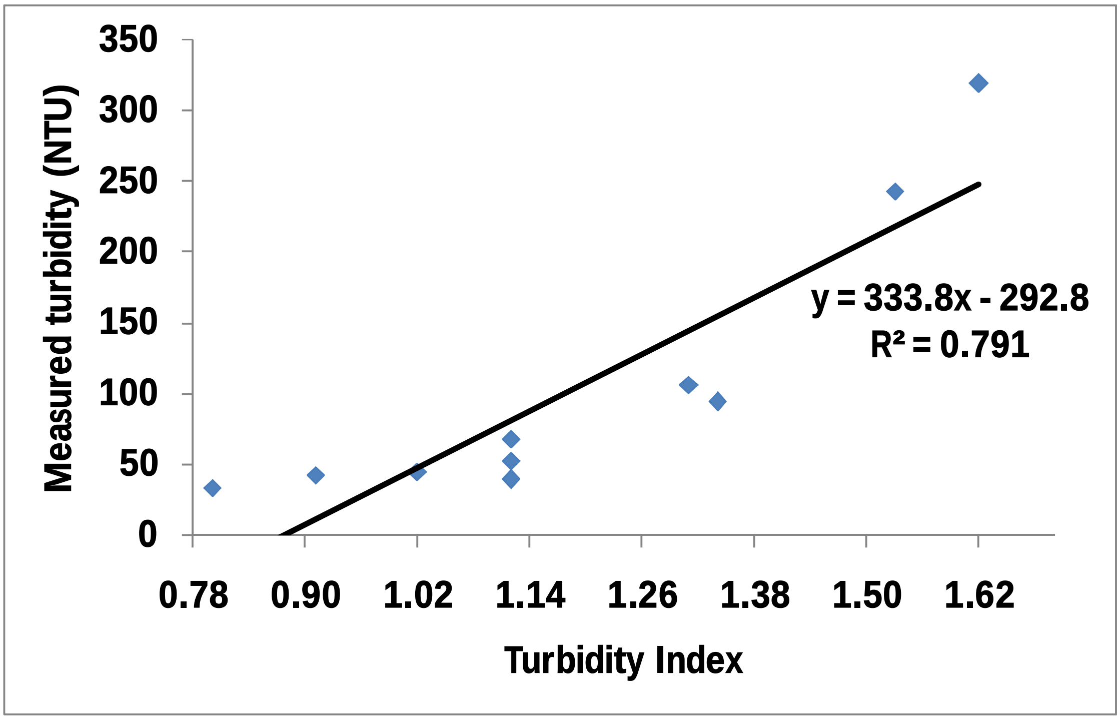


Figure 4.7. Correlations of measured Turbidity and Turbidity index

Figure 4.7 confirms that the turbidity index used based on remote sensing reflects a good trend of the actual turbidity of the reservoirs. In fact, it indicates a strong linear correlation, R^2 of 0.79 for linear correlation and Pearson correlation of 0.89, indicating a good fit.

To validate the characterisation of small reservoirs using the chlorophyll-a index, visual observations of 25 visited small reservoirs were noted in three classes according to the presence of floating vegetation which is a consequence of excessive nutrients loads in water (Table 4.4).

Table 4.4. Observed floating vegetation

	Name of small reservoir	Chlorophyll-a index	Field visual observation	Grouping
1	Ngonyama	2.95	dense floating vegetation	Above critical index
2	Mtaso	3.15	dense floating vegetation	
3	Dondoriyo	1.58	sparse floating vegetation	Below critical index
4	Mgodi	1.78	sparse floating vegetation	
5	Nyokande	2.27	sparse floating vegetation	
6	Langaphakathi 1	1.36	sparse floating vegetation	
7	Langaphakathi 2	1.43	sparse floating vegetation	
8	Sophaphu	1.85	sparse floating vegetation	
9	Masindisa	2.26	sparse floating vegetation	
10	Ntondokazulu	2.44	sparse floating vegetation	
11	Matambo	2.54	no floating vegetation	
12	Matsenyane	1.25	no floating vegetation	
13	Sivume	1.27	no floating vegetation	
14	Makhanka	1.55	no floating vegetation	
15	Gaswa	1.30	no floating vegetation	
16	Holela	1.42	no floating vegetation	
17	Sibona	1.41	no floating vegetation	
18	Hongwe	1.31	no floating vegetation	
19	Gwakwe	1.42	no floating vegetation	
20	Samadube	1.52	no floating vegetation	
21	Matabezulu	1.98	no floating vegetation	
22	Nqodini	1.61	no floating vegetation	
23	Sabachimba	1.97	no floating vegetation	
24	Masholomoshe	1.71	no floating vegetation	
25	Hulube	1.51	no floating vegetation	

Table 4.4 shows the observations made on the field regarding floating vegetation on the reservoir and the remotely-sensed index. Only the reservoirs with chlorophyll-a index greater than the critical index (that was 2.846) were found to have dense floating vegetation. In addition, the Pearson correlation between the encoded visual observations (as 3, 2, 1 for the three types of observations) and the chlorophyll-a index was found to be 0.68. Consequently, the status characterisation of small reservoirs based on the chlorophyll-a index was validated.

Considering the physico-chemical characterisation and validation above, the final number of small reservoirs was determined.

4.2.3. Final number of small reservoirs

The final identification and physico-chemical characterisation of small reservoirs from above is summarised in the Figure 4.8.

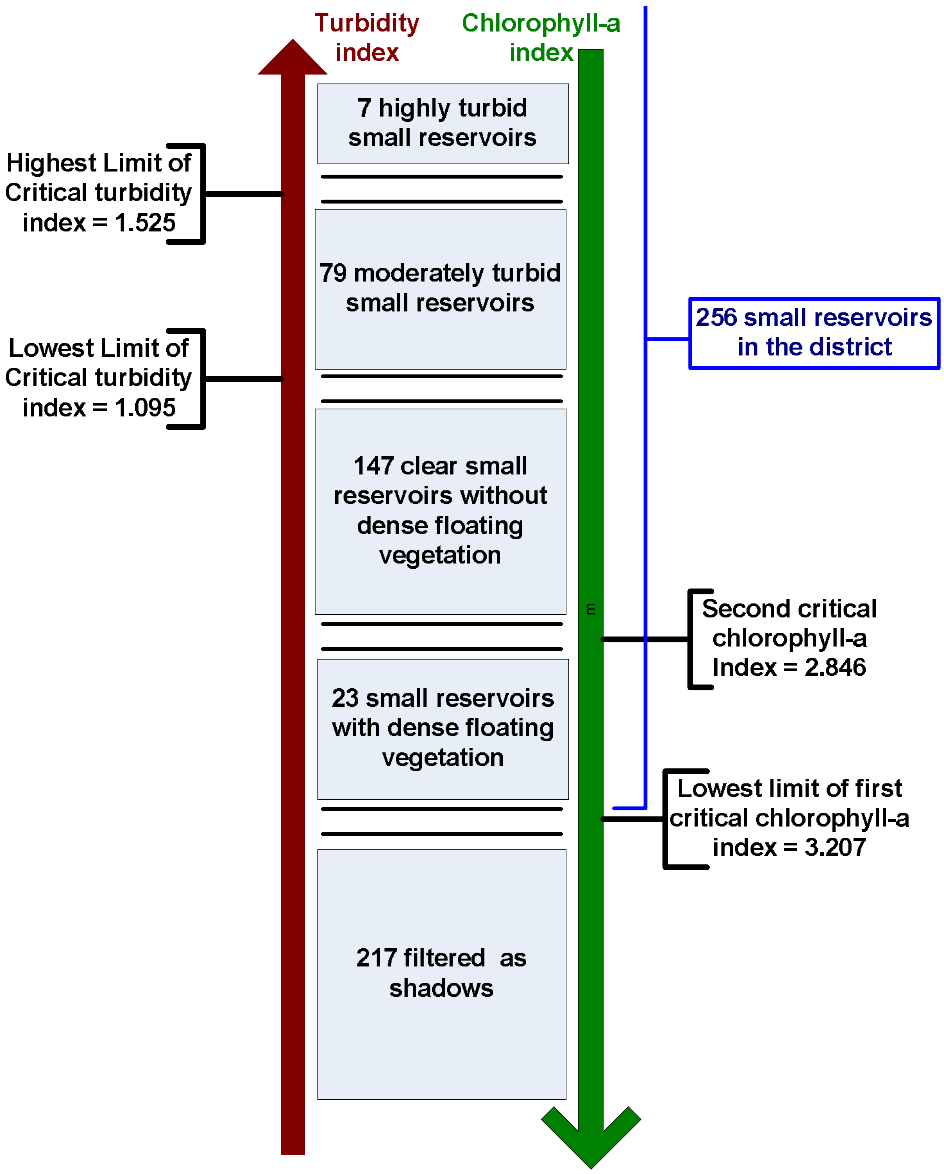


Figure 4.8. Summary of identification and physico-chemical characterisation

Figure 4.8 shows that there are 256 small reservoirs in the district. This number is relatively low compared to what was found by Sawunyama *et al.* (2006) in nearby Insiza district where an approximate number of 1000 was detected. This might be explained by filters applied in the present study by the use of water quality parameters to eliminate vegetations shadowed by hills and the negligible sizes (2 pixels) eliminated that could indicate residual waters in drainages. It is worth noting that some very small reservoirs may have been eliminated together with residual waters by the 2 pixels threshold. Still, the number of 256 small reservoirs is higher than the 149 small reservoirs identified by DDF, or 154 small reservoirs in the RDC records, or again 205 small reservoirs in ZINWA records for the whole area of Shashe, Upper and Lower Mzingwane subcatchements. The three subcatchments even cover an area that is wider than the district. Further field research may be necessary to confirm whether such difference is only due to disparate data in various organisations records or there were not captured small reservoirs that were finally identified.

