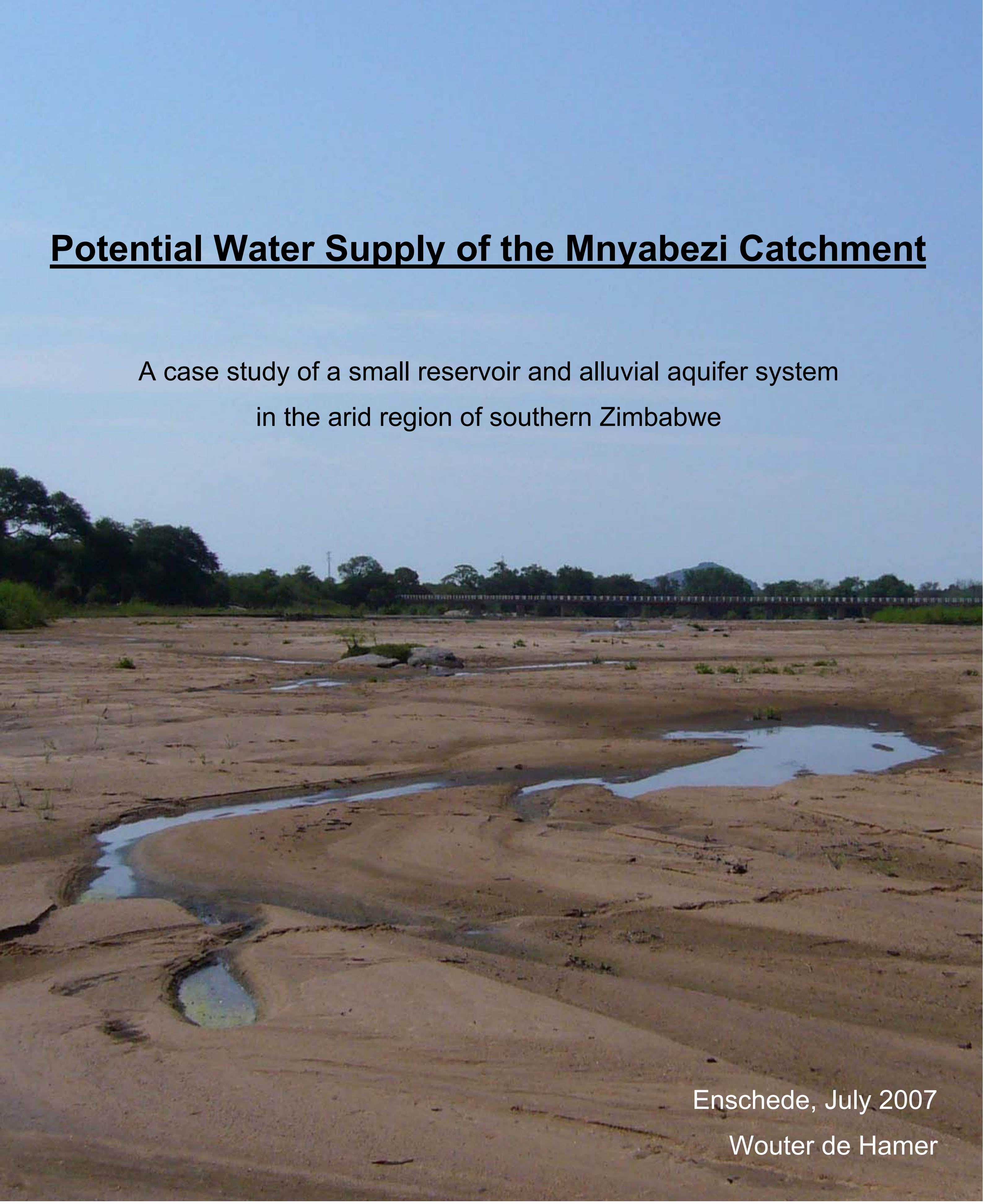

Potential Water Supply of the Mnyabezi Catchment

A case study of a small reservoir and alluvial aquifer system
in the arid region of southern Zimbabwe

Enschede, July 2007

Wouter de Hamer

WATERnet
CGIAR Challenge Program on WATER & FOOD
University of Twente
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Title	Potential Water Supply of the Mnyabezi Catchment: a case study of a small reservoir and alluvial aquifer system in the arid region of southern Zimbabwe	
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Project	This study represents Wouter de Hamer’s thesis to the MSc degree in Water Engineering & Management at the University of Twente.	
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Acknowledgements

Six months ago, I started to work on this research for my graduation to the MSc degree in Water Engineering & Management at the University of Twente. At the end of this period, the time has come to evaluate my research and thank some people who were very important for me.

Zimbabwe is not the first country thinking of for your graduation, because of its bad political and economical situation, but I have experienced these working conditions as a challenge. On the 6th of February, I flew to Harare knowing nothing more than the name of my supervisor, the company I would work for and the address I would sleep at. Already in the first week, I visited my study area in southern Zimbabwe, met several local people, experienced the African hospitality and knew this would become a fabulous time. Due to the alternation between fieldwork and desktop work, and the integration between several subjects in the field of geology, hydrology, ecology, soil science and water resource management, I have experienced my graduation period as very interesting and pleasant time.

Several people have assisted me during my research. First, I would like to thank my supervisors. Martijn, you always responded very elaborately on my questions, which was of great importance to improve my report adequately. Arjen, thank for the opportunity you gave me to do my graduation in Zimbabwe and your comments on mainly the structure of the report. David, your invitation to stay at your home in Zimbabwe says much about your hospitality and kindness. Thanks for your assistance and great time in Zimbabwe! I wish you all the best coming years with Faith and your daughter Kathleen. Patrick and Tutanang, I owe you much gratitude for your help during my field trips and the daily readings of the measuring equipments. Richard, your experience with the MODFLOW-model was of great help to me. At last, I would like to thank the people at WaterNet - Zimbabwe, ICRISAT - Bulawayo, Dabane Trust, the Zimbabwean Water Authority (ZINWA), the department of Civil Engineering and the department of Geology at the University of Zimbabwe for facilitating me with several things during my research period.

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Wouter de Hamer

Abstract

In the arid regions of southern Zimbabwe, dam reservoirs normally meet the domestic and agricultural water requirements of smallholder farmers in dry periods. Groundwater use by accessing alluvial aquifers of non-perennial rivers can be an important extra water resource. However, the storage capacity of alluvial aquifers is not used very intensively in southern Zimbabwe at this moment. The research objective is to calculate the potential water supply for the upper-Mnyabezi catchment in the arid region of southern Zimbabwe under current conditions and after implementation of two storage capacity measures. These measures are heightening the spillway of the Mnyabezi dam and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River. The upper-Mnyabezi catchment covers 22 km^2 and is a tributary of the Thuli River in southern Zimbabwe.

In this study, three coupled models are used to simulate the hydrological processes in the Mnyabezi catchment. The first is a rainfall-runoff model, based on the SCS-method. The second model is a spreadsheet-based water balance model of the dam reservoir, which is used to calculate the water level in the reservoir. This model has three functions; i) simulate the water balance of the reservoir, ii) calculate the potential water supply and iii) calculate the days of dam overflow. The finite difference groundwater model MODFLOW is used to simulate the water balance and drying process of the alluvial aquifer for a section of 1.0 km downstream of the Mnyabezi dam. For the calibration process, daily measured data from the period March to May 2007 is used.

Under current conditions, the period of water supply ranges from 5.7 months in an extreme dry year (total amount of water supply is 2,107 m^3) to 8.7 months in an extreme wet year (total amount of water supply is 3,162 m^3). In the case of a heightened spillway, the potential water supply increases respectively with 417 m^3 and 139 m^3. When constructing a sand storage dam in the alluvial aquifer, the potential water supply increases respectively with 252 m^3 and 316 m^3. After these two water management measures are implemented, the maximum period of water supply in an extreme dry year is 8.4 months (total amount of water supply is 2,776 m^3) and in an extreme wet year 10.8 months (total amount of water supply is 3,617 m^3).

For the Mnyabezi catchment, the alluvial aquifer is too small to sustain a storage capacity large enough to supply water whole year round. Thus, a sand storage dam can only be used as an additional water resource. However, when an ephemeral river is underlain by a larger alluvial aquifer, a sand storage dam is a promising way of water supply for smallholder farmers in southern Zimbabwe.

Contents

1. Introduction

This chapter introduces the water resource management problems in (semi-)arid regions and in particular to the Limpopo basin. Furthermore, this chapter provides insight into the way this MSc-thesis contributes to these problems by defining a research scope and objective. At last, an outline for the report is presented.

1.1 UN Millennium Development Goals

In the year 2000, the governments of the world adopted eight UN Millennium Development Goals as a blueprint to achieve a better world in the 21st century. These Millennium Development Goals try to meet the needs of the world's poorest on issues like poverty, health and education. The first millennium goal is to halve the proportion of people who suffer from hunger between 1990 and 2015 (UN Millennium Project, 2005). Approximately 50 % of the 850 million people living in serious and chronic hunger worldwide are smallholder farmers (FAO, 2004). For this reason the Millennium Project recommendations on rural development and food security focuses on improving the production and livelihoods of smallholder farmers (UN Millennium Project, 2005).

The Millennium Development Goals' target to halve the proportion of people who suffer from hunger is extremely important in southern Africa, where food security has become increasingly problematic. Although the poverty rate declined marginally, the number of people living in extreme poverty in southern Africa increased by 140 million between 1990 and 2005 (UN Millennium Project, 2005). Agriculture by smallholder farmers is the dominant economic activity in these countries, accounting for approximately 70 % of total employment (Love et al., 2006). Despite the technological advances in agricultural research in recent years, poverty, food insecurity and malnutrition remain major challenges in southern Africa (Sanchez & Swami Nathan, 2005).

1.2 Water availability in southern Africa

Agriculture by smallholder farmers in southern Africa is largely rain fed, which is risky in the event of recurrent droughts (Twomlow & Bruneau, 2000). A drought is a period of months or years in which a region suffers from a deficit in its water supply. A deficit in water supply occurs when the amount of available water is not enough to meet the local agricultural and domestic water requirements. To unlock paths for more food security and to improve the livelihoods of smallholder farmers, integrated water resource management (IWRM) is a basic requirement (Falkenmark & Rockström, 2003). IWRM is defined by Mostert et al. (1999) as "the management of the water system, being part of the broader natural environment and in relation to their socio-economic environment".

An example of a poverty-stricken area in southern Africa is the Limpopo basin (see figure 1***Figure 1***). The basin covers an area of approximately 282,000 km^2 and is draining an extensive area of Botswana, South Africa, Zimbabwe and Mozambique. Approximately 14 million people live in this basin area. Translating IWRM from concept to action, to secure water availability and food production for smallholder farmers, remains largely undone in this area (Love et al., 2004). New policies and structures developed by the water reforms since 1990 do not generally penetrate to the smallholder farmer (Jaspers, 2003). Water policy and institutions in the Limpopo Basin are mainly concerned with water for large-scale irrigation, cities, mines and industry, while rain fed agriculture is sustaining the production of smallholder farmers (Love et al., 2004).

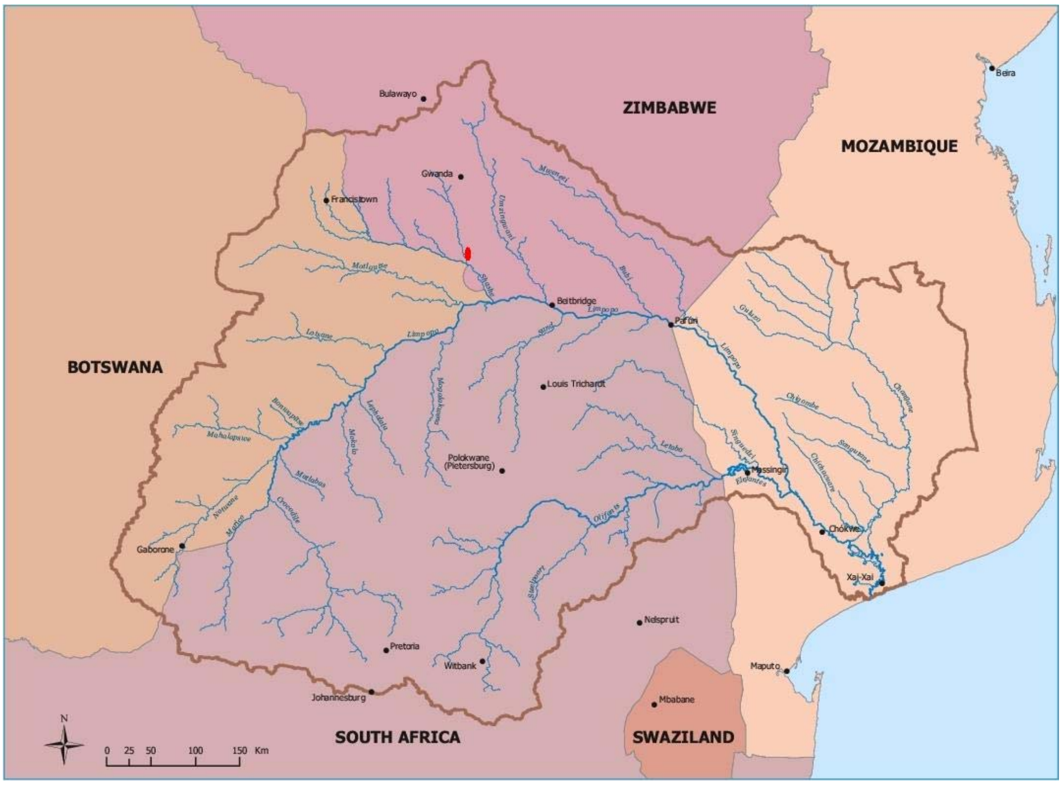

Figure 1: The Limpopo basin; the red dot indicates the location of the Mnyabezi catchment (INGC, 2003)

The rain fed production of food in semi-arid regions is risky and crop failure often occurs (Mwenge Kahinda, 2004; Mwakalila, 2006). Besides, many smallholder farmers cultivate on poor soils, which makes crop yields low (Twomlow & Bruneau, 2000). Mwakalila (2006) demonstrated for an arid area in Tanzania that the return on labour for smallholder farmers who irrigate their fields is about three times as high as smallholder farmers who cultivate rain-fed fields. Nevertheless, access to irrigation water for smallholder farmers remains limited in the Limpopo basin (Love et al., 2006). In the past, large-scale irrigation projects for food security have often failed due to the high maintenance costs. Therefore, the Millennium Project urges the use of appropriate irrigation technology such as low-cost drip kits (Moyo et al., 2006). Drip technology tends to improve water use efficiency, compared to the initial situation, but does not always increase yield especially during dry seasons (Maisiri et al., 2005). Alternatively, the availability of water can be improved through agricultural interventions in dry land farming (Twomlow et al., 1999; Woltering, 2005), through supplementary irrigation using rainwater harvesting (Mwenge Kahinda, 2004) or by accessing alluvial aquifers (Dahlin & Owen, 2005; Moyce et al., 2006).

1.3 WaterNet Challenge Program on Food and Water

WaterNet is a regional network in southern Africa of university departments and research and training institutes specialized in water resource management. The mission of WaterNet is to “enable the people of southern Africa to efficiently and effectively manage their water resources” (WaterNet, 2001). As elaborated on in the previous section, the high-risk failure of rain fed agriculture has a negative influence on food security in the Limpopo basin. This problem formed the basis for WaterNet to develop a project under the Challenge Program on Water and Food. The Challenge Program is a research initiative of the Consultative Group on International Agricultural Research (CGIAR). The overall goal of the WaterNet Challenge Program is contributing to the improvement of rural livelihoods of smallholder farmers through the development of an IWRM framework for increased productive use of water and risk management for drought and dry-spell mitigation at all scales in the Limpopo basin (WaterNet, 2004). The research focuses on three pilot sub-catchments of the Limpopo River basin in Zimbabwe (Mzingwane catchment), Mozambique (Chòkwé catchment) and South Africa (Olifants catchment).

1.4 Project scope

In the arid regions of the world, rivers are mostly non-perennial (do not flow throughout the year). These arid areas centre along the tropics, north and south of the equator, where over a billion people in 110 countries live on more than 30 % of the Earth’s surface. Twenty African countries have more than 90 % of their productive lands in vulnerable arid regions, illustrating the human dimensions of the issue (Turnbull, 2002). Although drought is a normal occurrence in arid regions, people are often unprepared when it happens. Periods of drought often result in increased pressure on the surface and subsurface water resources as well as the vegetation associated with non-perennial rivers (Seely et al., 2003).