4.2.4. Capacities estimations

To estimate the capacities of the identified small reservoirs, the remotely sensed surface area was considered specifically for each small reservoir. In order to apply Equation 6, depths measurements were carried out in the field for 10 small reservoirs; the resultant average depth was 4.25 m (Appendix B.3).

To compare the relative performance of Equations 5 and 6 using the RVD or the standard error of the estimates, capacities from 18 small reservoirs in the DDF records were used because their grid references could match with related small reservoirs identified through the study.

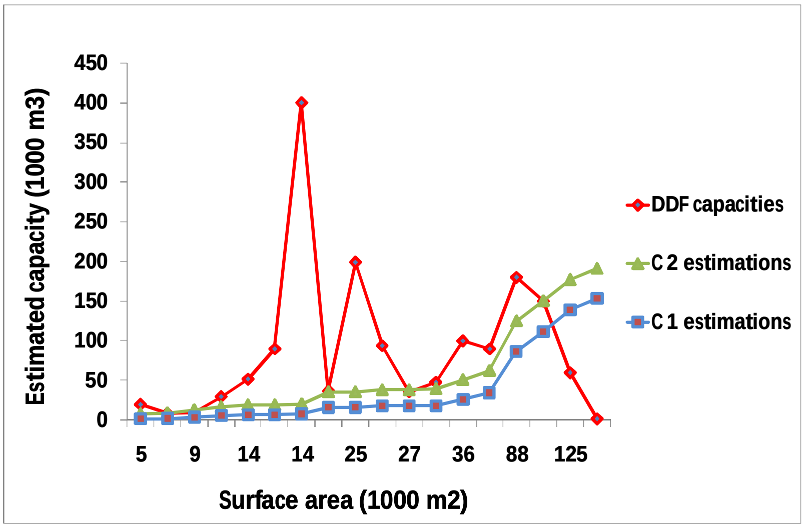


Figure 4.9. Comparison of capacities estimations with capacities in DDF records

Figure 4.9 shows that DDF records contain some errors marked by high pics despite low surface areas, and conversely. As far as capacities estimations are concerned, Equation 5 was found to provide capacities (C_1) that are -58% further from the design capacities in terms of RVD or with 264,572m^3 in terms of standard error. The RVD for Equation 6 was -35% and the capacities (C_2) were estimated with 184,923m^3 of standard error. Although the two equations underestimated the capacities, Equation 6 provided values that were deviating less from the design capacities, and thus less erroneous. Thus Equation 6 was applied to estimate the capacities of all the 256 small reservoirs (Figure 4.10). The total capacity of small reservoirs in the district was then estimated to 17 million m^3.

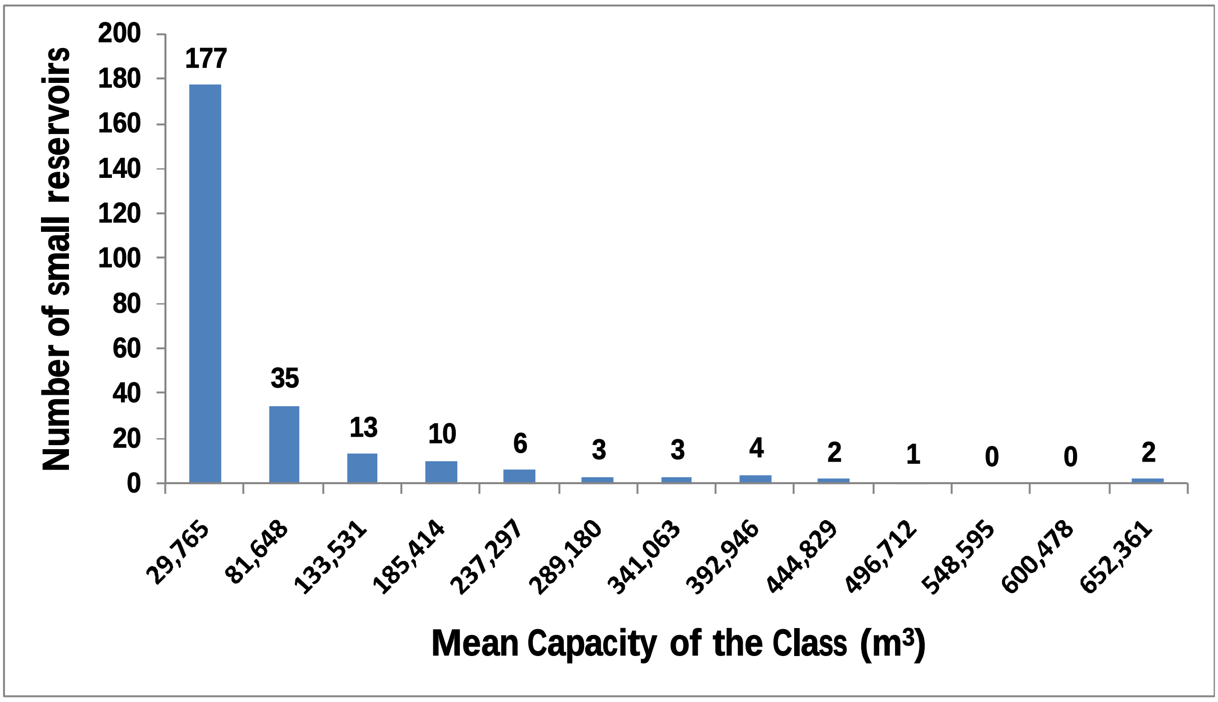


Figure 4.10. Distribution of estimated capacities in the district

The biggest estimated capacity value (678,300 m^3) is more than 150 times bigger than the smallest (3,824m^3), indicating a wide range of capacities for small reservoirs in the district. This wide range distribution of capacities is very much skewed to right (+ 2.97), in the same way the median (value which divides the distribution in two equal parts, in this case it is 28,687m^3) is lower than the half of the average value (67,919 m^3), indicating that the small reservoirs capacities are very much concentrated in the smaller values (Figure 4.10).

By comparison between the wet period and dry period estimated capacities, a relationship characterising how the small reservoirs shrink between the two periods was established (Figure 4.11).

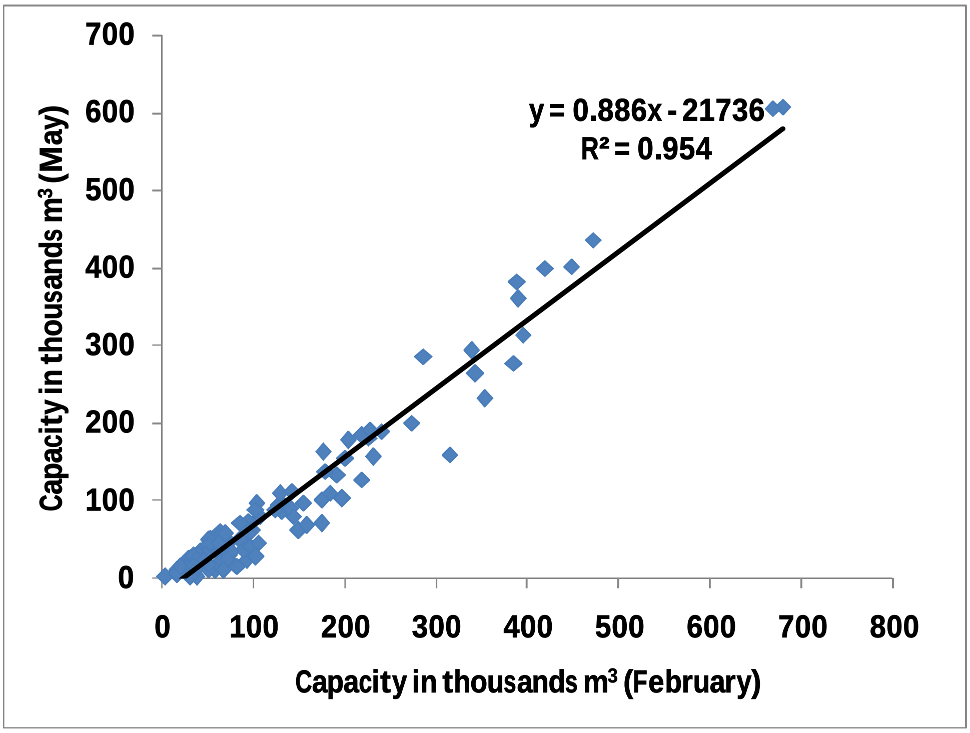


Figure 4.11. Drying relationship of small reservoirs

This trendline equation (Figure 4.11) was used to determine the wet period capacity for which the dry period capacity (around August-September) will be 0, a threshold of 52,222m^3 was calculated as the minimum size below which a reservoir is likely to dry up before next rains. Based on the above relationship, 174 small reservoirs (68% of the total number of small reservoirs) were identified as likely to fail before the next rainy season due to the dry season and their very small capacity. This is quite high number and is explained by the fact that the distribution of small reservoirs' capacities is skewed to concentrate in capacities around 30,000m^3 (Figure 4.10).