In the arid regions of Zimbabwe, dam reservoirs meet the domestic and agricultural water requirements of smallholder farmers in dry periods. However, a few months after the main rainy season these reservoirs dry out during years with little rainfall. Groundwater use by accessing alluvial aquifers of non-perennial rivers can be an important additional water resource, because in several arid regions people harvest water from these systems during droughts. Barker & Molle (2004) describe an alluvial aquifer as a groundwater unit, generally unconfined, hosted in laterally discontinuous layers of sand, silt and clay and deposited by a river in a river channel, banks or flood plain. On a small scale, alluvial aquifers in large perennial rivers meet agricultural and domestic water requirements in southern Africa (Seely et al, 2003; Love, 2006b). The groundwater storage of the alluvial aquifers of these large rivers, has a large potential water supply (Owen & Dahlin, 2005; Moyce et al., 2006). However, most smallholder farmers in southern Zimbabwe live near to smaller non-perennial rivers that make research to groundwater resources in these smaller alluvial aquifers interesting. In this study, with 'small non-perennial rivers' is meant a water systems with a catchment below 500 km^2.

This MSc-thesis concentrates on the hydrological processes occurring in the upper-Mnyabezi catchment. The upper-Mnyabezi catchment covers 22 km^2 and is situated in southern Zimbabwe (see figure 1; the red dot indicates the location of the catchment). Water is stored in the Mnyabezi dam reservoir (caused by human intervention) and in the alluvial aquifer of the Mnyabezi River (which is a natural process). These two ways of water storage ensure a water resource during the dry season for plants, animals and people, but is still not enough to bridge the gap of surface water shortage in a normal or dry year. Possible water management interventions to improve the total storage in the upper-Mnyabezi catchment are the heightening of the spillway of the reservoir dam, and the construction of a sand storage dam in the alluvial aquifer.

1.5 Research objective

The research objective is to calculate the potential water supply for the upper-Mnyabezi catchment in the arid region of southern Zimbabwe for current conditions and after implementation of two storage capacity measures. These measures are heightening the spillway of the Mnyabezi dam reservoir and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River.

<u>What is not included</u>

The study concentrates on surface water and sub-surface groundwater. Thus, it does not monitor groundwater storage in deeper layers. Furthermore, the research does not focus on the water quality. Possible long-term changes in input parameters and variables, for example due to climate change or change in land use, has not been taken into account as well.

Research questions

The formulation of research questions is important to acquire the knowledge, which is essential to answer the research objective.

a) What are the hydro(geo)logical characteristics of the upper-Mnyabezi catchment, the Mnyabezi dam reservoir and the alluvial aquifer system of the Mnyabezi River?

b) What are the relations between the inflows and outflows (water balance) of the upper-Mnyabezi catchment, the Mnyabezi dam reservoir and the alluvial aquifer system of the Mnyabezi River?

c) What are the influences on the amount of water supply, when heightening the spillway of the Mnyabezi dam reservoir and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River?

1.6 Outline

This report provides insight into the hydrological processes in a small catchment in the arid regions of southern Zimbabwe. The results contribute to the drought problems in small catchments in the Limpopo Basin as explained in section 1.2. The second chapter describes the theoretical background information about alluvial aquifer systems. The third chapter explains the characteristics of the study area. The fourth chapter clarifies the research, modelling and measuring methods. The fifth chapter presents the field measurement results and the sixth chapter the results of the calibration of the models. The seventh chapter is dedicated to the analysis of the results and the calculation of the potential water supply. The study ends with the conclusion of the MSc-thesis.

2. Literature Study

This chapter explains the theoretical concepts used in this MSc-thesis, concentrating on alluvial aquifer systems. The first section explains the definition of the river continuum. The second and third sections describe the complex water system of alluvial aquifer. The last section provides a review about the water use of alluvial aquifer systems and reservoirs of non-perennial rivers in arid regions of southern Africa.

2.1 Definition of the river continuum

In humid climates, rivers are generally perennial. Perennial rivers are characterized by periodic high flow events of varying magnitude and duration (occurring in response to individual rainfall events), superimposed on continuous, more slowly varying low flows derived from drainage out of catchment storages, including soil moisture, ground water and surface water (Hughes, 2005). In arid regions, most rivers are non-perennial (also referred to as temporal). Regarding hydroclimatic conditions, several different definitions of a (semi-)arid tropical environment exist. In this study the definition mentioned by Sandstrom (1997), based on annual values of rainfall in tropical dry lands, is used; 500 – 900 mm is semi-arid, 200 – 500 mm is arid and less than 200 mm per year is a hyper-arid area.

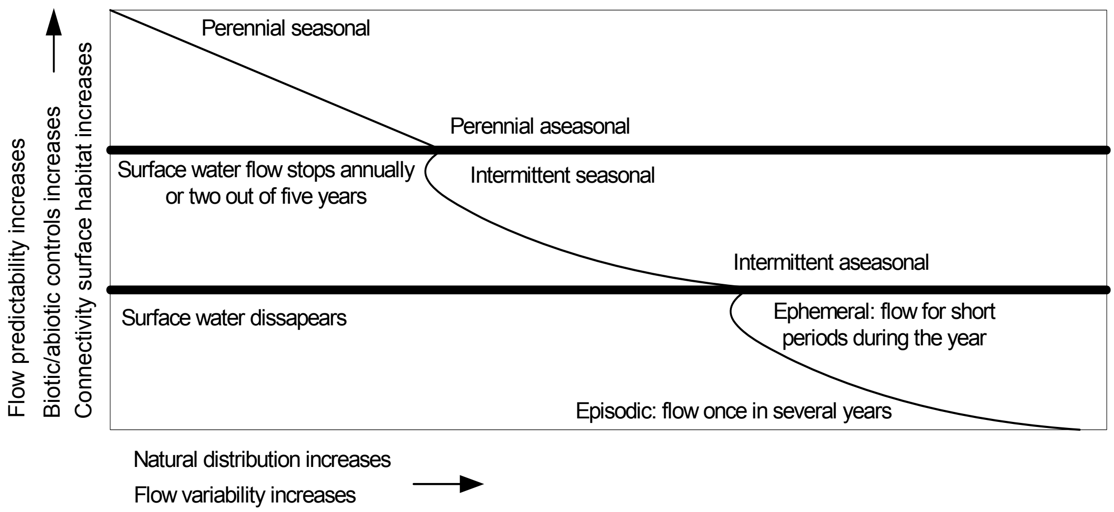

Figure 2: River continuum (Uys & O'Keeffe, 1997)

Non-perennial rivers are characterized by the phenomenon that flow stops and surface water may disappear along parts of the channel either yearly or during two or more years in a five-year period (Rossouw et al., 2005). Various authors have attempted to classify non-perennial rivers according to the percentage of annual flow, source of flow and periodicity of flow into for example ephemeral and intermittent streams. However, other descriptive terms such as seasonal and episodic rivers confuse the terminology. Uys & O'Keeffe (1997) provide a functional classification for non-perennial rivers (see figure 2). The most important characteristic of this classification is the definition of two hydrological state changes, which results in major biotic and a-biotic changes in the river system. The non-perennial river continuum represents these stages as steps.

The first step is where surface water flow stops, but surface water is still present in pools in the majority of a channel. The so-called intermittent rivers cease to flow and dry partly for a variable period during the year, or for two or more years in a five-year period. Flow may recommence seasonally, or highly variable (a-seasonal), depending on climatic influences and predictability of rainfall. An intermittent river may experience several cycles of flow and drying in a single year.

The second step is where surface water totally disappears from the majority of the channel. Ephemeral rivers flow for a shorter period than they are dry. They flow, in response to unpredictable high rainfall events, for short periods of most years during a five-year period. The rivers support a series of pools in parts of the channel. Episodic rivers are highly flashy systems that flow or flood only in response to extreme rainfall events, usually high in their catchments. They may not flow in a five-year period, or may flow only once in several years.

2.2 Hydrological characteristics of alluvial aquifers

Ephemeral and intermittent rivers primary drain (semi-)arid regions of the world. These arid regions are typically subjected to occasional high rainfall events and a consequent high degree of surface erosion (Nord, 1985). The rivers are not able to cope with the large sediment load, which cause settlement of large amounts of sand within the river channel. As a result, many of the rivers have become so-called 'sand rivers' (Hussey, 2003). 'Sand rivers' refer to the dry riverbed and the underlying alluvial aquifer, which usually contains groundwater throughout the year. Because of their shallow depth and vicinity to the streambed, alluvial aquifers have a direct relationship with the stream flow (Townley, 1998) and can significantly contribute to the water balance (De Vries & Simmers, 2002). River flow usually dominates recharge of alluvial aquifers (Nord, 1985; Owen & Dahlin, 2005). As a flood travels down a non-perennial river, water infiltrates into the sandy and gravel alluvial deposits of the channel beds. The amount of recharge depends on the intensity, volume and duration of a flood (Heyns et al., 1997). In non-perennial rivers in Botswana and Zimbabwe flow only occurs after the aquifer channel sands have become fully saturated (Nord, 1985; Hughes, 2005; Owen & Dahlin, 2005). Figure 3 shows the groundwater table development typical for alluvial aquifer systems. After a rainfall event, the groundwater table declines away from the stream, and thus groundwater flow leaks away from alluvial aquifer into the underlying granite (Sandstrom, 1997). Groundwater stored in the riverbed can also be perched above the weathered basement (Wikner, 1980; Davis et al., 1995; Anderson, 1997). Silt and fine sediments form an almost impermeable seal at the base of the river channel, which prevent seepage into the underlying basement layer.

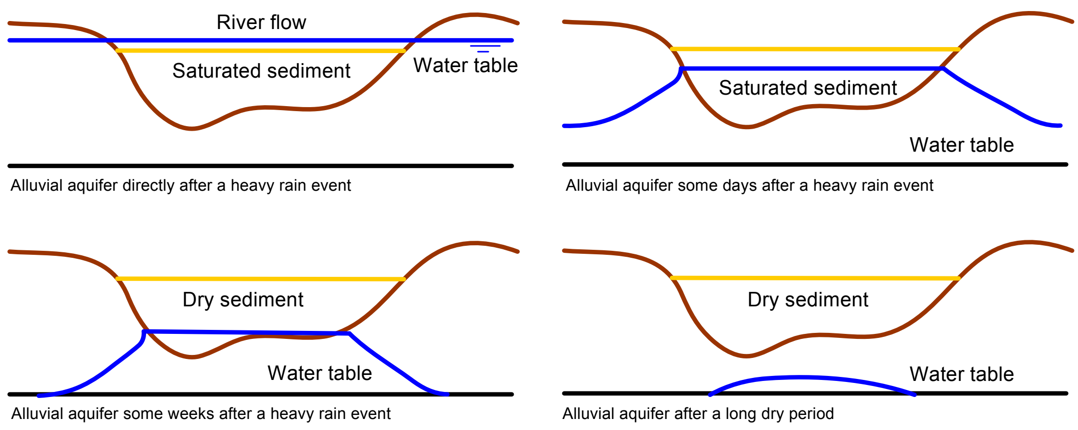

Figure 3: Groundwater development for alluvial aquifer systems (Hussey, 2003)

The recharge of alluvial aquifers ensures a water source during the dry season for plants, animals and people (Jacobson et al., 1995). The recharge process is therefore fundamental to an understanding of livelihood conditions and the sustainability of different types of water consuming activities. In arid areas, evaporation and transpiration have great effect on the hydrological cycle and thereby on the availability of water for vegetation (Sandstrom, 1997). Wipplinger (1958) and Nord (1985) showed the evaporation following saturation causing a 0.9 m drop of the groundwater table within three months. Evaporation stops when the water table recedes 0.9 m below the surface of the sand. Below this elevation, water is only lost due to evapotranspiration by riparian vegetation and leakage to deeper layers. Riparian vegetation can determine the character of the river. Gorgens & Lee (1992) show that removal of vegetation increases the total runoff in a South African catchment. Additionally, when eucalyptus plantations grow in the riverbanks a perennial river may turn ephemeral.

Despite the high hydraulic conductivity, the groundwater flow through the alluvial aquifers itself is rather slow due to the gentle slopes. Nord (1985) estimated the water velocity roughly to be about 1 – 2 m per day. During the dry season, the seepage and evapotranspiration are the main losses in alluvial aquifers. The groundwater flow in these smaller systems even seem to cease towards the end of the dry season, while there is still a substantial subsurface flow in the larger alluvial aquifers (Nord, 1985).

2.3 Water balance of an alluvial aquifer system

Sustainable water resource management requires an understanding of the hydrological processes dominant in an aquifers-river system (Uhlenbrook et al., 2004), therefore there is a need to quantify the water balance of such a system. The water balance is the equilibrium between the volume of water inputs, outputs and net changes over a fixed period in the alluvial aquifer (Shaw, 1994). The water balances of an alluvial aquifer and a river are presented in equations 1 and 2 (Schicht & Walton, 1961; Healy & Cook, 2002). Figure 4 visualizes the flows of the water balance of the alluvial aquifer system.

$$\Delta S_{ground} = Q_{ground,in} - Q_{ground,out} + Q_{leakage} - Q_{seepage} + -Q_{pump} - E + P \qquad (1)$$

$$\Delta S_{stream} = -Q_{leakage} + Q_{stream,in} - Q_{stream,out} \qquad (2)$$

Where all variables are in equal units [mm·day^{-1}],
ΔS_{ground} *is the change in groundwater storage,*
ΔS_{stream} *is the change in surface water storage,*
$Q_{leakage}$ *is the leakage from the river to the aquifer,*
$Q_{seepage}$ *is the seepage from the alluvial aquifer to the underlying ground layer,*
Q_{pump} *includes the amount of pumping,*
$Q_{ground,in} - Q_{ground,out}$ *is the net groundwater water flows,*
$Q_{stream,in} - Q_{stream,out}$ *is the net surface water flow,*
E is evapotranspiration from the unsaturated zone and
P is the precipitation, which percolates through the unsaturated zone.

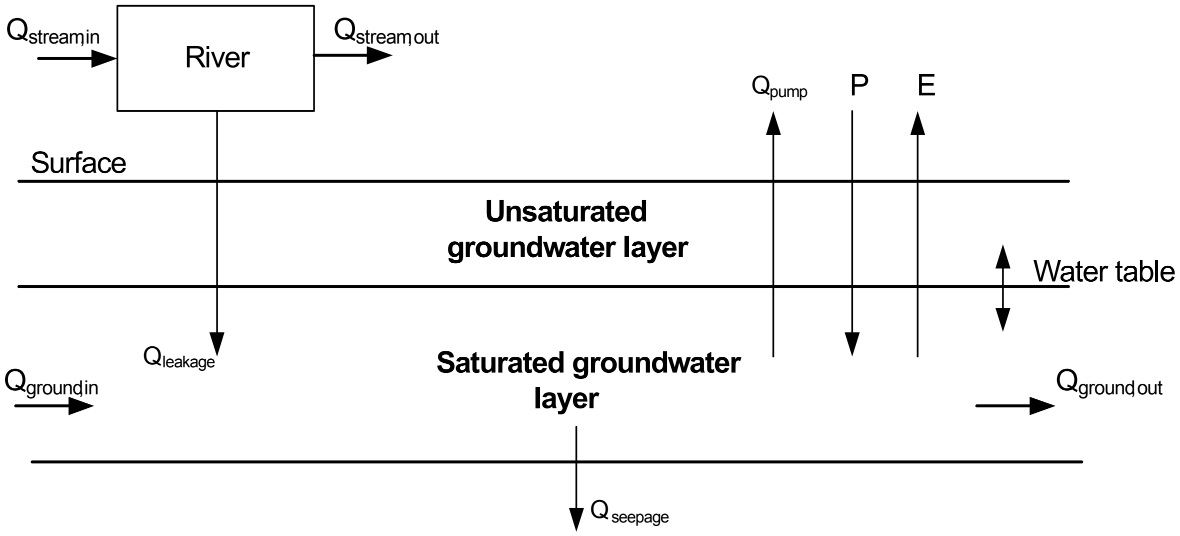

Figure 4: Water balance of an alluvial aquifer

Figure 4 visualizes the river as an isolated unit, while in nature the stream partially penetrates the unconfined aquifer (Osman & Bruen, 2002). This distinction between the surface water and groundwater flows is common in surface-groundwater models (Harbaugh, 2005; Arnold & Fohrer, 2005). The figure does not show lateral flows, but these form a part of the groundwater in- and outflow as well. In this MSc-thesis, a surface-groundwater model simulates the water balance of a small section of the Mnyabezi alluvial aquifer system.

Traditionally, groundwater models solve surface water without much detail. Similarly, groundwater models applied to aquifer-management problems assesses surface water without much detail (El-Kadi, 1989). Nowadays, alluvial aquifer systems can be modelled using a surface water model, with a groundwater component, such as SWAT (Arnold et al., 1993; Arnold et al., 1998; Arnold & Fohrer, 2005), or using a groundwater model with a stream component, such as MODFLOW (McDonald & Harbraugh, 1988; Harbaugh, 2005). Alternatively, a coupling between a surface water model and a groundwater model can be made with continuous communication or as a single integrated model. A drawback is that the increased flexibility comes at the expense of increased complexity. Another major source of difficulty in coupling surface- and groundwater models is the intrinsic difference in time scales between the two systems (Sophocleous & Perkins, 2000).

2.4 Water use in arid regions

In the arid regions of Zimbabwe, normally dam reservoirs meet the domestic and agricultural water requirements of smallholder farmers in dry periods. The rapid accumulation of silt in the reservoirs reduces the functionality of most reservoirs. In practice, cattle are the only consumer of the water in the smaller reservoir dams. Under normal circumstances, these reservoirs dry out a few months after the main rainy season. During these droughts, cattle have to move to other places or people have to pump the water from deeper groundwater layers. At several places in southern Zimbabwe the spillway of reservoirs are heightened to increase the period of water availability in the reservoirs. However, this heightening is limited to the strength of the dam.

An important feature of ephemeral rivers is that although the surface of a river channel may remain dry for most of the year, there is usually a significant volume of water stored in the alluvial aquifers of these rivers (Jacobson et al., 1995; Seely et al., 2003; Moyce et al., 2006). Thus, in arid regions groundwater use by accessing alluvial aquifers of ephemeral rivers can be important to meet the domestic and agricultural water requirements in dry periods. Boreholes and pumps along intermittent rivers already make water accessible for communities of southern Africa all year round. Examples are the water abstractions along the Mzingwane, Shashe and Save River in Zimbabwe (Hussey, 2003; Love, 2006b). The water supports farms and plantations by irrigation schemes. The alluvial aquifers of these larger non-perennial rivers in southern Zimbabwe do have a large potential water supply (Owen & Dahlin, 2005; Moyce et al., 2006). One small hand pump in such an alluvial aquifer is sufficient to supply the domestic water requirements and can adequately water more than 200 m^2 of garden (Hussey, 2003). On a smaller scale communities in the (semi-) arid regions of southern Africa, for example in western Namibia and southern Zimbabwe, dig wells in the riverbed of ephemeral systems after floods to obtain water for human and livestock consumption (Seely et al., 2003; Love, 2006b).

To improve the storage and use of groundwater in alluvial aquifers it is possible to build groundwater dams. An advantage of water abstractions from alluvial aquifers is that due to the natural filtration effect of sand, the water from alluvial aquifers contain only small quantities of particulate contaminants and is considerably less polluted with bacteria contaminants than surface water (Hussey, 2003). There are two types of groundwater dams; subsurface and sand storage dam (Hanson, 1987). Subsurface dams are constructed below ground level and arrest groundwater flow in an alluvial aquifer, which is fed by natural groundwater. Sand storage dams store water in sediments caused to accumulate by the dam itself. The sediment becomes only saturated after a river flow event. Sand storage dams can hold more water due to the larger dimensions, but require a substantial amount of sediment accumulation to fill the storage dam every year. Figure 5 shows the principle of a sand storage dam, where every stage represents one year of sediment accumulation upstream of the sand storage dam. Wipplinger (1958) has experimentally established that a slope of approximately 0.3 % is minimum required.

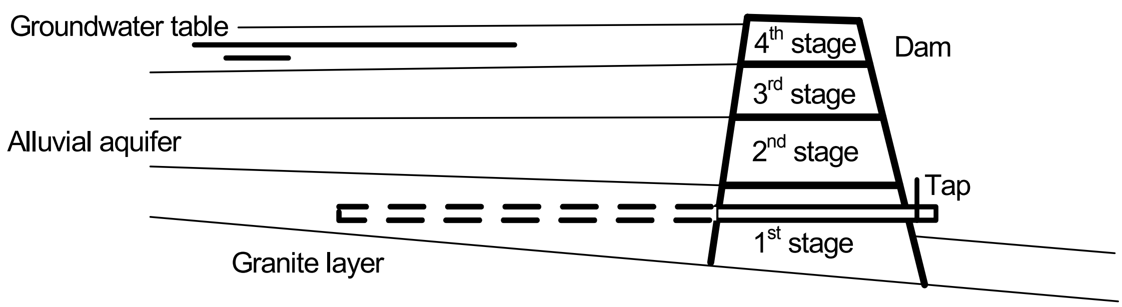

Figure 5: Sand storage dam; every stage representing one year of sediment accumulation upstream of the dam.

Most smallholder farmers in southern Zimbabwe live near to small ephemeral rivers. At this moment, little research is done on these smaller alluvial aquifer systems and the possibilities to increase the water supply. This study concentrates on the potential water supply of a small alluvial aquifer in the Mnyabezi River in southern Zimbabwe (see chapter 3) available for local smallholder farmers.

3. Study Area

This chapter describes the study area of the Mnyabezi catchment. The first section describes the general characteristics of Mnyabezi catchment. The second and third sections provide the precipitation and evapotranspiration within this area. The last section presents the hydrogeological characteristics of the Mnyabezi catchment.

3.1 General characteristics of the Mnyabezi catchment

The study area is located upstream of the Mnyabezi reservoir dam. The river upstream of the dam is about 8 km long and the study area covers approximately 22 km^2 (see figure 6). The study also concentrates on the alluvial aquifer 1.0 km downstream of the dam. The Mnyabezi River is a tributary of the Thuli River (Tuli River) in the arid region of southern Zimbabwe. The Thuli catchment is part of the Limpopo basin and covers an area of approximately 9,710 km^2 (Love, 2006c). The red dot in figure 1 shows the location of the Mnyabezi catchment.

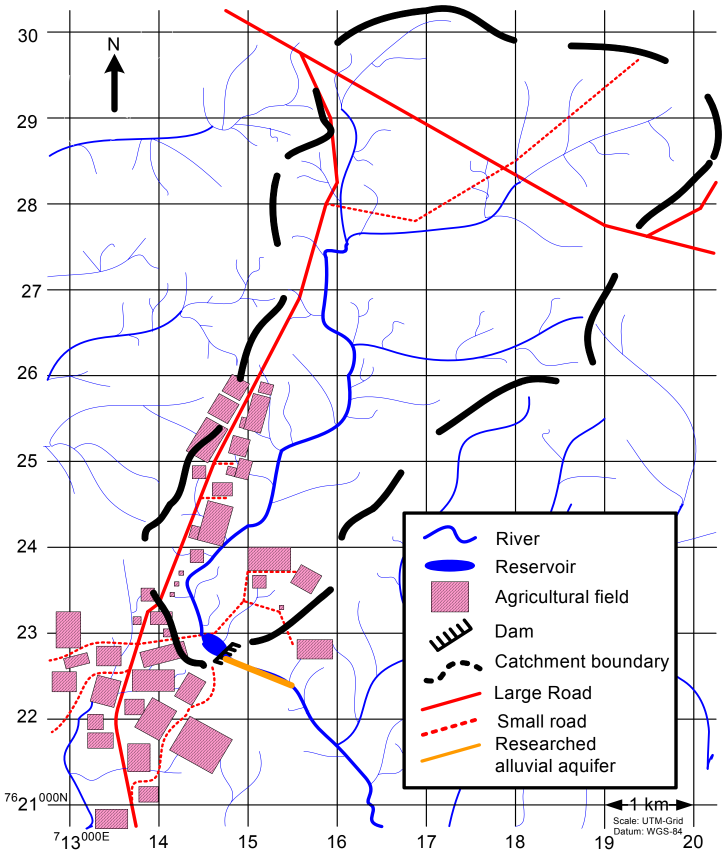

Figure 6: Mnyabezi catchment

The catchment soil consists of sandy loam soils and the underlying layer consists of weathered granite. The soil layer is shallow to moderately deep and is on average 50 cm thick (Moyo, 2001). The land use is a mixture of agricultural fields (4.0 %), farmsteads (0.5 %) and sparsely wooded degraded rangeland (95.5 %) where cattle graze.

3.2 Precipitation in the Mnyabezi catchment

A meteorological year is divided into four seasons, shown in table 1 (Meteorological Service of Zimbabwe, 1981). There is considerable variation from year to year in the time of change from one season to another. Moreover, the changes may be abrupt or gradual. The main rains tend to start and finish earlier in the south compared to the north.

Table 1: Seasons in Zimbabwe (Meteorological Service of Zimbabwe, 1981)

Season	Period
Cool season	Mid-May to August
Hot season	September to mid-November
Main rainy season	Mid-November to mid-March
Post-rainy season	Mid-March to mid-May

The rainfall in the region is erratic and ranges between 148 and 628 mm per meteorological year. The average rainfall is 385 mm per meteorological year. These values are based on data from 1987 – 2000 of the meteorological station at the Thuli Estate (approximately 20 km from the Mnyabezi catchment). This makes the area arid according to the definition of Sandstorm (1997; section 2.1).

3.3 Evapotranspiration in the Mnyabezi catchment

The open water evaporation in southern Zimbabwe ranges from 3.2 $mm \cdot day^{-1}$ in June to 8.0 $mm \cdot day^{-1}$ in January (Department of Meteorological Services Zimbabwe, 1981). These values are monthly averages, so the daily values are more variable according to changes in temperature and cloud conditions. The main vegetation types in the rangelands are Colosphermum Mopane and Acasia Combretum Terminalia (Coates Palgrave, 1997). The high drought tolerance characterizes these species, which is essential for survival in these arid areas. Along the alluvial aquifers, also less drought resistant species are found. In temperate climates, the greatest evapotranspiration limiting factor is available energy, whereas in arid regions, it is the availability of water. Due to the high evapotranspiration rates in arid regions, the recharge from the soil surface to the deeper groundwater is very low. As expressed by Barnes et al. (1994), most water from rainfall only penetrates the top meter from where water from the unsaturated zone is systematically removed by arid vegetation and by soil evaporation following capillary rise. Seepage to groundwater is localised to places where rainwater concentrates, for example in streambeds and in reservoirs (Sandstrom, 1997). Nevertheless, high transpiration rates (actual equals potential evapotranspiration) can develop in riparian zones where water supply is plentiful, for example in alluvial aquifers (Graf, 1988).

3.4 Hydrogeological characteristics of the Mnyabezi catchment

The main water use of the nearly silted reservoir is by drinking of cattle (see figure 8). The local community is planning to build a new spillway. The difference in maximum water level from the bottom of the reservoir until the top of the spillway is 0.73 m (for the new spillway it is 1.00 m). When the reservoir is full it covers an area of approximately 1.54 ha and reaches a total volume of 5600 m^3. The reservoir dries up during long periods of drought. In this period, people can still gain water from the alluvial aquifer downstream of the dam for a couple of months. Two pumping wells are located just upstream and downstream from the dam, which are used for domestic purposes and some gardening. The groundwater level is approximately 4.0 m deep.

Figure 7: Alluvial aquifer of the Mnyabezi River

Figure 8: Reservoir of the Mnyabezi River

The Mnyabezi River is highly ephemeral, which means it only flows after a heavy rain event. The alluvial aquifer downstream of the dam (see figure 7) has a width of approximately 10 meter, an average depth of 0.9 m and the slope is 0.28 %. The suggested silt or clay layer at the base of the aquifer by Davis et al. (1995) is not observed in the alluvial aquifer of the Mnyabezi River. The physical probing done during the field visits only indicate some locally thin clay layers at several depths, but the main material is fine to medium sand. The underlying granite layer has optimum weathering conditions. The vegetation along the aquifer is very drought resistant and is not directly dependent on the water table from the alluvial aquifer itself, because the alluvial aquifer dries out within a month.

4. Method

This chapter describes the methods used in this research. The first section explains the calculation of the potential water supply. The second and third sections describe the modelling process. The fourth section explains the measuring strategy for all the parameters and variables. The last section explains the calibration process of the models.

4.1 Calculation potential water supply

In this study, three coupled models are used to simulate the hydrological processes in the Mnyabezi catchment. A rainfall-runoff model is used to calculate the surface water runoff caused by precipitation. The runoff is the inflow variable for the dam reservoir model, which is used to simulate the water level in the reservoir. This model has three functions; i) simulate the water balance of the reservoir, ii) calculate the potential water supply and iii) calculate the days of dam overflow. The outcomes are calculated for current conditions and with a heightened spillway. The groundwater model is used to simulate the groundwater level s in the alluvial aquifer downstream of the dam. The output of groundwater model is the water balance and the potential water supply of the alluvial aquifer for the current situation and after the construction of a sand storage dam. In theory, the heightening of the dam could have influence on the days of dam overflow (recharge of the alluvial aquifer). In practice, rain events in the arid regions of southern Zimbabwe are always very heavy, which makes dam overflow not dependent on the dam height. Figure 9 visualises the flows between the models.

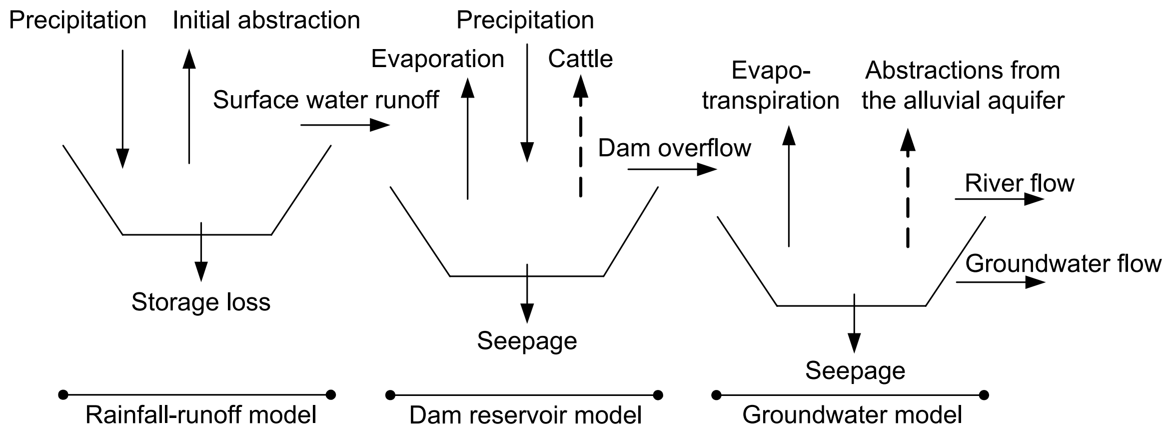

Figure 9: Schematization of flows between hydrological models; the dashed lines represent the potential water supply

Because of the sluggishness of the groundwater system, groundwater models usually use a monthly time step (Sophocleous & Perkins, 2000). However, the alluvial aquifers in the arid regions recharge relatively fast to normal conditions (Gorgens & Boroto, 1997; Moyce et al., 2006). Furthermore, the Mnyabezi River is highly ephemeral and thus only flows during and a short period after a rainfall event. These short hydrological processes require at least a daily time step for the modelling process. A daily modelling step requires daily input data as well, which has been collected between March 2007 until May 2007.

Every year the dispersion of rainfall events and the amount of rainfall differs. Consequently, the potential water supply differs for each year as well. The focus of the study is to calculate the potential water supply and the period of drought during a typical dry, normal and wet year. Note that in arid regions, the dispersion of rainfall events during a year mainly determines if a year will be typified as dry, moderate or wet. A period starting at the beginning of the main rainy season (1^{st} of November) until the end of the hot season (31^{st} of October) is used to make a year simulation. Three typical years are selected from the daily rainfall records of the Thuli Estate meteorological station between 1987 and 2000. A typical dry year was '88/'89 (259.2 mm), a normal year was '97/'98 (331.9 mm) and wet year was '96/'97 (568.4 mm).

4.2 Rainfall-runoff model

The rainfall-runoff model is a spreadsheet-based program, which is used to simulate the rainfall-runoff response of the catchment upstream the Mnyabezi reservoir. Earlier studies used semi-distributed models such as Monash and Pitman in arid regions of southern Africa (Hughes, 1995; Anderson, 1997). These models require many parameters, representing specific catchment characteristics. This study aims to simplify the hydrological processes by some lumped parameters, due to the relative short period of data collection. For small catchments, the most simple rainfall-runoff models are the Rational Method (Lloyd-Davies, 1906) and the SCS-method (USDA-SCS, 1986). The Rational Method is often applied in urban areas, and the SCS-method in sub-urban and rural areas (Dingman, 2002). For this reason, the SCS method is applied to simulate the rainfall-runoff processes in the Mnyabezi catchment. The method relates the discharge (Q) to total rainfall (P) and storage capacity via an empirical relation, presented in equations 3 and 4. The initial abstraction (I_a) is a lumped term for the interception of rainfall, depression storage and infiltration before the start of runoff. After runoff starts, all additional rainfall becomes either runoff or actual retention (S). The actual retention (S) is based on the CN-value, which is dependent on four characteristics: land use, land treatment, antecedent moisture conditions and hydrological soil group. The relations between these parameters are provided in tables, which are represented in appendix V.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad (3)$$

$$S = \frac{25400}{CN} - 254 \quad (4)$$

Where ,
Q [mm·day^{-1}] is the runoff,
I_a is the initial abstraction,
S [mm·day^{-1}] is the actual retention,
P [mm·day^{-1}] is the precipitation and
CN [-] is the curve number.