4.3. Database

The database design was successful for all the entities. To test its success, some queries were run to find specific information from the database. It also linked successfully with GIS interface to provide spatial analysis of the small reservoirs characteristics.

4.3.1. Queries

The query below illustrates finding the capacities, coordinates, ward, and water quality status for small reservoirs under Upper Mzingwane subcatchments that are likely to dry up before the next rains (syntax of the query is shown in Box 4.5). The query successfully returned 25 records (Table 4.5).

Box 4.1. Query syntax of results in Table 4.5

```
SELECT reservoir_id_source.res_id_new, reservoir_coords.coords, capacities4.capacity_m3_rainy_period, seasons_characterisation2.[seasonal reliability], turbidity.trb_indx, turbidity_class.trb_meaning, chlorophyl.chl_index, chlorophyl_class.chl_a_meaning, ward.ward_num, river.riv_nam, sub_cc.succ_nam FROM seasons_characterisation2 INNER JOIN ((((((((((((capacities4 INNER JOIN reservoir_id_source ON capacities4.res_id_new = reservoir_id_source.res_id_new) INNER JOIN ((chl_a_reservoir INNER JOIN chlorophyl ON chl_a_reservoir.chl_index_new = chlorophyl.chl_index_new) INNER JOIN chlorophyl_class ON chlorophyl.chl_a_class = chlorophyl_class.chl_a_class) ON reservoir_id_source.res_id_new = chl_a_reservoir.res_id_new) INNER JOIN reservoir_coords ON reservoir_id_source.res_id_new = reservoir_coords.res_id_new) INNER JOIN stream_reservoir ON reservoir_id_source.res_id_new = stream_reservoir.res_id_new) INNER JOIN strm_riv ON stream_reservoir.strm_id = strm_riv.strm_id) INNER JOIN (river INNER JOIN sub_cc ON river.scc_autoid = sub_cc.scc_autoid) ON strm_riv.riv_autoid = river.riv_autoid) INNER JOIN turb_reservoir ON reservoir_id_source.res_id_new = turb_reservoir.res_id_new) INNER JOIN turbidity ON turb_reservoir.trb_index_new = turbidity.trb_index_new) INNER JOIN turbidity_class ON turbidity.turb_class = turbidity_class.turb_class) INNER JOIN wardnum_reservoir ON reservoir_id_source.res_id_new = wardnum_reservoir.res_id_new) INNER JOIN ward ON wardnum_reservoir.ward_num = ward.ward_num) INNER JOIN ward_pop_hum_n_livestock2 ON ward.ward_num = ward_pop_hum_n_livestock2.ward_num) ON seasons_characterisation2.season_dyn_code = capacities4.season_dyn_code;
```

Table 4.5. Example of a query concerning small reservoirs that dry in Upper Mzingwane

Reservoir ID	coordinates	Capacity (m3) rainy period	Seasonal reliability	Turbidity index	Turbidity category	Chlorophyll-a index	Chlorophyll-a meaning	Ward number	River name	Subcatctment name
1	20°36'52.3"S, 29°01'11.00"E	7650	dry before next rains	0.91	clear or less turbid water	2.54	no excessive floating vegetation	4	Mzingwane (upper)	Upper Mzingwane
5	20°37'38.3"S, 29°05'15.00"E	39525	dry before next rains	0.98	clear or less turbid water	1.86	no excessive floating vegetation	3	Mzingwane (upper)	Upper Mzingwane
6	20°38'34.3"S, 28°47'04.00"E	3825	dry before next rains	0.85	clear or less turbid water	1.94	no excessive floating vegetation	6	Mzingwane (upper)	Upper Mzingwane
9	20°39'40.3"S, 29°07'24.00"E	29325	dry before next rains	1.19	moderately turbid water	1.49	no excessive floating vegetation	3	Mzingwane (upper)	Upper Mzingwane
10	20°40'04.3"S, 29°08'13.00"E	35700	dry before next rains	1.12	moderately turbid water	1.63	no excessive floating vegetation	3	Mzingwane (upper)	Upper Mzingwane
11	20°40'15.3"S, 28°44'53.00"E	5100	dry before next rains	0.92	clear or less turbid water	2.65	no excessive floating vegetation	7	Mzingwane (upper)	Upper Mzingwane
15	20°41'46.3"S, 29°05'07.00"E	7650	dry before next rains	1.12	moderately turbid water	1.78	no excessive floating vegetation	4	Mzingwane (upper)	Upper Mzingwane
17	20°41'56.3"S, 28°49'13.00"E	8925	dry before next rains	1	clear or less turbid water	2.27	no excessive floating vegetation	6	Mzingwane (upper)	Upper Mzingwane
21	20°42'46.3"S, 29°03'29.00"E	15300	dry before next rains	1.31	moderately turbid water	1.43	no excessive floating vegetation	4	Mzingwane (upper)	Upper Mzingwane
22	20°42'49.3"S, 29°01'41.00"E	3825	dry before next rains	1.09	clear or less turbid water	1.9	no excessive floating vegetation	5	Mzingwane (upper)	Upper Mzingwane
23	20°42'53.3"S, 29°08'09.00"E	35700	dry before next rains	1.02	clear or less turbid water	1.85	no excessive floating vegetation	4	Mzingwane (upper)	Upper Mzingwane
25	20°42'55.3"S, 29°02'04.00"E	12750	dry before next rains	1.08	clear or less turbid water	1.6	no excessive floating vegetation	5	Mzingwane (upper)	Upper Mzingwane
26	20°43'16.3"S, 28°51'03.00"E	6375	dry before next rains	1.25	moderately turbid water	1.79	no excessive floating vegetation	6	Mzingwane (upper)	Upper Mzingwane
31	20°45'43.3"S, 29°12'03.00"E	7650	dry before next rains	0.83	clear or less turbid water	3.15	excessive floating vegetation and	2	Mzingwane (upper)	Upper Mzingwane

Reservoir ID	coordinates	Capacity (m3) rainy period	Seasonal reliability	Turbidity index	Turbidity category	Chlorophyll-a index	Chlorophyll-a meaning	Ward number	River name	Subcatctment name
							requires intervention on nutrients loads from catchment			
32	20°45'50.3"S, 29°10'33.00"E	3825	dry before next rains	0.83	clear or less turbid water	2.78	no excessive floating vegetation	2	Mzingwane (upper)	Upper Mzingwane
37	20°48'02.3"S, 28°53'59.00"E	26775	dry before next rains	1.27	moderately turbid water	1.42	no excessive floating vegetation	6	Mzingwane (upper)	Upper Mzingwane
38	20°48'06.3"S, 29°09'05.00"E	38250	dry before next rains	1.14	moderately turbid water	1.52	no excessive floating vegetation	2	Mzingwane (upper)	Upper Mzingwane
41	20°48'23.3"S, 29°10'17.00"E	8925	dry before next rains	0.95	clear or less turbid water	2.26	no excessive floating vegetation	2	Mzingwane (upper)	Upper Mzingwane
45	20°49'15.3"S, 29°06'07.00"E	6375	dry before next rains	1.07	clear or less turbid water	1.98	no excessive floating vegetation	2	Mzingwane (upper)	Upper Mzingwane
46	20°49'35.3"S, 29°09'01.00"E	35700	dry before next rains	1.17	moderately turbid water	1.52	no excessive floating vegetation	2	Mzingwane (upper)	Upper Mzingwane
53	20°51'56.3"S, 29°14'35.00"E	38250	dry before next rains	1.35	moderately turbid water	1.38	no excessive floating vegetation	1	Mzingwane (upper)	Upper Mzingwane
57	20°53'00.3"S, 28°54'45.00"E	12750	dry before next rains	0.98	clear or less turbid water	1.82	no excessive floating vegetation	21	Mzingwane (upper)	Upper Mzingwane
61	20°55'58.3"S, 29°03'29.00"E	3825	dry before next rains	1.07	clear or less turbid water	1.74	no excessive floating vegetation	21	Mzingwane (upper)	Upper Mzingwane
63	20°56'30.3"S, 29°09'05.00"E	17850	dry before next rains	1.1	moderately turbid water	1.69	no excessive floating vegetation	22	Mzingwane (upper)	Upper Mzingwane
70	21°00'38.3"S, 29°08'37.00"E	5100	dry before next rains	0.87	clear or less turbid water	2.32	no excessive floating vegetation	22	Mzingwane (upper)	Upper Mzingwane

This example of query (Table 4.5) shows how integration of various aspects captured through the study has been achieved in the designed database. It also demonstrated how the database can enable filtering information within the database and, therefore, specific analysis according to the criteria can be implemented by the decision-maker.

Figure 4.12 shows the result of a query regarding the distribution of volume capacities of small reservoirs between subcatchments.