4.3 Reservoir model

The spreadsheet-based model directly couples the dam reservoir model and the rainfall-runoff model. The runoff from the Mnyabezi catchment, which is calculated by the SCS-method, forms the inflow variable for the reservoir model. The model also incorporates the variables direct recharge by precipitation, open water evaporation and abstraction by cattle to calculate the water level in the reservoir. Groundwater flow into the reservoir is negligible, because the groundwater table in the underlying granite layer is relatively deep (approximately 4.0 m deep). The model does not simulate pump abstractions by people from this deeper aquifer. It was not possible to measure the seepage loss from the reservoir directly, which is the reason the seepage is used as a fitting parameter during the calibration process.

Besides the determination of the water balance during a dry, normal and wet year, the reservoir model is also used to calculate the potential water supply and the days of dam overflow for the current situation and the situation with a heightened spillway. The potential water supply is the summation of the amount of water that cattle could consume from the reservoir. Dam overflow occurs when the water level in the reservoir is higher than the height of the spillway.

4.4 Groundwater model

The finite difference ground water model MODFLOW (McDonald and Harbaugh 1988; Harbaugh, 2005) divides the alluvial aquifer system into smaller units supposed to be homogeneous in terms of their physical characteristics. Based on this distributed character and the relative small spatial scale of the water system, Visual MODFLOW 4.2 is considered most suitable to simulate the hydrological processes in the alluvial aquifer.

The model consists of three layers (see appendix I). The grid is 230 m in width and 1000 m in length with a horizontal resolution of 5x5 m. The horizontal resolution of the grid, representing the alluvial aquifer and the riverbanks (width 10 m each), has a higher resolution of 2x5 m. The alluvial aquifer is modelled as a rectangular shape with a depth of 0.9 m, a width of 10 m and a slope of 0.28 %. The top layer (0.7 m) represents the soil, the second layer represents the alluvial aquifer and the lowest layer the granite. In the MODFLOW model, hydrogeological characteristics, like hydraulic conductivity, specific yield and porosity, have to be assigned to every layer seperately. Due to the loose characteristic of the alluvial material, the hydrogeological parameters are assumed to be constant in all directions. This is not true for granite due to its complex rock structure. Normally, fresh granite has a very low primary porosity, but granite always has a secondary porosity due to weathering and an interconnected system of fractures, fissures and joints, which allows the flow and storage of groundwater. Due to this secondary porosity the hydraulic conductivity, porosity and specific yield of granite are non-homogeneous. Nevertheless, MODFLOW calculates with average values. Due to the lack of a good measuring method to determine the value of the hydrolgeological parameters of the granite layer, these parameters are changed during the calibration process to make a best fit.

The head difference between the water level in the granite layer and the surface level of the alluvial aquifer is assumed to be constant over the entire length and is used as the initial water head in the MODFLOW model. At the up- and downstream side, a general head boundary condition is used to model the groundwater outflow. The RIVER-package is used to model the recharge from the river to the alluvial aquifer, assuming a constant water level of 1 cm above the riverbed. The streambed conductance is set high (200 $m^{2}\cdot day^{-1}$), which allows the aquifer to recharge completely within one day, like in the natural situation. Direct recharge by precipitation is modelled with the RECHARGE-package, which directly assigns the amount of recharge to the groundwater table. Overland flow due to recharge cannot be simulated in MODFLOW model. This is no problem, because most rain events in arid regions are or very small (negligible overland flow) or very heavy (cause dam overflow, in which case the alluvial aquifer saturates anyway). In the MODFLOW model evapotranspiration can only be assigned to the top-layer. The MODFLOW model simulates evapotranspiration with a linear relation between the user defined maximum rate at the surface of the top-layer and zero evapotranspiration at the user-defined ‘extinction depth’. Wipplinger (1958) has measured that the evaporation depth from alluvial aquifers in the arid regions of Botswana is 0.9 m. Borst and DeHaas (2006) found similar results for a small alluvial aquifer in Kenia. The evapotranspiration of the riparian vegetation is modelled by multiplying the potential evaporation rate by the crop coefficient and by enlarging the evaporation depth (equal to the root depth) for the riverbanks. It is assumed that the effective root depth of the riparian vegetation reaches to the bottom of the alluvial aquifer (1.6 m from the surface).

The potential water supply of the alluvial aquifer is calculated for the current situation and the situation with a sand storage dam. The potential water supply is the summation of daily domestic use during the period of water storage. The daily abstraction is equal to the domestic use and the water needed to maintain 10 gardens of 100 m^2. The sand storage dam is simulated by the WALL-package, which uses an impermeable row of cells perpendicular to the alluvial aquifer. The maximum height of the dam equals the height of the riverbanks at that point. The thickness of the alluvial aquifer is increased upstream of the dam until the maximum height of the dam, which causes an upstream influence of 200 m. When in the natural situation the tap in the sand storage dam opens (see figure 5), the water flows out of the dam with drains situated just above the impermeable underlying ground layer. A 200 m drain, using the DRAIN-package, is used to simulate this process in the MODFLOW model. Since the drainage capacity depends on the height of the groundwater level, the drain conductance [$m^2 \cdot day^{-1}$] has to be adjusted to regulate a constant daily discharge. Sand storage dams are normally built on top of a rock layer with a very low permeability. Since the underlying layer of the Mnyabezi catchment consists of heavily weathered granite, the seepage loss is large. To make sure that the sand storage dam has effect in this particular situation, a layer with a low permeability (for example clay) is modelled at the bottom.

4.5 Measuring strategy

This section discusses the measuring methods of the parameters and variables. Data acquisition is necessary to acquire direct quantitative information from the Mnyabezi catchment. Some weeks has been spent doing on-site field measurements in Zimbabwe, while two field assistants measured the hydrological variables every day. Two catchments have been observed during the measuring period; the Mnyabezi catchment itself and the Bengu catchment. The extra data from the Bengu catchment gives the opportunity to calibrate the rainfall-runoff and reservoir models better. The Bengu catchment covers 8 km^2, is located next to the Mnyabezi catchment and has similar hydro(geo)logical characteristics. The measurements in the alluvial aquifer have only been done for the Mnaybezi catchment, because the alluvial aquifer of Bengu River is to small to sustain a substantial amount of water in the sands.

By working with the models insight was obtained into the sensitivity of parameters and variables before the measurements started. The results of the sensitivity analyses are presented in sections 6.2 and 6.4. The analyses are performed by recording the change in output [%] after changing an input value [%] of certain parameter or variable, while keeping the other parameters and variables constant. The parameters and variables with a high sensitivity value required more attention to determine than those with a low sensitivity.

Tables 2, 3 and 4 provide an overview of the methods, locations and frequencies for all the measured parameters and variables in the Mnyabezi catchment. In the Bengu catchment the same measurements are conducted to determine the parameters and variables used in rainfall-runoff and the reservoir models.

Table 2: Measuring strategy parameters and variables rainfall-runoff model

Parameter	**Measuring Method**	**Location**	**Frequency**
Precipitation rate [$mm \cdot day^{-1}$]	7 standard rain gauges Documents	Distributed over the catchment Thuli Estate meteorological Station	Daily at 8 a.m. Daily; in the period from 1987 – 2000
Area catchment	Topographical map	-	Once
Hydrological soil group	Sieving test	3 ground samples of soil	Once
Land use catchment area [ha]	Survey with GPS Topographical map	Upper-Mnyabezi catchment	Once
Land treatment	Observation field	Upper-Mnyabezi catchment	Once
Hydrological condition	Observation field Satellite image	Upper-Mnyabezi catchment	Once
Initial abstraction [%]	Calibration	-	-

Table 3: Measuring strategy parameters and variables reservoir model

Parameter	**Measuring Method**	**Location**	**Frequency**
River inflow	Rainfall-runoff model	-	-
Water level reservoir [mm]	Gauging plate	In the reservoir	Daily at 9 a.m.
Evaporation rate [$mm \cdot day^{-1}$]	American class A Pan Documents	Pan at Bengu School Beitbridge metrological station	Daily at 8 a.m. Monthly (average); in the period from 1935 - 1980
Profile of the reservoir [m^3]	GPS-device Dumpy level	Points where the height of the reservoir equals the spillway height	Once
Height spillway [m]	Dumpy level	Spillway	Once
Abstractions cattle [$m^3 \cdot day^{-1}$]	Survey farmsteads in the surroundings	Number of cattle in the surroundings of the dam	Once
Water use livestock unit [$l \cdot day^{-1}$]	Literature	-	-
Seepage [$mm \cdot day^{-1}$]	Calibration	-	-

Table 4: Measuring strategy parameters en variables MODFLOW model

Parameter	**Measuring Method**	**Location**	**Time scale**
Days of river flow	Reservoir model	-	-
Hydraulic head in alluvial aquifer [m]	8 piezometers	4 perpendicular lines along the aquifer every 250 m downstream of the dam	Daily at 9 a.m.
Hydraulic head in granite layer [m]	Dip-measure	Wells up-and downstream of the dam	Monthly
Potential Evapotranspiration rate [$mm \cdot day^{-1}$]	Documents Penman equation	Beitbridge metrological station	Monthly (average); in the period from 1935 - 1980
Crop coefficient	Literature	-	-
Evaporation depth	Literature	-	-

Domestic use people [$m^3 \cdot day^{-1}$]	Survey farmsteads in the surroundings	Amount of water used per day per farmstead	Average of 5 days
Water use people to maintain a garden for personal use [$m^3 \cdot day^{-1}$]	Survey farmsteads in the surroundings	Water used to maintain a garden near the pump.	Average of 10 gardens
Profile of the aquifer [m]	Physical probing Resistivity test	4 perpendicular lines along the aquifer	Once
Slope riverbed [%]	Dumpy-level Tape-line	In the riverbed	Once
Streambed conductance	Literature	-	-
Hydraulic conductivity of the alluvial aquifer [$m \cdot day^{-1}$]	Sieving test Permeability test Slug test	6 samples alluvial material (in lab) 60 dm^3 of alluvial material (in lab) In the alluvial aquifer itself (in situ)	Once Once Once
Hydraulic conductivity of the soil [$m \cdot day^{-1}$]	Sieving test Literature	3 ground samples of the soil	Once
Porosity [-] for the alluvial material and the soil layer	Porosity test for alluvial material and soil	6 ground samples of alluvial material and the 2 ground samples of soil	Once
Specific yield [-] for the alluvial material and the soil layer	Literature	-	-
Hydraulic conductivity [$m \cdot day^{-1}$], specific yield [-] and porosity [-] of the underlying granite	Calibration	-	-

Most parameters and variables mentioned in the previous tables are determined with straightforward hydro(geo)logical methods and need no extra explanation. The only methods that need some explanation are those determining the hydraulic conductivity of the alluvial material. Since this parameter depends on the grain size distribution and structure of the alluvial material, the value can differ per area. According to Wipplinger (1958) the composition of sands in an alluvial aquifer generally shifts from fine sands at the top, medium sands in the middle to coarse sand at the bottom. Sieving tests have been conducted to determine the grain size distribution of the alluvial material (samples were taken from the mid-section of the alluvial aquifer). Shephard (1989) developed a commonly used equation, which relates the grain size and the hydraulic conductivity. He found equation 5, which represents the relation for alluvial deposits.

$$K = Cd_{50}{}^{j} = 450 \cdot d_{50}{}^{1.65} \qquad (5)$$

Where,
K [$ft \cdot day^{-1}$] is the hydraulic conductivity,
d_{50} [mm] is the mean grain size,
C [-] is the shape factor and
j is an exponent.

Supplementary to the sieving test, a slug test and a permeability test have been conducted to measure the vertical hydraulic conductivity. Darcy's law is the basis for these tests (see respectively equations 6 and 7). Figures 10 and 11 visualize the tests schematically. The tests work with a vertical slope (i = 1). For the slug test a pvc-tube has been used with a length of 1.00 m and a diameter of 0.07 m representing a vertical water column. The tube has been dug into the alluvial aquifer 19 cm under the groundwater level. Sluts has been made within the reach of the groundwater level and the end of the tube was closed (H = 0.165 m and h = 0.835; first slut have been made 0.025 m above the bottom of the tube). Next, water has been poured into the pvc-tube until the top. A stopwatch measured the time needed to attain the initial water level.

$$\left.\begin{aligned} K &= \frac{Q}{A \cdot i} \\ K_z &: i = 1 \end{aligned}\right\} K = \frac{Q}{A} = \frac{(\pi \cdot (0.5d)^2 \cdot h)/T}{\pi \cdot d \cdot H} \qquad (6)$$

$$\left.\begin{aligned} K &= \frac{Q}{A \cdot i} \\ K_z &: i = 1 \end{aligned}\right\} K = \frac{Q}{A} = \frac{V/T}{\pi \cdot (0.5d)^2} \qquad (7)$$

Where,

K [m·day^{-1}] is the hydraulic conductivity,

Q [m^{3}·day^{-1}] is the flow rate,

i [-] is the slope,

h [m] is the head difference

A_1 [m^2] is the cross-sectional area of the sample,

T [day] is the time,

d[m] is the diameter of the sample and

V [m^3] is the volume of percolated water

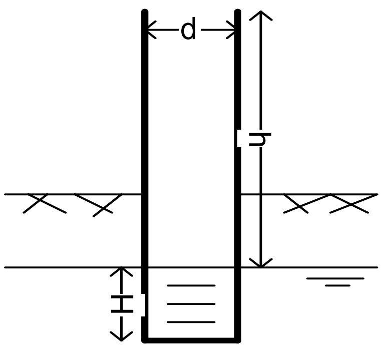

Figure 10: Schematization of the slug test

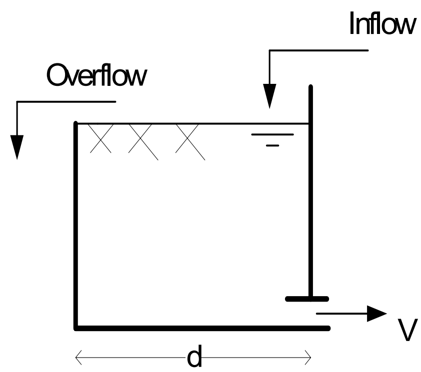

Figure 11: Schematization of the permeameter test

For the permeability test a bucket with a volume of 60 dm^3 has been filled until the top with alluvial material (d_{top} = 0.48 m, d_{bottum} = 0.41 m, h = 0.40 m). A continual inflow of water held the hydraulic head constant. The outlet at the bottom of the bucket was 25 mm in diameter. A coarse gravel filter placed at the outlet prevented sediment flowing out of the bucket. A stopwatch measured the time needed to fill another 5 dm^3 bucket.

4.6 Calibration method

It is desirable that models reflect the physical reality as closely as possible. In a calibration process, some parameters are varied to make a best fit between the measured and equivalent simulated values (Hill, 1998). Three calibration approaches are commonly used; manual calibration, automatic calibration and Monte Carlo simulations. In this research a manual calibration is conducted, since it provides most insight into the behaviour of models. To reduce subjectivity in fitting models, it is necessary to use an index of agreement or disagreement between the observed and simulated results (Weglarczyk, 1998). Nash & Sutcliffe (1970) developed one of the most used methods for hydrological purposes, i.e. the efficiency coefficient represented by equation 8. As a “rule of thump”, it can be said that the model performs reasonably well when values between 0.6 and 0.8 are obtained. Values between 0.8 and 0.9 indicate that the model performs very well and values between 0.9 and 1.0 indicate that the model performs extremely well.

$$E = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \qquad (8)$$

Where, E [-] is the efficiency coefficient, O [-] are the observed values andP [-] are the predicted values.