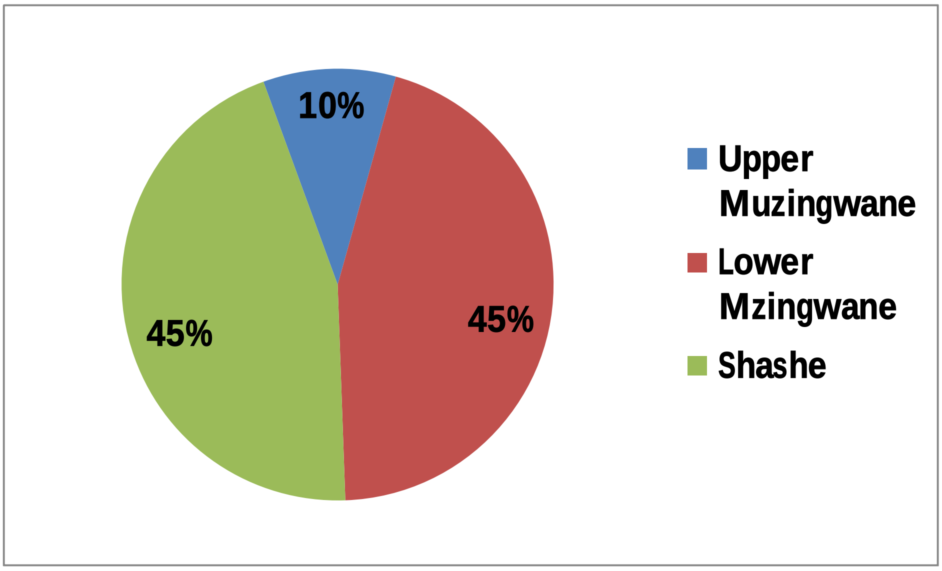


Figure 4.12. Distribution of volume capacities in subcatchments

Lower Mzingwane subcatchment, which covers 42% of the area of the district, accounted for up to 45% of the small reservoirs capacities while Shashe subcatchment, which occupies 48% of the district, accounted for 45% of the small reservoirs' capacities. Upper Mzingwane, which occupies 10% of the district accounted for 10% of the small reservoirs' capacities.

The example of Figure 4.12 shows how the designed database integrated secondary data from RDC on households and from the Veterinary Department on livestock at the ward level of the district.

4.3.2. Interface with GIS

Some thematic mapping and analyses were produced by joining GIS data with the small reservoirs database.

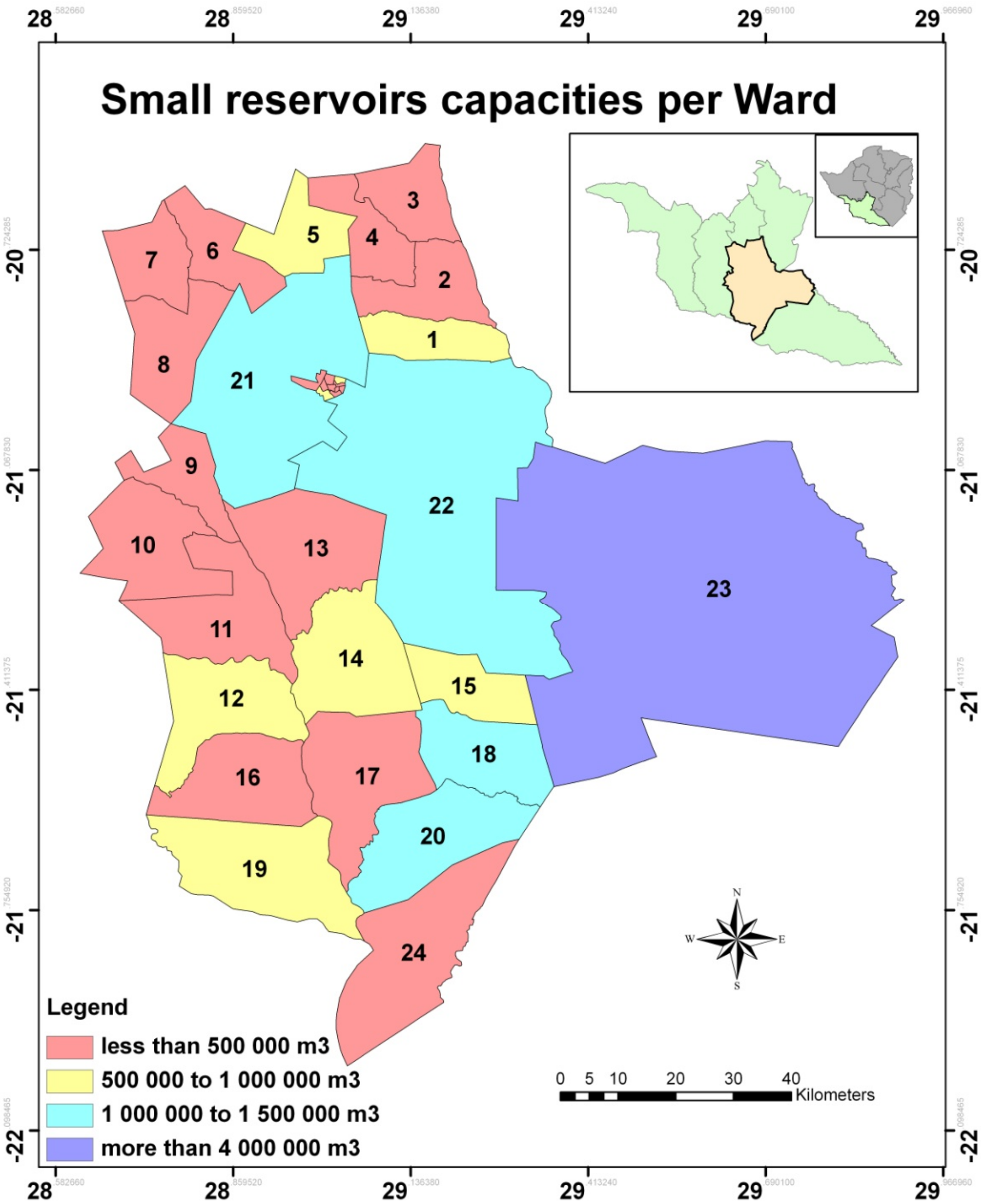


Figure 4.13. Small reservoirs capacities distribution per ward

The largest capacity of small reservoirs was found within 5 wards of the 24 rural wards in Gwanda. Ward 23 accounted for 85 of the 256 small reservoirs and between them held more than 4 million m^3.

4.4. Decision Support System

The Decision Support System produced, namely GDSS-SR v.1.0, enables water resources managers to take informed decisions regarding the management of small reservoirs in Gwanda district. In fact, GDSS-SR v.1.0 is not intended to replace the decision maker’s role, rather to facilitate the latter take informed and responsible decisions. This is also the way earlier research conceptualise the types of DSS as in their recent development (Jansky and Uitto, 2005; Koutsoyiannis *et al.*, 2003; USEPA, 2000).

Primarily, GDSS-SR v.1.0 incorporates a comprehensive database of small reservoirs that provides water resources planners and managers with basic information in terms of surface water resources assessment. This concerns specifically the location, the number, the capacity, the reliability, and the status of small reservoirs in the district (Figures 4.14 and 4.15).

In terms of location of each small reservoir in the district, the decision makers concerned can use GDSS-SR v.1.0 to get the geographic coordinates, the ward in which it is contained, the river system to which it is associated, the subcatchment under which it falls. Holistic water resources management could therefore be improved. This is also particularly important to bridge and integrate the types of management that characterise water related institutions that focus on administrative boundaries (RDC, DDF, AGRITEX, NGOs) with those focusing on hydrological boundaries (ZINWA, Mzingwane catchment, Shashe, Upper and Lower Mzingwane subcatchments). Consequently, institutional coordination can be achieved with the use of the tool like. Such an approach was achieved in the case of developing a water management plan for the city of Athens (Koutsoyiannis *et al.*, 2003).

Considering the location and the capacity provided by the tool and in view of secondary data on the uses of small reservoirs, decision makers utilising GDSS-SR v.1.0 can decide on valuably improving the use of stored water. Again, the dry season capacity and subsequent reliability is a basis for better informing decisions on the types and magnitude of uses to be undertaken.

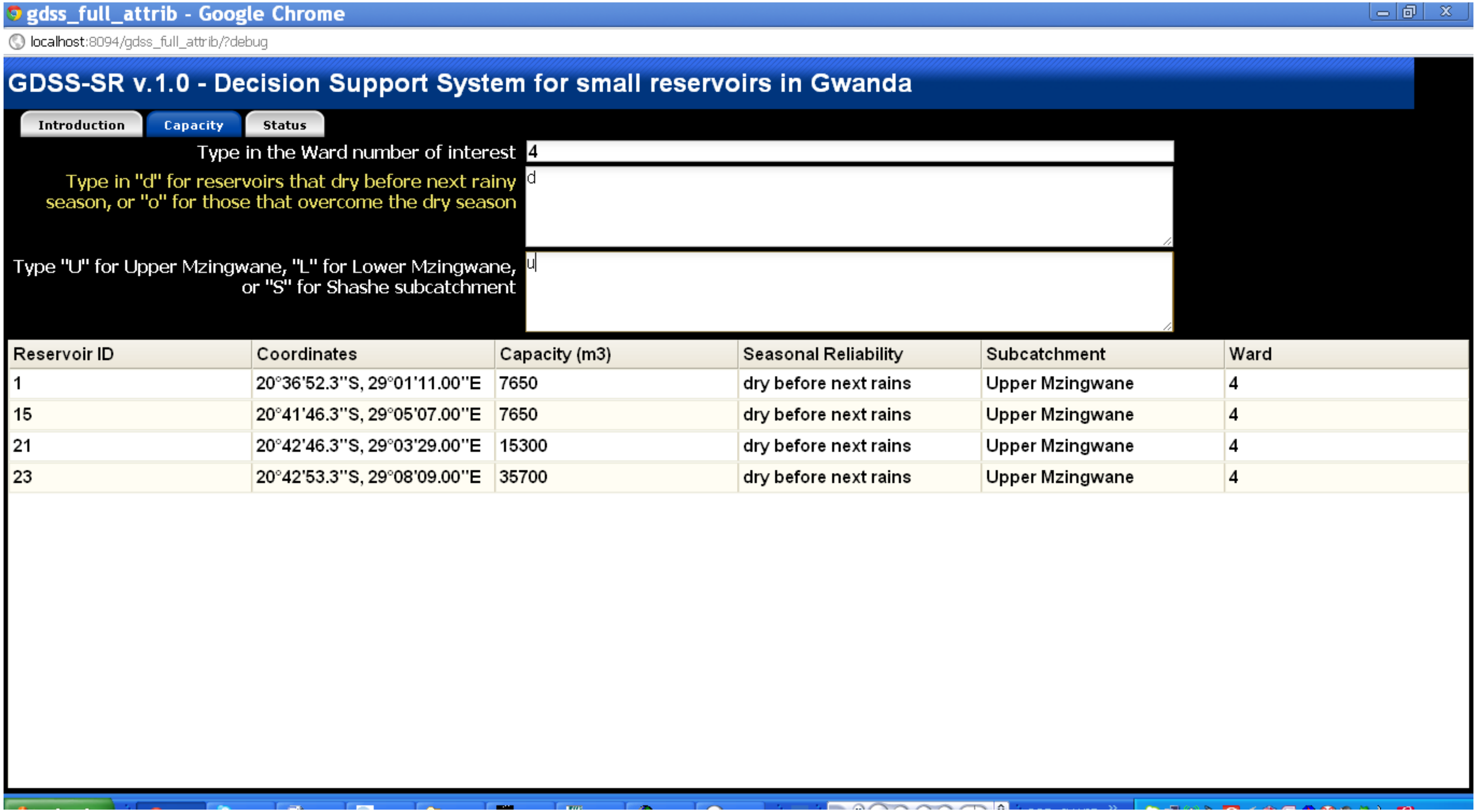
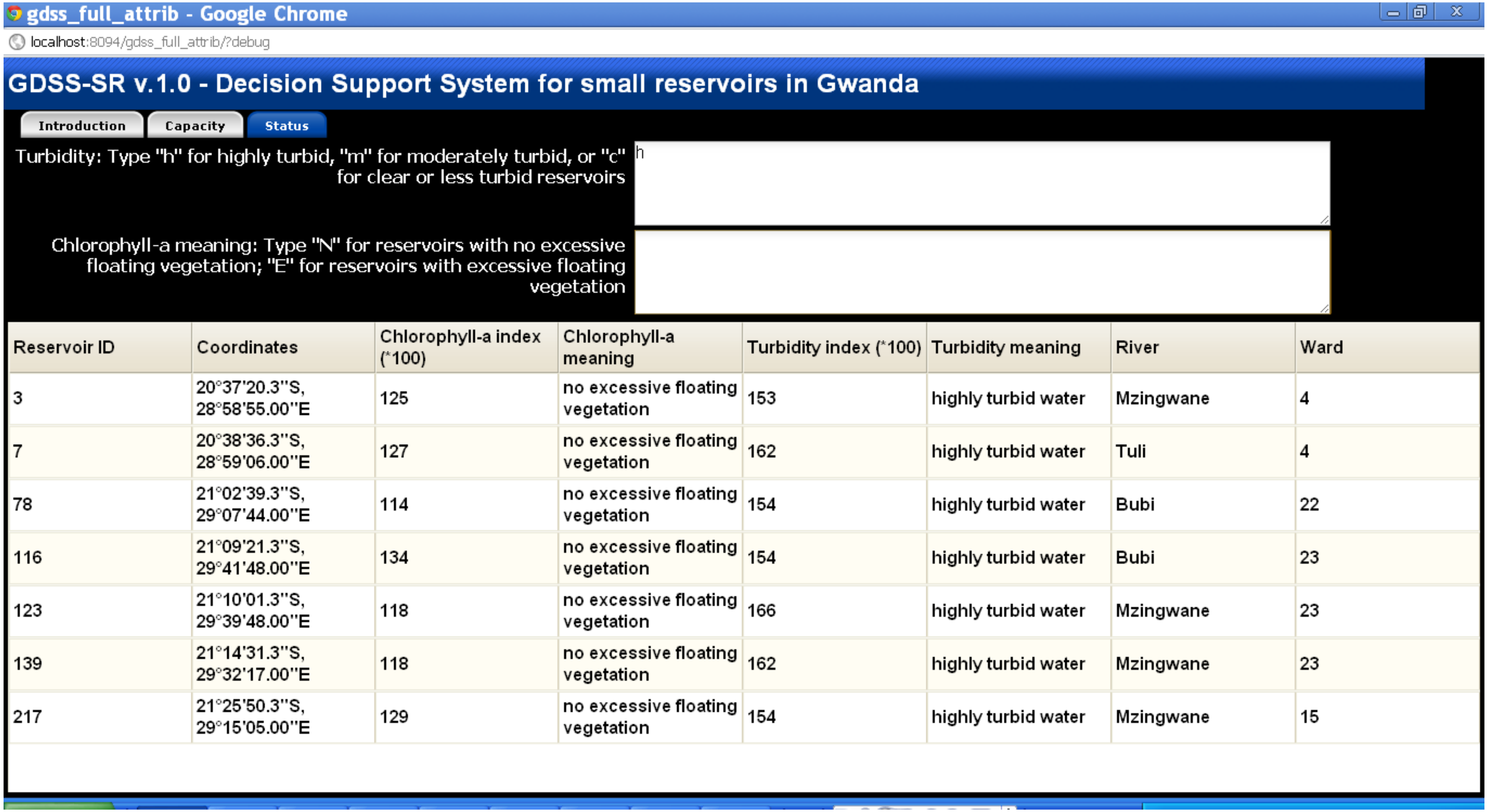


Figure 4.14. An illustration of reservoirs' capacities query through GDSS-SR v.1.0 running in web interface

The Figure 4.14 shows how GDSS-SR simplifies information query. This example was about finding the capacities of small reservoirs that are in ward 4 and that could dry before next rains and under Upper Mzingwane subcatchments.



Reservoir ID	Coordinates	Chlorophyll-a index (*100)	Chlorophyll-a meaning	Turbidity index (*100)	Turbidity meaning	River	Ward
3	20°37'20.3"S, 28°58'55.00"E	125	no excessive floating vegetation	153	highly turbid water	Mzingwane	4
7	20°38'36.3"S, 28°59'06.00"E	127	no excessive floating vegetation	162	highly turbid water	Tuli	4
78	21°02'39.3"S, 29°07'44.00"E	114	no excessive floating vegetation	154	highly turbid water	Bubi	22
116	21°09'21.3"S, 29°41'48.00"E	134	no excessive floating vegetation	154	highly turbid water	Bubi	23
123	21°10'01.3"S, 29°39'48.00"E	118	no excessive floating vegetation	166	highly turbid water	Mzingwane	23
139	21°14'31.3"S, 29°32'17.00"E	118	no excessive floating vegetation	162	highly turbid water	Mzingwane	23
217	21°25'50.3"S, 29°15'05.00"E	129	no excessive floating vegetation	154	highly turbid water	Mzingwane	15

Figure 4.15. An illustration of reservoirs' turbidity query through GDSS-SR v.1.0 running in web interface

Figure 4.15 shows an illustration of finding the highly turbid reservoirs, their locations, the river they are associated with, and the ward in which they are.

From the above examples, it is clear that the decision maker does not need to know how to configure a query, as it could be the case in Access. It is only about clicking in the text area and type in a letter as the indication shows and the system retrieves itself the information required. So, in general information is easily generated via GDSS-SR v.1.0.

Furthermore, in terms of decision making related to the reliability of the reservoirs, it was found primarily related to the very small sizes. Therefore, depending on the use, decision makers could improve water security to livelihoods by designing small reservoirs above 52,000 m^3 of capacity. Of course, in case that requires designing a small reservoir further downstream where more runoff could be captured, such a decision involves an opportunity cost between the proximity of a small reservoir that may become unreliable in dry periods and a bit more distanced small reservoir that is able to sustain livelihoods. Another option could be raising the wall of existing small reservoirs where that is feasible.

The status of a small reservoir is a proxy for deciding where and what type of catchment protection is needed to ensure the sustainability of the reservoir. Decision makers could therefore consider erosion control measures where a reservoir is highly turbid, and nutrients loads control where reservoirs are indicated to have excessive floating vegetation (for instance sensitization of the people on effective methods of fertilisers' application, or small artificial wetlands). For future development of small reservoirs, both erosion and nutrients loads controls should be important parameters to ensure sustainability of small reservoirs prior to their development.

4.5. Conclusion

The results that have been presented in this chapter show that both the methodology and the methods that were used to identify and characterize small reservoirs in Gwanda district were appropriate. The same is true for the design and application of the decision support system.

With regards to the identification of small reservoirs the selected satellite images were found to meet acceptable quality for the classification of land cover and the identification of small reservoirs. However, availability of satellite images of required quality was a constraint in relation to capacity estimation of reservoirs in the dry period.

Physico-chemical characterization of the identified small reservoirs demonstrated that there were some that needed erosion and nutrient load control measures upstream. Uneven distribution of volume capacities was found among wards. Very small reservoirs were found susceptible to drying up in the dry season.