The efficiency coefficient is used to judge on the rainfall-runoff and reservoir model, using the observed and calculated water levels of the Mnyabezi and Bengu reservoirs. Since the Mnyabezi and Bengu rivers are ungauged, it is necessary to calibrate the rainfall-runoff model in combination with the reservoir model. Figure 12 shows this relation between both models during the calibration process. By knowing the increase in water level of the reservoir after a rain event, the amount of river inflow is calculated. This value is used to calibrate the rainfall-runoff model. For the rainfall runoff model the initial abstraction is used as the fitting parameter for the calibration of the model. The initial abstraction is difficult to determine in arid regions due to surface crust forming (FAO, 1991) and the high transmission losses into the alluvial aquifer (Anderson, 1997). These features make the normal assumption of $I_a = 0.2 \cdot S$ (Soil Conservation Service, 1972) not valid. Studies in southern Africa have used percentages of 10 % and less (Schulze et al., 1993; Hranova, 2006). To obtain the best fit, the initial abstraction is changed between 5.0 and 15.0 % of actual retention *S*. For the reservoir model the seepage is used as the fitting parameters for the calibration of the model, due to the lack of a good method to determine this parameter. The seepage is assumed less than the open water evaporation and has been varied between 0.0 and 1.0 $mm \cdot day^{-1}$.

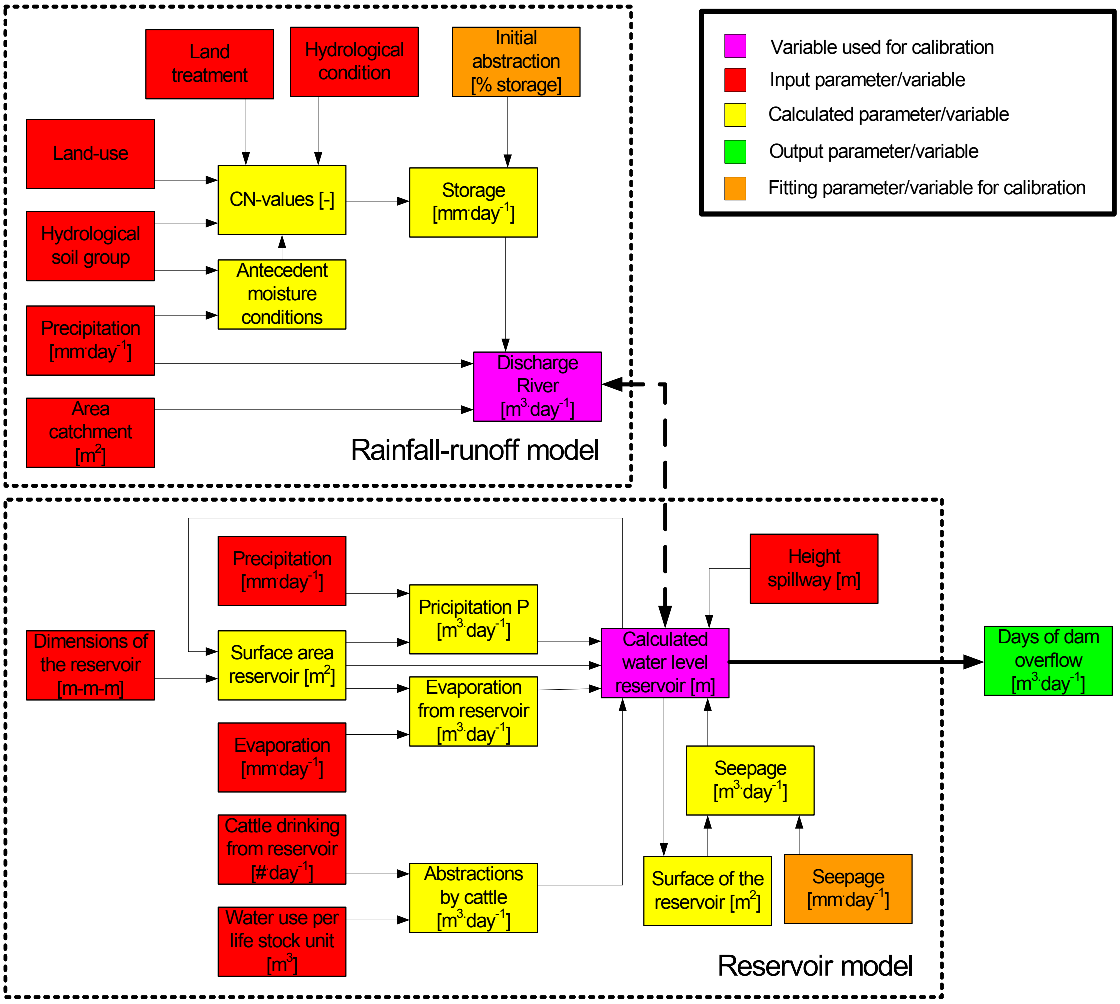

Figure 12: Relation between parameters and variables for the rainfall-runoff and reservoir models

In the MODFLOW model the observed and calculated groundwater level in the alluvial aquifer are used to calibrate the model. Figure 13 shows the relation between the parameters and variables during the calibration process. The MODFLOW model calculates automatically a correlation coefficient after importing ‘observation wells’. The underlying granite layer consists of rock with heavy weathering conditions. Due to the lack of a good method to determine the values for the hydraulic conductivity, specific yield and effective porosity for the granite layer, these parameters are used as fitting parameters for the calibration of the model. The hydraulic conductivity for weathered granite ranges between 0.5 – 1.4 m·day^{-1} (Morris & Johnson, 1967; Davis, 1969; Shaw, 1994). The specific yield for weathered granite ranges between 0.01 and 0.05 and the effective porosity ranges between 0.05 and 0.15 (Todd, 1980; Rushton & Weller, 1989). The hydraulic conductivity and the specific yield were manually varied between the above ranges to make a best fit. Since the sensitivity of the porosity was low, this value was assumed constant at a value 0.08. After the manual calibration, the PEST-module of the MODFLOW model fine-tuned the calibration automatically.

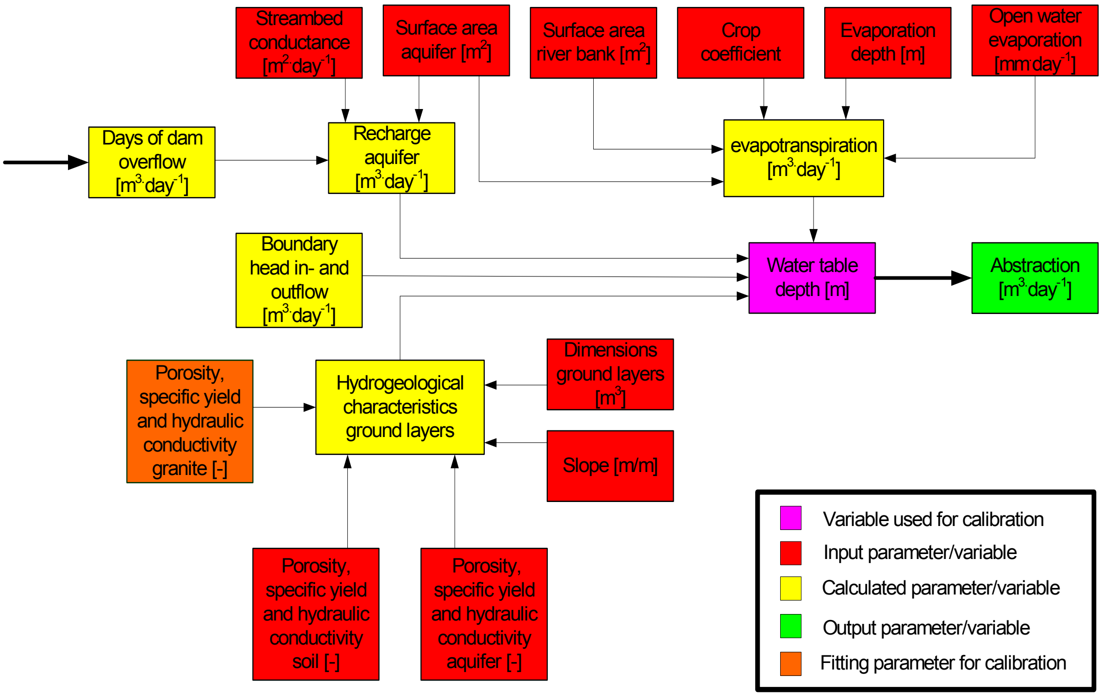

Figure 13: Relation between parameters and variables for the groundwater model

5. Results field measurements

This chapter presents the results of the field measurements. The first section describes the field measurement results of the rainfall-runoff model. The second section provides the results for the reservoir model. At last, the results for the groundwater model are presented

5.1 Rainfall-runoff model

This section provides the results for the parameters and variables used in the rainfall-runoff model. The first sub-section describes the determination of the hydrological soil group. The second sub-section discusses the average CN-value and the last the rainfall records.

5.1.1 Hydrological soil group

According to Moyo (2001), who has done soil analysis in the Fumukwe catchment (10 km away from the Mnyabezi catchment), soils in the area are well drained and consist of loamy sand. The results of the sieving tests for the Mnyabezi catchment provide similar results (see table 5; appendix XIII). According to Maidment (1992), soils consisting of loamy sand result in hydrological soil group "A".

Table 5: Comparison results grain size analysis soil (* estimates; total is 11 %)

	Fumukwe catchment	Mnyabezi catchment
Clay	7 %	7 %*
Silt	3 %	4 %*
Fine sand	36 %	35 %
Medium sand	27 %	31 %
Coarse sand	20 %	20 %
Gravel	8 %	3 %
Soil type (USDA classification)	Loamy sand	Loamy sand
Soil type (BSI)	Fine sand	Fine sand

Appendix VI presents hydraulic conductivities for several soil textures. The average K-value for loamy sand is 13.48 $m \cdot day^{-1}$ (Dingmans, 2002), which is used for the hydraulic conductivity of the soil in the MODFLOW model.

5.1.2 Average CN-value

The Thiessen polygons divide the Mnyabezi catchments into seven polygons (each rain gauge representing one polygon). For each polygon, a specific CN-value is calculated based on the land-use, land treatment, hydrological condition and antecedent moisture conditions. A field survey has been done to map the land use (see appendix III). Appendix IV presents the results for the Bengu catchment. The rangelands are classified as “pasture lands”. The hydrological condition depends on the intensity of grazing activities and vegetation coverage (see appendix II). In general, there is much activity near the reservoir (poor condition), which decreases upstream (good condition). The agricultural fields are classified as “row crops” in poor hydrological conditions, because the maize is planted in rows far enough apart that most of the soil surface is directly exposed to rainfall. Table 6 presents the average curve numbers per polygon for the Mnyabezi catchment with normal antecedent moisture condition. The rainfall-runoff model calculates automatically the antecedent moisture conditions based on the amount of rainfall in the preceding five days.

Table 6: CN-value of the Thiessen polygons for the Mnyabezi catchment

Polygon	Area [ha]	Rangeland [%]	fields [%]	Farmsteads [%]	Hydrological condition	CN-value [-]
1	20	90	0	10 (2 farms)	Poor	67.1
2	50	88	2	10 (5 farms)	Poor	67.2
3	220	75	20	5 (5 farms)	Fair	54.1
4	150	80	18	2 (3 farms)	Fair	53.3
5	350	97	3	0	Fair	49.7
6	400	100	0	0	Good	39.0
7	1010	100	0	0	Good	39.0

5.1.3 Rainfall-events

It was extremely dry in southern Zimbabwe during the measuring period, which was caused by El Niño effects (FewsNet, 2006). Due to this drought, only three major rain events occurred; on the 26th of February (20 – 40 mm), on the 29th of March (40 – 70 mm) and on the 5th of April (2.5 – 30 mm). The effects on the water level in the reservoir of the first rain event has not been recorded with gauging plates, because they had not been installed yet. However, the field assistant for the Bengu reservoir recorded a water level heightening from nearly dry to approximately 50 cm on the 26th of February. The heavy rain event of the 29th of March was followed by dam overflow at both catchments. The rainfall event on the 5th of April only lead to water level rise in the Mnyabezi reservoir. Appendix VII presents the rough precipitation records. Figure 14 shows the effects of the rainfall on the water level in both reservoirs.

5.2 Reservoir model

This section provides the results for the parameters and variables used in the reservoir model. The variables are described in the first sub-section and the parameters in the second sub-section.

5.2.1 Variables concerning the water level in the reservoir

Figure 14 presents the water level of the Mnyabezi and Bengu reservoirs, which has been measured with gauging plates in the reservoir. As stated in sub-section 5.1.3 a heavy rain event occurred on the 29th of March. The figure shows clearly the dam overflow events in both reservoirs, caused by this rain event. The open water evaporation, measured with a standard American A pan, is on average 6.1 $mm{\cdot}day^{-1}$ (s.d. = 2.5 $mm{\cdot}day^{-1}$) in March and 5.0 $mm{\cdot}day^{-1}$ (s.d. = 1.8 $mm{\cdot}day^{-}$) in April 2007. The open water evaporation at Beitbridge meteorological station for these months, which are based on data from 1935 – 1980, are respectively 6.4 $mm{\cdot}day^{-1}$ and 5.0 $mm{\cdot}day^{-1}$ (see table 8). Thus, the recorded pan evaporation at Bengu are comparable to the evaporation records of this meteorological station. The abstractions by cattle from the reservoir, determined by a field survey, are 11.6 $m^{3}{\cdot}day^{-1}$ for the Mnyabezi reservoir and 31.8 $m^{3}{\cdot}day^{-1}$ for the Bengu catchment. Appendices VIII to XI present all the rough data for the precipitation, open water evaporation and abstraction by cattle.

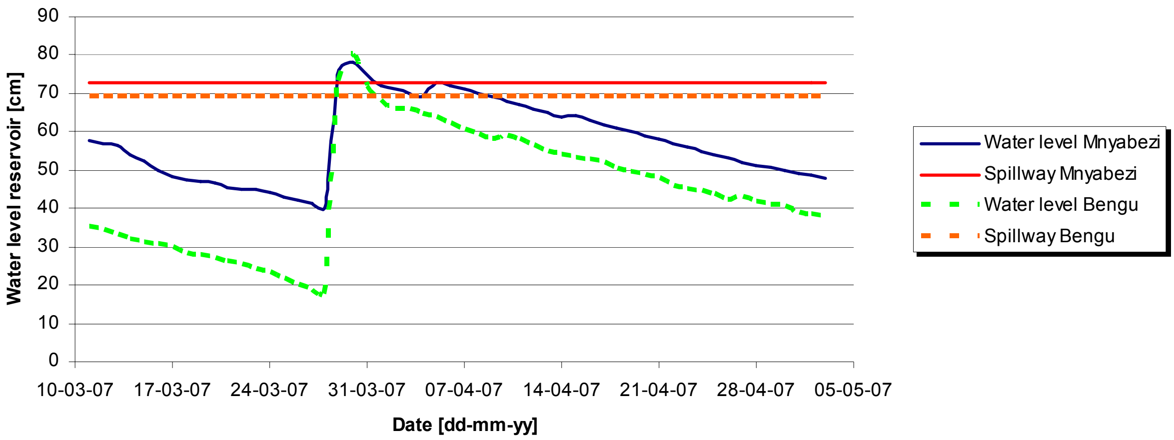

Figure 14: Water level Mnyabezi and Bengu reservoirs

Appendix XII provides the results of the survey done to determine the total domestic water use from the people in the surroundings of the Mnyabezi reservoir dam (3.6 $m^{3}{\cdot}day^{-1}$) and the amount of water needed to maintain one garden of 100 m^2 (0.35 $m^{3}{\cdot}day^{-1}$).

5.2.2 Dimensions of the reservoir

The dimensions of the reservoir have been determined by a GPS-device and a dumpy level. Points have been marked for the Mnyabezi and Bengu reservoir where the height of the surface area equalled the height of the spillway, which resulted in the maximum supply level of both reservoirs (see table 7). After consult from a water engineer of ZINWA (Zimbabwe Water Authority), a 1.00 m height of the spillway is assumed reasonable without danger of dam failure during heavy rain events. For this height of the spillway the maximum supply level has been measured as well. The reservoir is simplified by a rectangular surface as shown in figure 15. With the equations provided beside the figure, the surface area, volume and water level are calculated. See appendices XV and XVI for additional information about the dimensions of the Mnyabezi and Bengu reservoir.

Table 7: Dimensions reservoirs used in the model

Parameter	Normal dimensions Mnyabezi reservoir [m]	Dimensions with a heightened spillway Mnyabezi reservoir [m]	Dimensions reservoir Bengu [m]
B	140	150	200
L	110	400	90
h_{max}	0.73	1.00	0.69

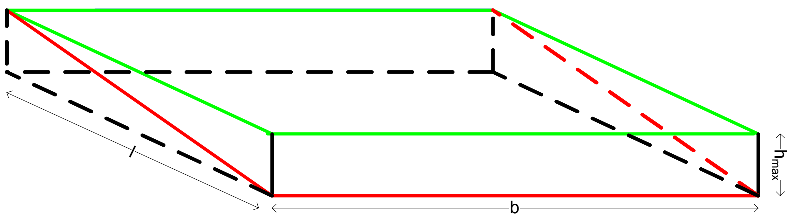

Figure 15: Visualization reservoir used in the model

$$Surface\ area = b \cdot l \cdot \frac{h}{h_{max}}$$

$$Volume : V = \frac{b \cdot l \cdot h}{2}$$

$$Water\ level : h = \frac{2 \cdot V}{b \cdot l}$$

5.3 Groundwater model

This section provides the results for the parameters and variables used in the groundwater model. The change in groundwater level are described in the first sub-section, the profile of the alluvial aquifer in the second and the third sub-section discusses the results of the evapotranspiration in the area. At last, the hydraulic conductivity and specific yield of the ground layers are described.