The designed database successfully integrated the results of the study and assisted in spatial analyses and creation of maps. The developed DSS, GDSS-SR v.1.0, successfully operated in a web interface and provides decision-makers with a basis of informed decision-making regarding small reservoirs management. It was tested for query of information on the spatial distribution of small reservoirs, their capacities in the district, and the status of their environmental degradation. Some of the practical benefits of GDSS-SR v.1.0 are in regard to:

- allowing information sharing between and among institutions that have a responsibility for managing small reservoirs;
- assisting in the assessment of small reservoirs surface water resources in the district; and
- providing a preliminary assessment of environmental degradation.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

The purpose of this study was to develop and apply an ICT-based Decision Support System (DSS) for effective management of small reservoirs in a semi-arid district (Gwanda district) that falls in the Limpopo river basin in Zimbabwe. To this end the study sought to identify and characterise small reservoirs in terms of location, capacity, physico-chemical and socio-economic characteristics. This was then used to build a database from the generated information. A DSS was developed using the output information and tested in a web interface.

5.2. Main findings and conclusions

5.2.1. Identification

Some 256 small reservoirs were identified in the district. Most of them were concentrated in five of the 24 rural wards that constitute the district. Ward 23 accounted for more than 40% of the total volume of the reservoirs. The total capacity of the small reservoirs in the district was estimated to 17 million m3, proportionally distributed between the three subcatchments (Shashe, Upper and Lower Mzingwane) in terms of surface area of the district. The range of capacities was found to be very wide; from around 4,000 m3 to 650,000 m3. About 68 % of the reservoirs had small capacities around 30,000 m3, which made them vulnerable to drying up during the four-month dry season. A threshold of 52,222 m3 was estimated to be minimum size for a small reservoir to carry water throughout the year. However, investigations could be necessary over a long term to validate or improve this threshold, as well as the opportunity cost that such an approach might involve in case small reservoirs may need to be developed further downstream.

While the methodology was found to be effective there were some challenges. On the basis of rainy period satellite images, it is difficult to decide whether a water body of 1 or 2 pixels is a small reservoir or only residual water in a river. The other challenge related to the use of dry period images; some small reservoirs of a size less than 12 pixels were found to have dried up and such reservoirs may not have been captured.

5.2.2. Characterisation

Physico-chemical characterisation of small reservoirs was undertaken using turbidity and chlorophyll-a indices based on remote sensing. Categorisation of small reservoirs status based on critical indices was found to fall within the limits of the determined confidence levels (that were generally greater than 80%). Four main groups of reservoir status were identified:: 7 small reservoirs were classified as highly turbid, 79 moderately turbid, 23 clear but with high levels of nutrients loads characterised by dense floating vegetation, and 147 that were clear without excessive floating vegetation. The highly turbid and nutrients overloaded reservoirs were identified and recommended as requiring specific attention in terms of erosion control and addressing nutrients leaching in the catchment.

As far as assessing the contribution of small reservoirs to livelihoods, the study was limited by disparate information held by the Veterinary Department and the Rural District Council.

5.2.3 Database creation

The database of small reservoirs was designed in Structured Query Language (SQL) format. It integrated the aspects that were identified in the study. Specific queries in the database enabled extraction of information on small reservoir capacity, ability to cope with the dry season, GPS coordinates, location in ward and subcatchments, the river associated with each reservoir, and the status based on physico-chemical characterisation. The database also assisted to produce thematic mapping and analyses.

In terms of generating management-ready information, the approach of designing a database to integrate remote sensing and GIS data with attribute data from ground and records from organisations involved in small reservoirs management was proven efficient.. Challenges of using the database are related to the prior knowledge of SQL. This challenge was overcome by the development of the DSS.

5.2.4 DSS design and testing

The DSS that was established, named GDSS-SR v.1.0 , had the aim of facilitating informed decisions with respect to location, capacity, environmental status and environmental degradation. This was done by incorporating all the attributes determined in the study. It was found to be a dynamic tool that could be easily updated to incorporate more data such as reservoirs names, uses, and new reservoirs. The DSS was organised in themes that enable the decision maker to know where the small reservoirs are located, how much capacities are found at a specified locations (such as ward, subcatchments, or combinations), and the status of the small reservoirs (such as highly turbid or floating vegetation loaded). It could be used by any institution involved in small reservoir development or management (such as local NGOs, local authority – RDC or DDF, ZINWA, Mzingwane Catchment council, and its subcatchments). Its advantages include a web user friendly interface, little physical requirements in terms of computer memory and disk space, and enhanced interoperability on different computer operating systems. Institutions involved in the management of small reservoirs could use the output CD format.

5.3. Recommendations

The study confirmed the possibility and potential of using ICTs to generate information that is necessary for effective management of small reservoirs in the Limpopo river basin in Zimbabwe. However, some challenges were encountered and need to be addressed. First of all, there are uncertainties related to remote sensing that provides data per pixel (square of 30m by 30m, in the case of this study). To identify small reservoirs, there were challenges of either picking residual water bodies when using rainy season images or missing out very small reservoirs when using dry season images. To strike the balance between the two choices, rainy season images were used and a threshold of 2 pixels was applied as a minimum size to filter noisy identification of small reservoirs mixed with temporary ponds.

Secondly, considering that average indices per pixel were used to characterise small reservoirs, it is recommended to consider small reservoirs with values closer to the critical indices as possibly in the next category, and orient decisions accordingly. Further studies are needed using longer series of data to validate or fine-tune the threshold of a small reservoir to reach the end of the dry season.

Thirdly, regarding the database design, although the main challenge was finding all the data pertaining to all small reservoirs, the generated information could be integrated to facilitate informed decision-making. The exact decisions to make on small reservoirs cannot be specified in advance. They depend on the issues under investigation and the decision makers' specific goals. In addition, GDSS-SR v.1.0 integrates administratively-based location of small reservoirs (used by the local authority) with the hydrological boundaries approach (used by water management institutions). The tool is thus recommended to the institutions involved in small reservoirs management in the area. The approach could be used for other areas.

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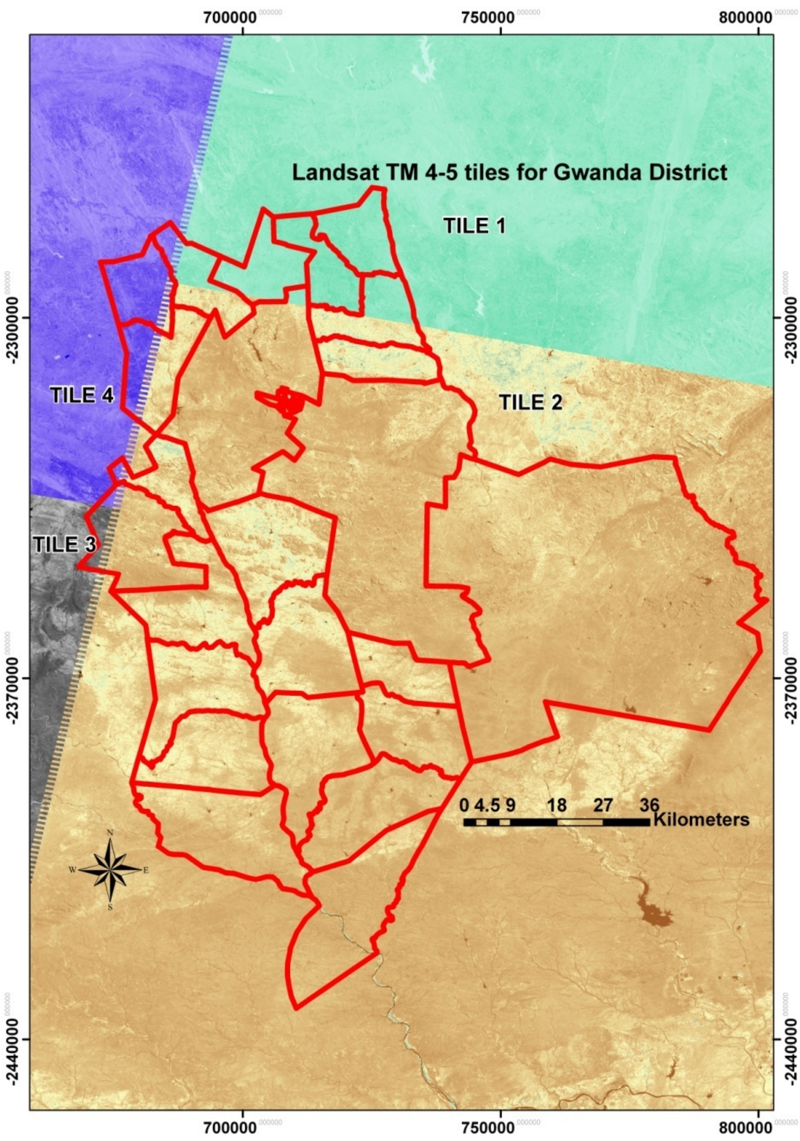
APPENDICES

APPENDICES A (CHAPTER 3)

Appendix A.1. Overlay of Gwanda district on Landsat TM 4-5 images



Appendix A.2. Metadata of selected satellite images

TILE 1 FOR WET PERIOD (FIRST SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51700742009082JSA01
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	170
WRS Row	74
WRS Type	2
Date Acquired	23/03/2009
Start Time	2009:082:07:47:14.00631
Stop Time	2009:082:07:47:40.61938
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	7
Quality Band 2	7
Quality Band 3	7
Quality Band 4	7
Quality Band 5	7
Quality Band 6	7
Quality Band 7	7
Cloud Cover	0.03%
Cloud Cover Quadrant Upper Left	0.01%