5.3.1 Groundwater level in the alluvial aquifer

Figure 16 presents the daily groundwater level in the alluvial aquifer of the Mnyabezi River. These values are average values of all piezometers. There are quite some differences between water levels at the measured locations (average standard deviation = 11.0 cm). This is probably caused by small local differences in storage characteristics. Nevertheless, an average value is used in the MODFLOW-model, because the model works with a homogenous shape of the alluvial aquifer over the entire section. The last reading in the piezometers has been done at the 16th of April, after which the water level dropped below the bottom of the piezometers. The drying time is estimated by extrapolating the trend until the average depth of the alluvial aquifer (0.9 m). The data suggests that the alluvial aquifer completely dried out after the 18th of April, which results in a drying period of 20 days (see figure 16). Appendix XVIII shows the groundwater levels in the alluvial aquifer.

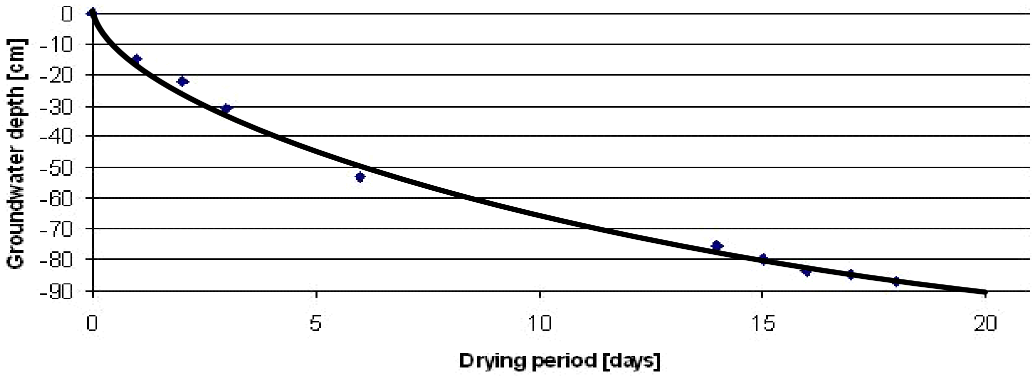

Figure 16: Groundwater level in the alluvial aquifer; measured from the surface area (average values over the piezometers; s.d. = 11.0 cm)

The initial water level in the granite layer is 3.9 m beneath the surface of the alluvial aquifer, which has been measured with a dip measure in the water pumps.

<u>5.3.2 Profile of the ground layers</u>

The width of the alluvial aquifer has been measured with a tapeline. The depth of the alluvial aquifer has been measured at four rectangular lines by physical probing. A weathered granite layer underlies the river, so it was easy to determine the depth manually with an iron rod. Appendix XVII shows the results of the physical probing of the aquifer. The average width in the first 1.0 km downstream of the dam ranges between 9.0 and 10.5 m. The maximum depth is 1.30 m with an average of 0.91 m. The thickness of the soil layer, observed at the riverbed of the alluvial aquifer, is estimated between 0.5 and 0.8 m.

Figure 17: Measuring the height with a dumpy level

Figure 18: Resistivity test in the alluvial aquifer

Supplementary to the physical probing, direct current electronical resistivity tests has been done to determine the thickness and hydrogeological characteristics of the underlying granite layer (see figure 18). In earlier studies, resistivity tests gave valuable results for the Mzingwane River and Shangani

River in Zimbabwe (Beckman & Liberg, 1997; Owen & Dahlin, 2005). The sand of the alluvial aquifer has a high resistivity signature and this made it relatively easy to distinguish from underlying bedrock (Owen & Dahlin, 2005). After analysing the results, the measurements for only two lines gave reasonable results. Based on the recorded data it is possible to distinguish two ranges of resistivity values, one representing the alluvial material and one the granite. Alluvial material has resistivity values above 100 Ω·m and has a maximum depth of 2.0 m. The resistivity values for granite ranges between 40 to 100 Ω·m and has a depth between 2.0 and 15.0 m. This range indicates rock with heavy weathering conditions and optimum groundwater potential (Mudzingwa, 1998). The resistivity in the granite remains quite constant for an increasing measuring depth, which indicates that the granite layer is uniform for at least 15 m.

5.3.3 Potential evapotranspiration for riparian vegetation

The potential evapotranspiration rate (PET_0) is the rate of evapotranspiration from a large area covered by green grass which grows actively, completely shades the ground and which is not short of water (FAO, 1991). To calculate the evapotranspiration of riparian vegetation (PET_t), the PET_0 has been multiplied by a crop coefficient (k_c). The crop coefficient for riparian vegetation has been estimated from similar drought resistant crop vegetation (olives and citrus trees) and is equal to 0.7 (FAO, 1991).

Table 8: Data meteorological station Beitbridge (Metereological Service of Zimbabwe, 1981)

Month	Average temp. [°C]	Dry bulb temp. [°C]	Wet bulb temp. [°C]	Wind [$m \cdot s^{-1}$]	Sunshine [$h \cdot day^{-1}$]	PET_0 [$mm \cdot day^{-1}$]	PET_t [$mm \cdot day^{-1}$]	ET_0 [$mm \cdot day^{-1}$]
Jan	27.45	24.0	22.0	4.30	7.2	3.34	2.34	7.97
Feb	27.05	22.6	19.6	3.99	7.0	4.22	2.95	7.07
Mar	25.90	24.5	20.5	3.79	7.8	4.62	3.23	6.42
Apr	23.55	22.2	19.4	3.17	8.1	3.91	2.74	4.97
May	19.95	22.7	19.4	2.46	8.9	3.79	2.65	3.81
Jun	16.80	22.4	19.8	2.35	8.5	3.16	2.21	3.17
Jul	16.65	23.4	20.8	2.56	9.1	2.99	2.09	3.58
Aug	19.10	25.4	23.6	3.17	9.6	2.85	2.00	4.74
Sep	22.60	23.4	22.8	4.09	9.6	2.57	1.80	6.63
Oct	25.35	23.8	22.4	4.81	8.8	3.23	2.26	7.52
Nov	26.35	22.4	21.8	4.50	7.1	2.73	1.91	7.43
Dec	26.95	24.0	22.6	4.30	6.7	3.24	2.27	7.58

Table 8 provides monthly data of the meteorological station in Beitbridge, the calculated evapotranspiration and the open water evaporation per month. The meteorological station in Beitbridge has approximately the same height as the Mnyabezi catchment (450 m above sea level and atmospheric pressure of 96.1 kPa) and is located about 110 km eastwards. According to the Meteorological Service of Zimbabwe (1981), the meteorological conditions from Beitbridge are similar to those in the Mnyabezi catchment.

5.3.4 Hydraulic conductivity of the alluvial material

The hydraulic conductivity (K_x, K_y and $K_{z)}$) of the alluvial material is an important parameter. This section presents the results of the sieving test, slug test and permeability test. The sieving test results show a hydraulic conductivity (K-value) of 76.2 $m \cdot day^{-1}$ for a d_{50}-value of 0.7 mm. However, the d_{50}-value can vary +/- 0.05 mm, resulting in a range for the hydraulic conductivity between 67.4 and 85.4 $m \cdot day^{-1}$. Appendix XIV presents the rough data of the sieving tests.

Table 9 shows the results of the slug test. The last four measurements are used to calculate the hydraulic conductivity. The first two measurements are not taken into account, because here the equilibrium was not reached yet. The average K-value is 62.2 $m \cdot day^{-1}$. However, the results are most sensitive to the diameter of the pvc-tube (7 cm). The uncertainty in thickness of the tube is +/- 3 mm, which cause a possible range in diameter between 6.7 and 7.3 cm. This results in a hydraulic conductivity between 59.7 $m \cdot day^{-1}$ and 65.0 $m \cdot day^{-1}$. Table 10 shows the results of the permeability test. The average K-value is 63.6 $m \cdot day^{-1}$. The results are very sensitive to the average diameter of the bucket (44.5 cm). Assuming an error of +/- 1.0 cm in average diameter, the hydraulic conductivity value ranges between 62.0 $m \cdot day^{-1}$ and 64.9 $m \cdot day^{-1}$.

Table 9: Results slug test

Test	T [s]	Q [$m^3 \cdot day^{-1}$]	K [$m \cdot day^{-1}$]
1	105	2.56	70.69
2	110	2.45	67.48
3	119	2.26	62.73
4	120	2.24	61.85
5	118	2.28	62.90
6	121	2.22	61.34

Table 10: Results permeability test

Test	T [s]	Q [$m^3 \cdot day^{-1}$]	K [$m \cdot day^{-1}$]
1	43.5	9.93	64.07
2	42.4	10.19	65.73
3	45.2	9.56	61.66
4	43.7	9.89	63.78
5	43.5	9.93	64.07
6	44.1	9.80	63.20
7	43.9	9.84	63.49
8	44.4	9.73	62.77

To conclude, the average hydraulic conductivities of the three tests do not differ much, although the uncertainty differs for each test. The average hydraulic conductivity is 62.9 $m \cdot day^{-1}$. Due to the large uncertainty in the sieving test results, this value is not taken into account to calculate the average value. The result is comparable to the value Wipplinger (1958) found for the hydraulic conductivity (61 $m \cdot day^{-1}$) for alluvial sands in Namibia.

5.3.5 Specific yield and porosity

The total porosity *n* [-] is defined as the portion of pore spaces in a volume of soil (Mainment, 1992; Shaw, 1994). The specific yield s_y [-] describes the volume of water that drains by gravity out of a ground layer (Mainment, 1992; Shaw, 1994). The value is an indication of an aquifer's storage characteristics. Tables are known in literature (see appendix VI), which provide values for the porosity and specific yield for different soil and rock types. In this study ground sample analysis of the alluvial material and soils near to the river have been conducted to determine the porosity. Table 11 presents the porosity results for the alluvial material. According to Dingman (2002), the porosity of alluvial material (medium sand) ranges from 0.29 to 0.49. Therefore, the value found for the porosity (0.33) seems to be realistic. When linearly interpolating the values provided by Dingman (2002), the specific yield in medium sand equals 0.27 (for a porosity of 0.33).

Table 11: Porosity of the alluvial material

Test	Weight dried sample [g]	Weight saturated sample [g]	Volume water [ml]	Volume baker [ml]	Porosity [-]
1	1008.3	1177.7	169.4	500	0.339
2	976.7	1156.3	179.6	500	0.359
3	698.5	799.2	100.7	300	0.336
4	636.4	732.7	96.3	300	0.321
5	617.8	713.1	95.3	300	0.318
6	668.8	769.9	101.1	300	0.337
				Average	**0.33**

Table 12 presents the porosity results for the soil samples, which has been measured in a baker with a volume of 500 ml. According to Dingman (2002), the porosity of the soil ranges from 0.29 to 0.53. Therefore, the calculated value for the porosity (0.37) seems to be realistic. When linearly interpolating the values presented by Dingman (2002), the specific yield in fine sand equals 0.22 (for a porosity of 0.37).

Table 12: Porosity of the surface soil

Test	Weight dried sample [g]	Weight saturated sample [g]	Volume water [ml]	Porosity [-]
1	1139.0	1327.6	188.6	0.377
2	972.1	1155.6	183.5	0.367
			Average	**0.37**

6. Results models

This chapter shows the results of the sensitivity and calibration process. The first two sections highlight the results for the rainfall-runoff model. The third and fourth sections provide the MODFLOW model results. The last section discusses the uncertainty in the outcomes.

6.1 Sensitivity of the reservoir and rainfall-runoff models

A sensitivity analysis shows the parameters and variables that mostly contribute to the output variability. The parameters mentioned in table 2 and 3 are analysed together. This is done by varying the input values between -20 % and 20 %, while keeping the other parameters and variables constant. Figure 19 presents the results for the parameters and variables with the largest sensitivity values. The figure shows clearly that the parameters and variables concerning the rainfall-runoff relation are most sensitive. The sensitivity of the parameters concerning the reservoir model are less sensitive, except for the parameter 'height spillway'.

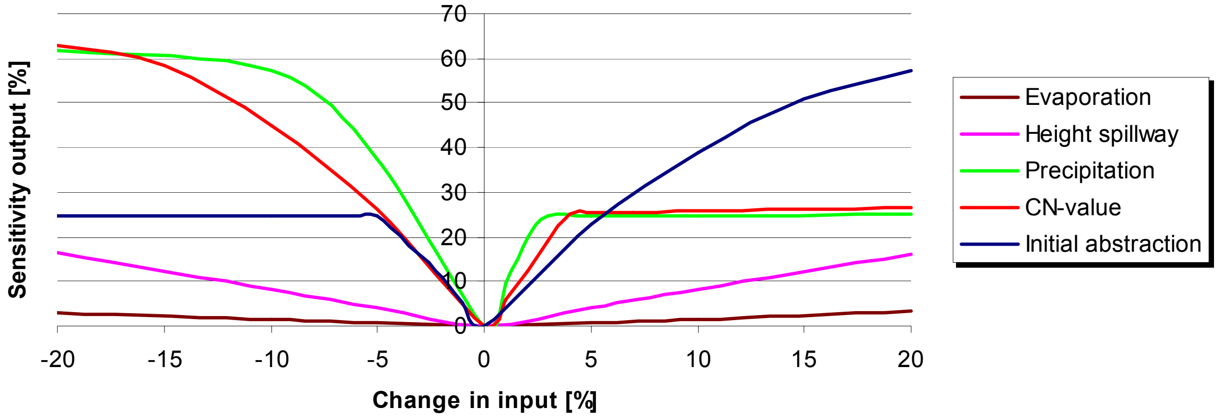

Figure 19: Sensitivity parameters and variables rainfall runoff model

Precipitation is the only input variable; the output is logically very sensitive to changes in this variable. The most sensitive parameters are the 'CN-value' and the 'initial abstraction'. The initial abstraction is a very complex lumped parameter dependent in soil characteristics. The CN-value is also a lumped parameter, which include land use, land treatment, antecedent moisture conditions and a hydrological soil group. Since both depend on soil characteristics in the catchment, is it necessary to investigate the combined sensitivity. Figure 20 shows that the combined sensitivity does not have a higher sensitivity values than the separate sensitivity values.

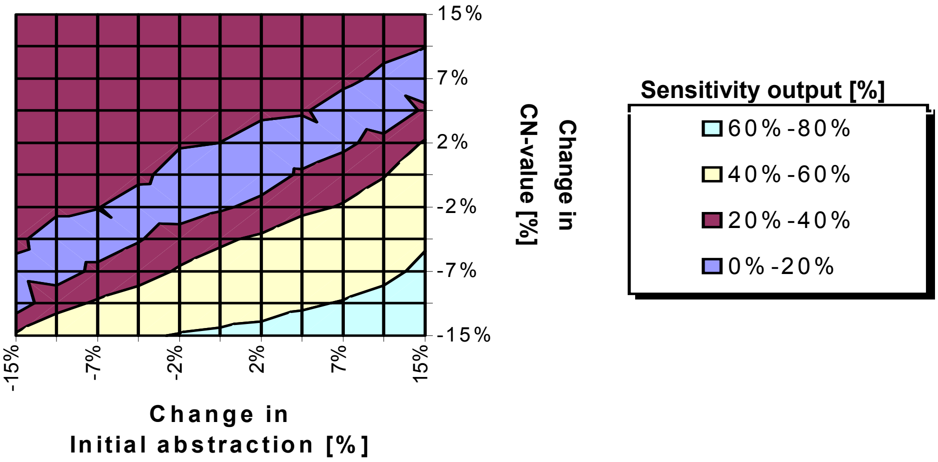

Figure 20: Sensitivity CN-value and initial abstraction

6.2 Calibration of the reservoir and rainfall-runoff models

As stated in section 4.6, the water level records of the Mnyabezi and Bengu reservoirs are used to calibrate the models. During the measuring period, three rainfall events occurred; one without dam overflow on the 26th of February (only recorded for the Bengu reservoir) and one with dam overflow on the 29th of March (in both reservoirs) and one without dam overflow on the 5th of April (only in the Mnaybezi reservoir). The effects on the water level in the reservoirs of the first rainfall event have not been recorded with gauging plates, because they had not been installed yet. However, the field assistant recorded a water level heightening from nearly 0 cm until approximately 50 cm during this rain event. Because of this extra information, the calibration process started with the Bengu rainfall-runoff model. Next, the value found for the initial abstraction [% of actual retention] is used for the Mnyabezi reservoir model. Hereafter, the seepage [$mm \cdot day^{-1}$] is used to calibrate the Mnyabezi reservoir model further and this seepage value is transferred to the Bengu reservoir model. In the Bengu rainfall-runoff model the initial abstraction is changed again to make an even better fit. This iterative way gave eventually the optimum values for the initial abstraction and seepage. An efficiency coefficient of 0.99 is obtained for both models, using an initial abstraction of 7.6% of the actual retention and seepage of 0.0 $mm \cdot day^{-1}$. These results are in line with similar studies conducted in arid regions in southern Africa (Schulze et al., 1993; Hranova, 2006).

During the calibration process, it has been assumed that both reservoirs have equal values for the initial abstraction and seepage. Since both catchments have the same meteorological conditions, land use and hydrogeological characteristics, this assumption seems to be justifiable. The graphs in figures 21 and 22 show clearly an increase of water level in both reservoirs after the heavy rain event on the 29th of March. The model does not simulate the water level above the spillway, which gives the opportunity to calculate the amount of dam overflow (amount of water inflow after reaching the spillway height). This can also be seen in the figures, where the observed water levels are higher than calculated water levels just after the heavy rain event on the 29th of March.

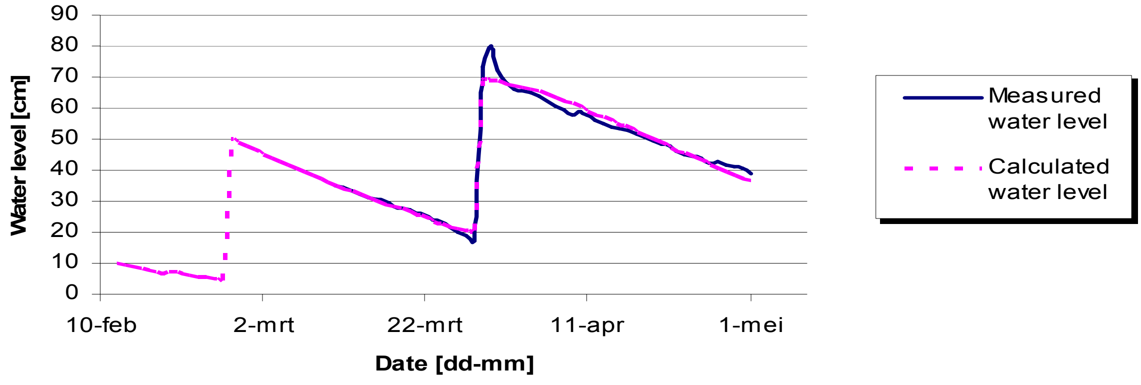

Figure 21: Calibration results Bengu reservoir

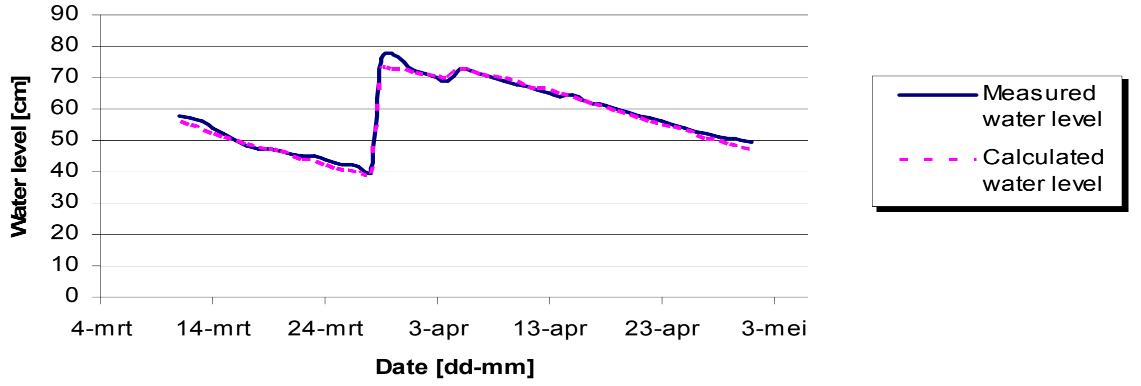

Figure 22: Calibration results Mnyabezi reservoir

6.3 Sensitivity of the groundwater model

The sensitivity analysis for the MODFLOW model is not performed as extensively as for the rainfall-runoff model. The analysis is more qualitatively, based on experiences obtained during the model building process and the calibration process. The main sensitivity lies within the hydraulic conductivity and specific yield of the granite layer, which are the fitting parameters during the calibration process. The porosity has a negligible sensitivity, which makes the assumed constant value of 0.08 during the calibration process legitimate. The hydraulic conductivities of the alluvial aquifer and soil layer have a minor influence on the output. Another parameter with a significant influence on the output is the streambed conductance, which regulates the river leakage into the alluvial aquifer. This value is chosen in such a way that it exactly recharges the alluvial aquifer during one river flow event.

6.4 Calibration of the groundwater model

In the MODFLOW model, two "head observation wells" (at 100 m and 600 m downstream of the dam) were imported. These wells compared the groundwater levels measured with piezometers and the calculated groundwater levels (see figure 23). Hereafter, the MODFLOW model calculated automatically a correlation coefficient between the observed and calculated values for every run. During the calibration process the hydraulic conductivity of the granite layer was changed between 0.5 and 1.4 m·day^{-1} and the specific yield between 0.01 and 0.05 to make the best fit. At the end, the PEST-module automatically fine-tuned the manual calibration process. A correlation coefficient of 0.99 is obtained using a value of 0.55 m·day^{-1} for the hydraulic conductivity and 0.03 for the specific yield.

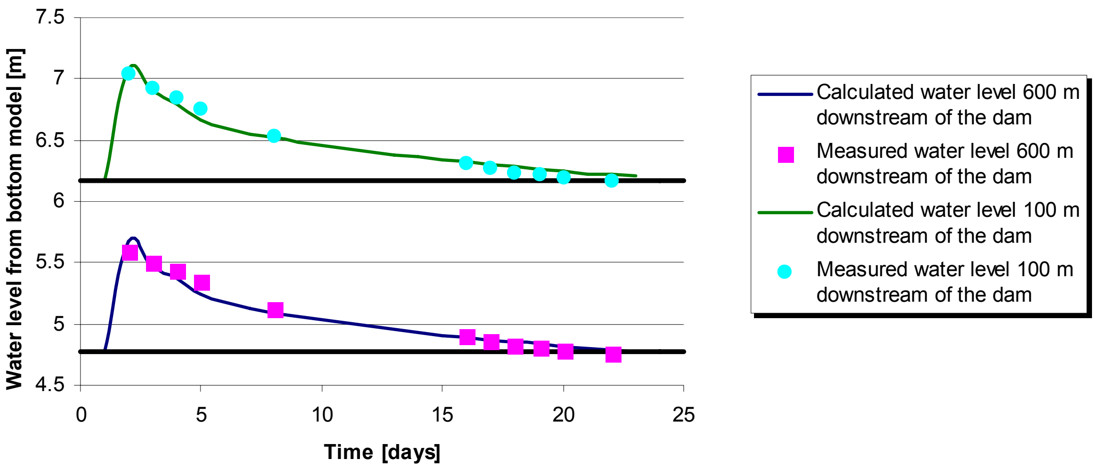

Figure 23: Calibration results groundwater model

The MODFLOW model also provides the discrepancy in mass balance results. In general, a discrepancy between in- and outputs of less than 2% is a good performance of the model (Waterloo Hydrologic, 2006). The water mass balance resulted in a maximum error of 5.0 % (during the day of river flow). Hereafter, the river flow discrepancy in mass balance remained within a +/- 1.0 % boundary.

6.5 Uncertainty in outcomes

Walker et al. (2003) describe uncertainty as "being any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system". Due to uncertainty in input data and relations between parameters and variables, the results used in the models are always subjected to uncertainty. However, downplaying the usefulness of models by claiming that modelling by definition denies the essence of uncertainty was not very useful either. A more constructive approach is to analyse how uncertainty materializes in the catchment modelling (Van Asselt & Rotmans, 2002). Due to a lack of data to verify the outcomes and due to a short measuring period, the uncertainty in outcomes for the Mnyabezi catchment is high. The main interest for this study lies in the uncertainty of the measuring and modelling methods, for which a qualitative analysis has been performed.

Walker et al. (2003) provide a framework to describe systematically uncertainties in models, which is used in this study. Appendix XX presents one framework for every model. The “context uncertainty” is negligible in all models, because there is no discussion about the boundaries of the hydrological system. The “technical uncertainty” in the spreadsheet-based models is negligible as well, because the calculation method does not have errors in water balance outcomes. There is a small “technical uncertainty” in the groundwater model, because the finite difference model has a small error in water balance outcomes (+/- 1%). The uncertainty caused by external driving forces that produce changes within the system, like in influence of climate change, goes outside the scope of this research and is therefore not relevant in this situation. The natures of all “parameter uncertainties” are epistimetic, which means that uncertainty can reduce by more research and empirical efforts. The most important uncertainties for each model are described in more detail below.

The main uncertainty for the rainfall-runoff model lies within the model structure on scenario level. At this moment, the complex hydrogeological relations are lumped in an equation to calculate the runoff, linking the parameters CN-value, initial abstraction and the variable precipitation. The CN-value and initial abstraction, which are sensitive parameters (see figure 19), are assumed to be constant during the whole year. Nevertheless, the CN-value can vary in time due to change in land use or land treatment. The initial abstraction can vary in time due to crust forming on the surface or saturation of the alluvial aquifer. The rainfall-runoff model has only been calibrated on one rainfall event in the Bengu and Mnyabezi catchment. This causes a large uncertainty in the outcomes of the rainfall-runoff model. Nevertheless, the drying periods of the reservoirs have been monitored quite well. Since the main objective of the study is to calculate the potential water supply after the start of main rainy season (where the reservoir fills up completely anyway), the results still provide useable outcomes.

The main “parameter uncertainty” within the reservoir model, besides the uncertainty in the river inflow described above, are the dimensions of the reservoir in relation to the water level. The dimensions of the reservoir have not only influence on the “statistical uncertainty” under normal circumstances, but on the “scenario uncertainty” (heightening of the spillway) as well. The sensitivity analysis (see figure 19) also shows a relative high sensitivity of this parameter. At this moment, a simple rectangular shape simulates the dimensions of the reservoir. This can be improved by measuring the exact shape of the reservoir with a dumpy level when the reservoir is dry.
In arid regions, heavy rain events are mostly followed by large amounts of dam overflow, which causes a complete saturation of the alluvial aquifer. In that situation, the uncertainty in amount of dam

overflow, caused by the “parameter uncertainty” in the dimensions of the reservoir, has no influence on the groundwater model outcomes. Only when the dam overflow is very small, which causes the alluvial aquifer to saturate only partly, the outcomes of the groundwater model are influenced by the uncertainty in the reservoir model.

One uncertainty in the MODFLOW model structure is the calculation of evapotranspiration from riparian vegetation. The model has some disadvantages in modelling evapotranspiration. MODFLOW uses a linear relation for the evapotranspiration, which depends on the groundwater depth from the top-layer. Since the evapotranspiration highly depends on the water content characteristics of the unsaturated soil, this is not the most accurate way to model evapotranspiration. The MODFLOW-SURFACT engine can solve this problem, but than information about pf-curves, water contents in the unsaturated zone and other soil science parameters are required. The sensitivity analysis results in a small influence from the evapotranspiration of riparian vegetation on the output (the water level in the alluvial aquifer). Most of the water evaporated directly from the alluvial aquifer itself, which makes it possible to work with the current data. Nevertheless, the model restriction causes a little underestimation of the total evapotranspiration.

Another main uncertainty in the MODFLOW model structure is on scenario level. The calculations for the sand storage dam are conceptual and the outcomes are not verified with measured data. This causes a large uncertainty in the relations between seepage, evapotranspiration and abstractions by users. In continuation of this research, it would be very interesting to monitor the hydrological processes of a sand storage dam in situ to reduce this uncertainty.

7. Analysis

This chapter presents the analysis of the modelling results. The first and second sections provide the water balance and potential water supply of the rainfall-runoff model. The third and fourth sections describe the same results for the MODFLOW model. The last section discusses the outcomes of the models.

7.1 Water balance of the Mnyabezi reservoir

The reservoir model has been used to analyse the hydrological characteristics of the reservoir during a dry year (‘89/’99), a normal (‘97/’98) and wet year (‘96/’97). Note that in arid regions, the dispersion of rainfall events during a year mainly determines if a year will be typified as dry, moderate or wet. The water balance results of the reservoir for these three years are presented in figure 24. The results show approximately the same proportions between natural losses; the evaporation loss is 79 %, cattle abstractions count for 21 % and the seepage losses are negligible. Of course, this means that the total amount of evaporation and abstractions by cattle increases for wetter years in comparison to drier years. The differences in reservoir inflow are caused by the different rainfall patterns: in dry years, the rainfall is mainly concentrated during a few heavy rain events and in wetter years, the rain events are less heavy, but more frequent and better dispersed over a longer period. In drier years all rain events cause river flow, that directly spills over the dam (99%). In wetter years smaller rain events without causing river flow occur more frequently, which is the reason the proportion of direct precipitation in the reservoir is higher.

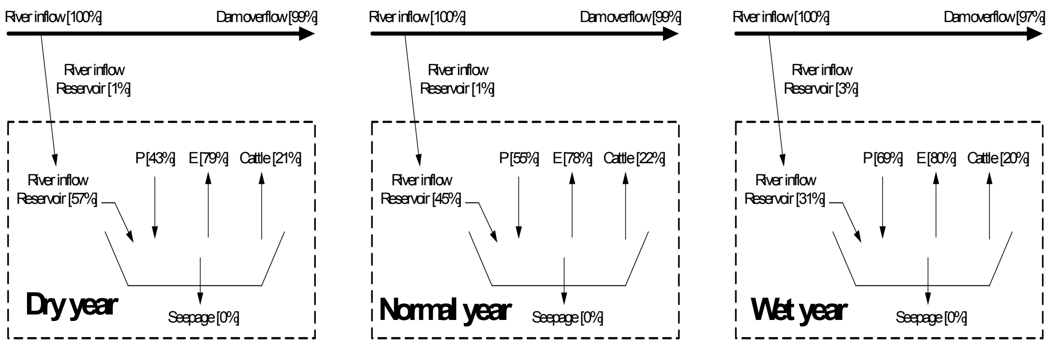

Figure 24: Water balance results of the Mnyabezi reservoir for a dry, normal and wet year

7.2 Potential water supply of the Mnyabezi reservoir

The reservoir model is used to calculate the amount of potential water supply for the current situation and the situation with a heightened spillway. The period of available water in the reservoir is calculated as well. The potential water supply is the summation of the amount of water that cattle consume in days when the reservoir is not dry. Dam overflow occurs when the water level in the reservoir is higher than the height of the spillway. Figure 25, 26 and 27 show the calculated water levels in the reservoir for the current situation and the situation with a heightened spillway.