Cloud Cover Quadrant Upper Right	0.11%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0.01%
Sun Elevation	49.68767946
Sun Azimuth	62.18995921
Scene Center Latitude	-20.22941 (20°13'45"S)
Scene Center Longitude	29.86179 (29°51'42"E)
Corner Upper Left Latitude	-19.30660 (19°18'23"S)
Corner Upper Left Longitude	29.17578 (29°10'32"E)
Corner Upper Right Latitude	-19.55979 (19°33'35"S)
Corner Upper Right Longitude	30.91713 (30°55'01"E)
Corner Lower Left Latitude	-20.89325 (20°53'35"S)
Corner Lower Left Longitude	28.79793 (28°47'52"E)
Corner Lower Right Latitude	-21.14895 (21°08'56"S)
Corner Lower Right Longitude	30.55652 (30°33'23"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 2 FOR WET PERIOD (FIRST SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51700752009082JSA01
Spacecraft Identifier	5

Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	170
WRS Row	75
WRS Type	2
Date Acquired	23/03/2009
Start Time	2009:082:07:47:37.83675
Stop Time	2009:082:07:48:04.44981
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	7
Quality Band 2	7
Quality Band 3	7
Quality Band 4	7
Quality Band 5	7
Quality Band 6	7
Quality Band 7	7
Cloud Cover	0.04%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0.16%
Sun Elevation	48.81268776
Sun Azimuth	60.93153195

Scene Center Latitude	-21.66357 (21°39'48"S)
Scene Center Longitude	29.52504 (29°31'30"E)
Corner Upper Left Latitude	-20.73973 (20°44'23"S)
Corner Upper Left Longitude	28.83373 (28°50'01"E)
Corner Upper Right Latitude	-20.99519 (20°59'42"S)
Corner Upper Right Longitude	30.59068 (30°35'26"E)
Corner Lower Left Latitude	-22.32571 (22°19'32"S)
Corner Lower Left Longitude	28.45014 (28°27'00"E)
Corner Lower Right Latitude	-22.58389 (22°35'02"S)
Corner Lower Right Longitude	30.22584 (30°13'33"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 3 FOR WET PERIOD (FIRST SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51710752010044MLK00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	MLK
Day Night	DAY
WRS Path	171
WRS Row	75

WRS Type	2
Date Acquired	13/02/2010
Start Time	2010:044:07:57:59.47194
Stop Time	2010:044:07:58:26.08513
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	54.75834546
Sun Azimuth	82.44128144
Scene Center Latitude	-21.65937 (21°39'33"S)
Scene Center Longitude	27.98253 (27°58'57"E)
Corner Upper Left Latitude	-20.73554 (20°44'07"S)
Corner Upper Left Longitude	27.29124 (27°17'28"E)
Corner Upper Right Latitude	-20.99099 (20°59'27"S)

Corner Upper Right Longitude	29.04814 (29°02'53"E)
Corner Lower Left Latitude	-22.32151 (22°19'17"S)
Corner Lower Left Longitude	26.90767 (26°54'27"E)
Corner Lower Right Latitude	-22.57969 (22°34'46"S)
Corner Lower Right Longitude	28.68331 (28°40'59"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 4 FOR WET PERIOD (FIRST SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51710742010044MLK00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	MLK
Day Night	DAY
WRS Path	171
WRS Row	74
WRS Type	2
Date Acquired	13/02/2010
Start Time	2010:044:07:57:35.78413
Stop Time	2010:044:07:58:02.39725
Sensor Anomalies	N

Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	55.14103616
Sun Azimuth	84.35135435
Scene Center Latitude	-20.23319 (20°13'59"S)
Scene Center Longitude	28.31627 (28°18'58"E)
Corner Upper Left Latitude	-19.31038 (19°18'37"S)
Corner Upper Left Longitude	27.63025 (27°37'48"E)
Corner Upper Right Latitude	-19.56357 (19°33'48"S)
Corner Upper Right Longitude	29.37164 (29°22'17"E)
Corner Lower Left Latitude	-20.89703 (20°53'49"S)
Corner Lower Left Longitude	27.25239 (27°15'08"E)

Corner Lower Right Latitude	-21.15273 (21°09'09"S)
Corner Lower Right Longitude	29.01102 (29°00'39"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 1 FOR DRY PERIOD (SECOND SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51700742009114JSA00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	170
WRS Row	74
WRS Type	2
Date Acquired	24/04/2009
Start Time	2009:114:07:47:52.30894

Stop Time	2009:114:07:48:18.92200
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	43.83490117
Sun Azimuth	46.78406611
Scene Center Latitude	-20.22606 (20°13'33"S)
Scene Center Longitude	29.86036 (29°51'37"E)
Corner Upper Left Latitude	-19.30325 (19°18'11"S)
Corner Upper Left Longitude	29.17437 (29°10'27"E)
Corner Upper Right Latitude	-19.55643 (19°33'23"S)
Corner Upper Right Longitude	30.91568 (30°54'56"E)
Corner Lower Left Latitude	-20.88991 (20°53'23"S)
Corner Lower Left Longitude	28.79653 (28°47'47"E)

Corner Lower Right Latitude	-21.14559 (21°08'44"S)
Corner Lower Right Longitude	30.55508 (30°33'18"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 2 FOR DRY PERIOD (SECOND SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51700752009146JSA00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	170
WRS Row	75
WRS Type	2
Date Acquired	26/05/2009
Start Time	2009:146:07:48:51.42225
Stop Time	2009:146:07:49:18.03531
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9

Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	36.72908159
Sun Azimuth	38.63227879
Scene Center Latitude	-21.65700 (21°39'25"S)
Scene Center Longitude	29.52354 (29°31'24"E)
Corner Upper Left Latitude	-20.73317 (20°43'59"S)
Corner Upper Left Longitude	28.83226 (28°49'56"E)
Corner Upper Right Latitude	-20.98861 (20°59'18"S)
Corner Upper Right Longitude	30.58913 (30°35'20"E)
Corner Lower Left Latitude	-22.31915 (22°19'08"S)
Corner Lower Left Longitude	28.44870 (28°26'55"E)
Corner Lower Right Latitude	-22.57732 (22°34'38"S)
Corner Lower Right Longitude	30.22431 (30°13'27"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N

DCT Source Available	N
Film Source Available	N

TILE 3 FOR DRY PERIOD (SECOND SET)	
Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT51710752010124JSA00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	171
WRS Row	75
WRS Type	2
Date Acquired	04/05/2010
Start Time	2010:124:07:57:53.88006
Stop Time	2010:124:07:58:20.49313
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9

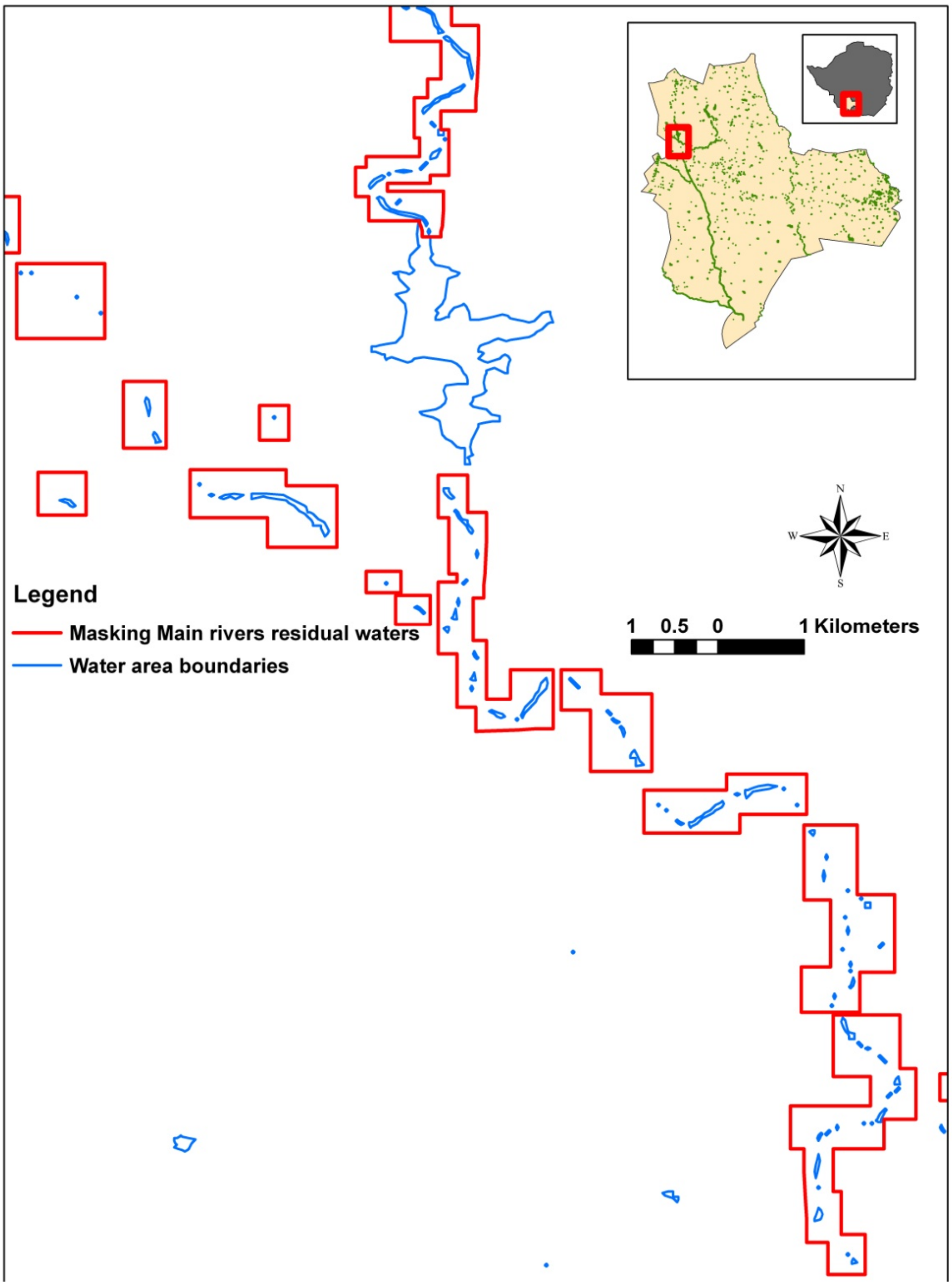
Cloud Cover	0.03%
Cloud Cover Quadrant Upper Left	0.02%
Cloud Cover Quadrant Upper Right	0.02%
Cloud Cover Quadrant Lower Left	0.09%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	41.20717578
Sun Azimuth	42.15992033
Scene Center Latitude	-21.66249 (21°39'44"S)
Scene Center Longitude	27.99733 (27°59'50"E)
Corner Upper Left Latitude	-20.73866 (20°44'19"S)
Corner Upper Left Longitude	27.30603 (27°18'21"E)
Corner Upper Right Latitude	-20.99411 (20°59'38"S)
Corner Upper Right Longitude	29.06296 (29°03'46"E)
Corner Lower Left Latitude	-22.32463 (22°19'28"S)
Corner Lower Left Longitude	26.92244 (26°55'20"E)
Corner Lower Right Latitude	-22.58281 (22°34'58"S)
Corner Lower Right Longitude	28.69812 (28°41'53"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

TILE 4 FOR DRY PERIOD (SECOND SET)	
Dataset Attribute	Attribute Value

Landsat Scene Identifier	LT51710742010124JSA00
Spacecraft Identifier	5
Sensor Mode	BUMPER
Station Identifier	JSA
Day Night	DAY
WRS Path	171
WRS Row	74
WRS Type	2
Date Acquired	04/05/2010
Start Time	2010:124:07:57:30.19238
Stop Time	2010:124:07:57:56.80538
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%

Cloud Cover Quadrant Lower Right	0%
Sun Elevation	42.41243087
Sun Azimuth	42.79729887
Scene Center Latitude	-20.23512 (20°14'06"S)
Scene Center Longitude	28.33088 (28°19'51"E)
Corner Upper Left Latitude	-19.31230 (19°18'44"S)
Corner Upper Left Longitude	27.64485 (27°38'41"E)
Corner Upper Right Latitude	-19.56550 (19°33'55"S)
Corner Upper Right Longitude	29.38626 (29°23'10"E)
Corner Lower Left Latitude	-20.89896 (20°53'56"S)
Corner Lower Left Longitude	27.26698 (27°16'01"E)
Corner Lower Right Latitude	-21.15466 (21°09'16"S)
Corner Lower Right Longitude	29.02564 (29°01'32"E)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N
Film Source Available	N

Appendix A.3. Masking of residual waters in major rivers



Appendix A.4. Metadata of the small reservoirs database

Entity	Description and attributes
reservoir	The central entity of the database obtained after denormalisation and to which all the other entities are connected. res_id_new: the field of identifiers for each small reservoir in the database. This is also the primary key (ID) of the entity. source: indicates where the small reservoir was captured from; either through remote sensing and GIS done through this study (IDs 1 to 256), or from decentralized institutions (IDs 20xx if only in the DDF inventory, or IDs 30xx if in the LDS inventory)
dam_type_reservoir & dam_type	Third table created to connect the reservoir entity to the dam type entity dam_tpe: encoding for the dam type (1, 2,or 3) dam_tpe_code: relates the encoding above to its meaning (1 for earth embarkement, 2 for concrete, or 3 concrete and earth embarkment)
chl_a_full	chl_index: specifies the chlorophyll-a index of each small reservoir chl_a_meaning: relates the chlorophyll-a index to its significance in terms of the categories of reservoirs of excessive floating vegetation or not. An automatic identifier was generated for this entity
turbidity_full	trb_index: specifies the turbidity index of each small reservoir trb_meaning: relates the turbidity index to its significance in terms of reservoirs that are highly turbid, moderately turbid, or less turbid/clear . An automatic identifier was generated for this entity

reservoir_coords	coords: provides the geographic coordinates of small reservoir res_id_new: foreign key connecting this entity to the main entity of reservoirs
ward_number	ward_num: provides the number of the rural ward in the district; this is also the primary key of the entity zimwardid: provides the identifier of the ward in Zimbabwe res_id_new: connects to the main entity of small reservoirs hhlds: provides the number of households that are in the ward (from RDC data); cattle, sheep, donkeys, pigs, goats, dogs, are entities that provide specifically to their names the number of livestock in each ward (data from the Veterinary Department in Gwanda)
lds_res	This entity provides some small reservoirs inventoried by LDS as this organization built or rehabilitated them. res_id_new: provides the ID of the small reservoir (primary key), starting by 30xx lds_name: name of the small reservoir provided by LDS village: place or village in which the small reservoir is located beneficiaries_hhlds: provides the number of households that benefit from a small reservoirs
river_and_subcc	Provides the stream, river, and subcatchments to which a small reservoir is associated

	strm_id: provides the code identifying a stream (primary key) strm_nam: provides the stream name to which a small reservoir is associated riv_nam: identifies the river name (Tuli or Mzingwane) to which a small reservoir is associated succ_nam: provides the name of the subcatchment (Shashe, Upper, or Lower Mzingwane) to which the small reservoir is associated
reservoir_use	Provides the use of a small reservoir. use: specifies the use of a small reservoir (livestock, irrigation, domestic, as well as combinations of the previous) observ: provides some specific observation. An automatic identifier was generated for the entity.
reservoir_name	This entity provides the name of a small resercoirin regards to: ddf_name: the name in the DDF records; lds_name: the name in the LDS records; field_name: the name recorded during field visits to small reservoirs in the purpose of this study.
ddf_final	This entity provides some data on small reservoirs from the DDF records. ddf_name: provides the name of a small reservoir in the DDF records; chairman: the name of the chairman of a small reservoir; design_cap_m3: provides the design capacity of a small reservoir;

	dam_tpe: provides the type of the dam; silt pct: provides the siltation percentage in the DDF records; irr_pot_ha: provides the irrigation potentioal of the small reservoir in hectares; utm_coords: provides the coordinates in UTM after transformation from Grid references. res_id_new: identifier of small reservoirs (primary key), starting by 20xx.
constrct	Provides historical details of small reservoirs. year: provides year in which the small reservoir was built; built by: provides the organization; constr_autoid: provides a unique identifier, automatically generated; village: the village in which the small reservoir was built
capacity	surf_feb_m2: the surface area (in m^2) of the small reservoir derived from remote sensing in end of rainy period 2009; surf_may_m2: the surface area (in m^2) of the small reservoir derived from remote sensing in starting dry period 2009; capacity_m3_rainy_period: estimated capacity (in m^3) of small reservoirs for rainy period on the basis of February 2009 images; capacity_m3_may: estimated capacity (in m^3) of small reservoirs for rainy period on the basis of May 2009 images; seasonal reliability: the reliability of the small reservoir depending on its

	ability to reach the next rainy season.

Appendices B (Chapter 4)

Appendix B.1. Confusion matrix of land cover classification in the wet season

	forest and shrubs	white soil/sand	healthy vegetation	brown soil/clay	clear or deep water	shallow or turbid water	Unclassified	accuracy
forest and shrubs	126	0	0	0	0	0	0	1
white soil/sand	0	66	0	0	0	0	0	1
healthy vegetation	0	0	66	4	0	0	0	0.94
brown soil/clay	0	29	0	37	0	0	0	0.56
clear or deep water	1	0	0	0	74	0	0	0.99
shallow or turbid water	0	0	0	0	0	115	0	1
RELIABILITY	0.99	0.69	1	0.9	1	1		

Appendix B.2. Confusion matrix of land cover classification in the dry season

	Deep or clear water	forest and shrubs	healthy vegetation	shallow or turbid water	Brown soil/clay	White soil/sand	unclassified	accuracy
Deep or clear water	98	0	0	0	0	0	0	1
forest and shrubs	0	29	0	0	0	0	0	1
healthy vegetation	0	37	42	0	4	0	0	0.51
Shallow or turbid water	0	0	0	63	0	0	0	1
Brown soil/clay	0	0	0	0	125	0	0	1
White soil/sand	0	0	0	0	0	89	0	1
reliability	1	0.44	1	1	0.97	1		

Appendix B.3. Measured depths from sampled small reservoirs

Reservoir ID	name	depth (m)
1	Matambo	5
3	Matsenyane	4
7	Sivume	2
8	Dondoriyo	4
13	Makhanka	7
15	Mgodi	4.5
19	Langaphakathi 1	5
21	Langaphakathi 2	4
23	Sophaphu	3
27	Ngonyama	4
	average depth, D	**4.25**