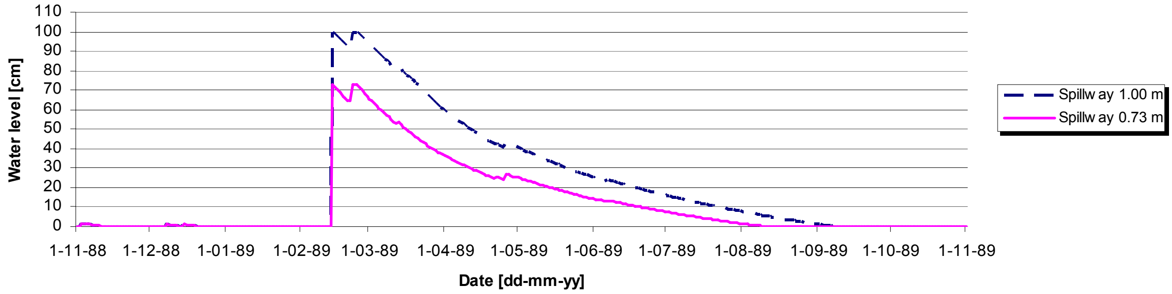

Figure 25: Water level in the Mnyabezi reservoir during the dry year '88/'89

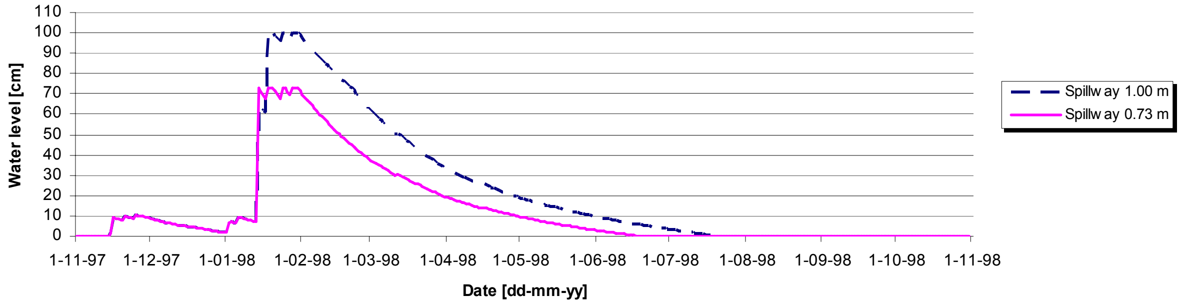

Figure 26: Water level in the Mnyabezi reservoir during the dry year'97/'98

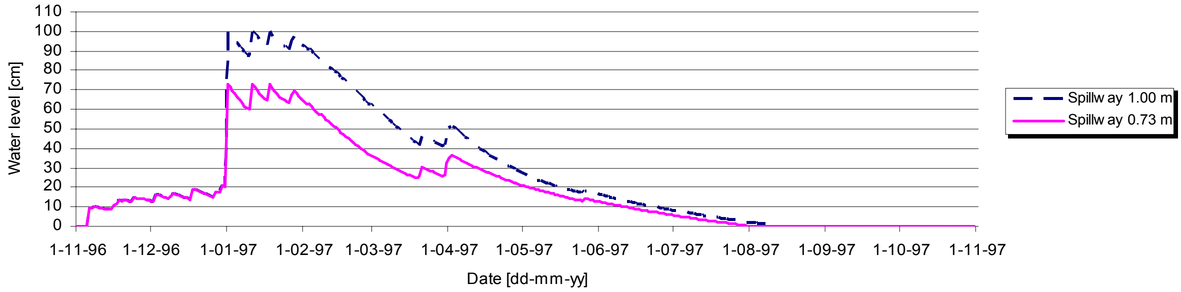

Figure 27: Water level in the Mnyabezi reservoir during the dry year '96/'97

The results show clearly that the potential water supply increases when the yearly rainfall rate increases. The days of dam overflow concentrate during a small period in the main rainy season for all years (see appendix IXX). The drying time of the reservoir is approximately 4.5 months, based on a situation after the last dam overflow event and without rain events during that period. The potential water supply increases from 1,984 m^3 in a dry year and 2,424 m^3 in a normal year to 3,039 m^3 in a wet year. Figure 25, 26 and 27 also show that the reservoir holds water for approximately five weeks longer after increasing the spillway to a height of 1.0 m. During a wet year this increase in drying period is only two weeks, which is caused by the rainfall event in the beginning of April. Table 13 provides an overview of the results in several situations. The water supply after the last dam overflow event in the normal year shows a low value in comparison to other years, because no rain events occurred after the last dam overflow in that year.

Table 13: Potential water supply reservoir for several situations

	Water supply and period for a dry year	Water supply and period for a normal year	Water supply and period for a wet year
Reservoir spillway 0.73; including rainy season	1,984 m^3 5.7 months	2,424 m^3 7.0 months	3,039 m^3 8.7 month
Reservoir spillway 0.73; after last overflow-event	1,865 m^3 5.4 months	1,531 m^3 4.4 months	2,192 m^3 6.3 month
Reservoir spillway 1.00; including rainy season	2,401 m^3 6.9 months	2,807 m^3 8.1 month	3,178 m^3 9.1 month
Reservoir spillway 1.00; after last overflow-event	2,285 m^3 6.6 months	1,926 m^3 5.5 month	2,320 m^3 6.7 month

7.3 Water balance of the alluvial aquifer

The MODFLOW model is used to analyse the hydrological characteristics of the alluvial aquifer. An analysis is made for the natural losses in the period after a single river flow event. The total amount of water that can be stored in the alluvial aquifer over the section of 200 m is 630 m^3. The total amount of evapotranspiration is approximately 88 m^3 (14 %) and the seepage to the underlying granite layer is 529 m^3 (86%). The in- and outflow through the alluvial aquifer is 13 m^3 (2%), which is small compared to the other flows. This is logical, taking into account the average vK-value (69 $m \cdot day^{-1}$). The K-value is a measure of the permeability in the vertical direction. Therefore, when the alluvial aquifer has a slope of 0.28 % the velocity of the water in the aquifer is only 0.18 $m \cdot day^{-1}$ and the maximum outflow equals 1.6 $m^3 \cdot day^{-1}$. An overview of the water balance is shown in figure 28.

The same analysis is done for the situation with a sand storage dam constructed in the alluvial aquifer. The total amount that can be stored in the sand storage dam is 980 m^3. The maximum water abstraction from the sand storage dam equals 603 m^3 (62%). The only natural loss is due to evapotranspiration (38%), since the groundwater flow is blocked and the underground of the sand storage dam is made of an impermeable layer.

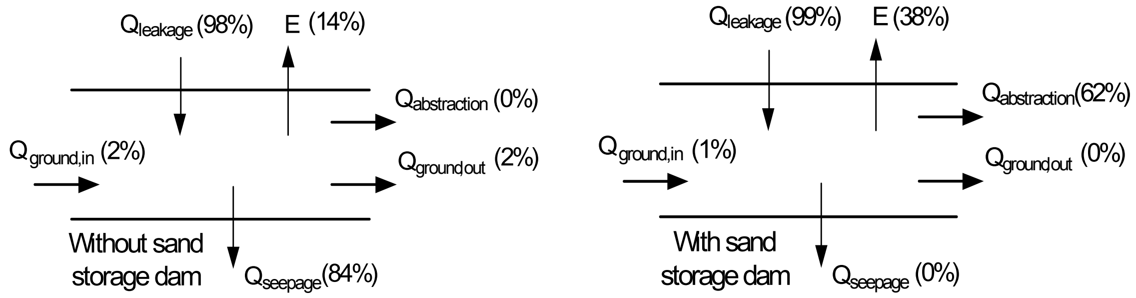

Figure 28: Water balance alluvial aquifer

7.4 Potential water supply alluvial aquifer

As stated in section 4.4 the potential water supply is calculated for the current situation and the situation with a sand storage dam after the last dam overflow event. The abstractions are held constant on 7.0 m^3, which is the amount of domestic water use plus the water needed to maintain 10 gardens of 100 m^2 as stated in section 5.1 and appendix XII. An advantage of a sand storage dam is that the water does not have to be used immediately. However, the longer the water is stored behind the dam, the larger the amount of natural losses (only evapotranspiration) becomes. Figure 29 provides insight into the relation between the potential water supply and start of the abstractions after the last river flow event for the sand storage dam in the Mnyabezi River.

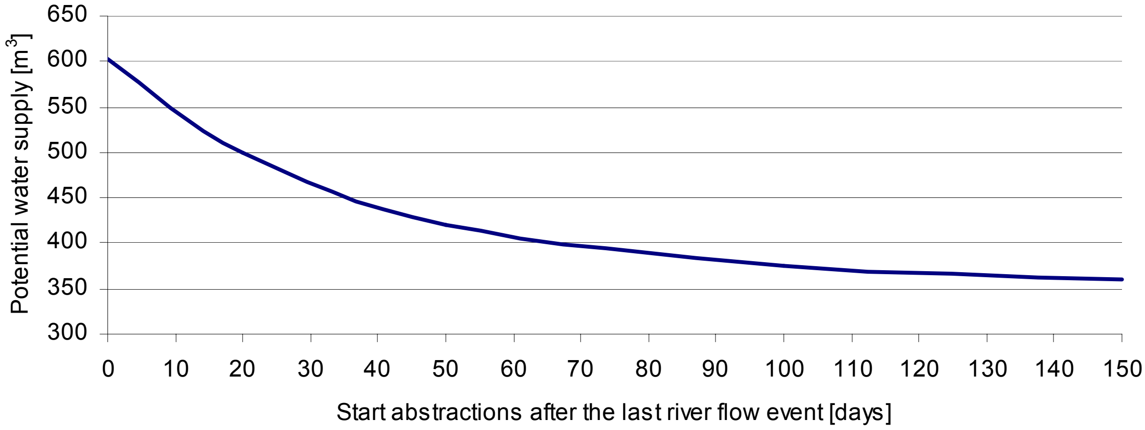

Figure 29: Water storage in the sand dam

The total water supply after the last dam overflow event from the alluvial aquifer of the Mnyabezi River in the current situation equals 123 m^3. In that situation, the alluvial aquifer can provide water for only 14 days. In the situation of the sand storage dam, water is provided for a maximum of 70 days.

The water supply than improves with 480 m^3 to a total amount of 603 m^3 and extent the period of supply with 56 days. When the water is not used directly, but for example after 100 days, the potential water supply is 375 m^3 for maximum period of 45 days. During the wet year '96/'97 a rain event (35 mm) occurred two months after the last dam overflow event, which increased the potential water supply in the sand storage dam (total of 439 m^3) and extended the drying period with an extra 2 weeks. Table 14 provides an overview of the results for the reservoir and alluvial aquifer in several situations.

Table 14: Potential water supply alluvial aquifer for several situations

	Water supply and period for a dry year	Water supply and period for a normal year	Water supply and period for a wet year
Alluvial aquifer; including rainy season	193 m^3 0.8 month	235 m^3 1.0 month	242 m^3 1.1 month
Alluvial aquifer; 0 days after last overflow-event	123 m^3 0.5 month	123 m^3 0.5 month	123 m^3 1.5 month
Sand storage dam; including rainy season	673 m^3 2.6 month	715 m^3 2.8 month	800 m^3 3.1 month
Sand storage dam; 0 days after last overflow-event	603 m^3 2.3 month	603 m^3 2.3 month	681 m^3 2.5 month
Sand storage dam; 100 days after last overflow-event	375 m^3 1.5 month	375 m^3 1.5 month	439 m^3 1.7 month

The water supply from the Mnyabezi reservoir is meant for cattle drinking and the water supply from the sand storage dam is meant for domestic purposes. But, in other catchments in southern Zimbabwe sometimes both are used for irrigation of small agricultural fields. For this reason, it is interesting to investigate the combined use of both measures. The results show that the period of water supply extends for 1.5 to 1.7 months after the reservoir has been dried out. This makes the total period of water supply approximately 7.2 months in an extreme dry year and 10.4 months in an extreme wet year. Heightening the spillway increases this period to respectively 8.4 (total amount of water supply is 2776 m^3) and 10.8 months (total amount of water supply is 3617 m^3). Thus, there is still a gap to bridge of maximum 3.6 months and minimum 1.2 months, depending on the rainfall that year.

7.5 Discussion

One solution to overcome the gap in water supply is to strengthen the reservoir dam, where after the spillway can be heightened even further. Another solution is to build several sand storage dams in the alluvial aquifer. A disadvantage of this solution is that it is not possible to build sand storage dams short after each other, because they require a distance of several kilometres to function properly. For the Mnyabezi catchment the alluvial aquifer is too small to sustain a large storage capacity, and can only be used as an additional water recourse. However, when an ephemeral river is underlain by a larger alluvial aquifer, a sand storage dam is a very efficient way of storing water in the arid regions of southern Zimbabwe. An alluvial aquifer twice as large as the Mnyabezi catchment, could store between 1000 m^3 to 1500 m^3 water (depending on the seepage losses) for the whole year. Assuming the same domestic water use as in the Mnyabezi catchment, the sand storage dam could supply water for 4.5 to 7.0 months.

Sand storage dams in Zimbabwe are normally built on top of a fresh granite layer, which has a low permeability. The granite layer underlying the alluvial aquifer of the Mnyabezi River is heavily weathered (relative high permeability), which allows water to percolate downwards relatively fast. In this study, a layer with a low permeability is assumed at the bottom that reduced the amount of seepage. The results of the calculations for the sand storage dam are conceptual and the outcomes could not be verified with measured data. This causes a large uncertainty in the water balance results. Nevertheless, the drying time results (2 to 3 months) are comparable with the information obtained during field visits at similar sand storage dams in southern Zimbabwe. The practical implication of the assumption is that an impermeable layer (for example a clay layer) has to be constructed at the bottom of the sand storage dam. Since the sand of the alluvial aquifer has to be removed to place drains anyway, this seems to be a possibility. However, a proper feasibility study would be interesting.

8. Conclusions

In this study the potential water supply is calculated of upper-Mnyabezi catchment for current conditions and after implementation of storage capacity measures. These measures are heightening the spillway of the Mnyabezi dam reservoir and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River. Three coupled models are used to simulate the hydrological processes in the Mnyabezi catchment: a rainfall-runoff, a reservoir and a groundwater model.

The rainfall-runoff model, based on the SCS-method, has been used to simulate surface water runoff caused by precipitation in the Mnyabezi catchment. The runoff was the main input variable for a dam reservoir model, which is used to calculate the water balance of the Mnyabezi reservoir. The calibration process of the rainfall-runoff model resulted in an initial abstraction of 7.6 % of the actual retention, which is in line with similar studies conducted in arid regions in southern Africa. The results of the water balance show that the seepage is negligible, the cattle abstractions are 21 % and the evaporation 79 % of the total amount of losses from the reservoir. For a period of 5.7 to 8.7 months (depending on the amount of yearly rainfall) the reservoir is filled with water and is used to supply drinking water for cattle. The finite difference groundwater model MODFLOW is used to simulate the water balance of the alluvial aquifer. The groundwater level measurements resulted in a drying period from the alluvial aquifer of 20 days after a dam overflow event. This relatively fast depletion time is caused by heavy weathering conditions (hydraulic conductivity of 0.55 $m \cdot day^{-1}$ and specific storage of 0.03) of the underlying granite layer. The losses from the alluvial aquifer in the current situation are caused by seepage (84 %), evapotranspiration (14 %) and groundwater flow (2 %).

The potential water supply under current conditions ranges from 2,107 m^3 in a dry year to 3,162 m^3 in a wet year. To increase the water storage of the reservoir, the spillway of the Mnyabezi dam is heightened from 0.73 to 1.00 m. In that case, the potential water supply extends for an extreme dry year with 417 m^3 and for an extreme wet year with 139 m^3. The potential water supply from the alluvial aquifer after the last dam overflow event in the current situation equals 123 m^3. In that situation, the alluvial aquifer can provide water for only 14 days. When constructing a sand storage dam in the alluvial aquifer, the water supply increases with 480 m^3 in an extreme dry year and in an extreme wet year with 558 m^3.

The sand storage dams stores water underground, which reduces the evaporation loss from 79 % to 38 % compared to the reservoir. Since the Mnyabezi reservoir dries out after 5.7 to 8.7 months, the sand storage dam could be used as an additional water resource. The results show that the period of water supply could be extended for 1.5 to 1.7 months after the reservoir has been dried out. This makes the total period of water supply 7.2 months in an extreme dry year and 10.4 months in an extreme wet year. Heightening the spillway will increase this period to respectively 8.4 (total amount of water supply is 2,776 m^3) and 10.8 months (total amount of water supply is 3,617 m^3).

The rainfall-runoff model is calibrated on only one rainfall event, which causes a large uncertainty in the inflow of the reservoir model. Nevertheless, the drying periods of the reservoirs are monitored quite well. Since the main interest of the study is to calculate the potential water supply after the main rainy season, the water balance results of the reservoir still provide useable outcomes. Besides, rainfall events in the arid region of southern Zimbabwe are usually very heavy, which cause dam overflow in the reservoir and complete saturation of alluvial aquifer anyway. Since the results concerning the sand storage dam are not validated at this moment the results are uncertain. It would be very interesting to monitor the hydrological processes of a sand storage dam in situ to reduce this uncertainty. The suggested implementation of an impermeable bottom-layer to prevent water percolating to the underlying granite is a new concept, for which the practical implementation needs further research.

This study has researched the hydrological processes in the alluvial aquifer of the Mnyabezi River. For the Mnyabezi catchment the alluvial aquifer is too small to sustain a large storage capacity, and can only be used as an additional water resource. However, when an ephemeral river is underlain by a larger alluvial aquifer, a sand storage dam is a promising way of water supply for smallholder farmers in southern Zimbabwe. In this study, the main concepts are established for a small catchment. Possibly, these results can also be used for a better understanding of the hydrological processes in larger alluvial aquifer systems in the Mzingwane catchment.

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Appendices

Appendix I: Grid MODFLOW model

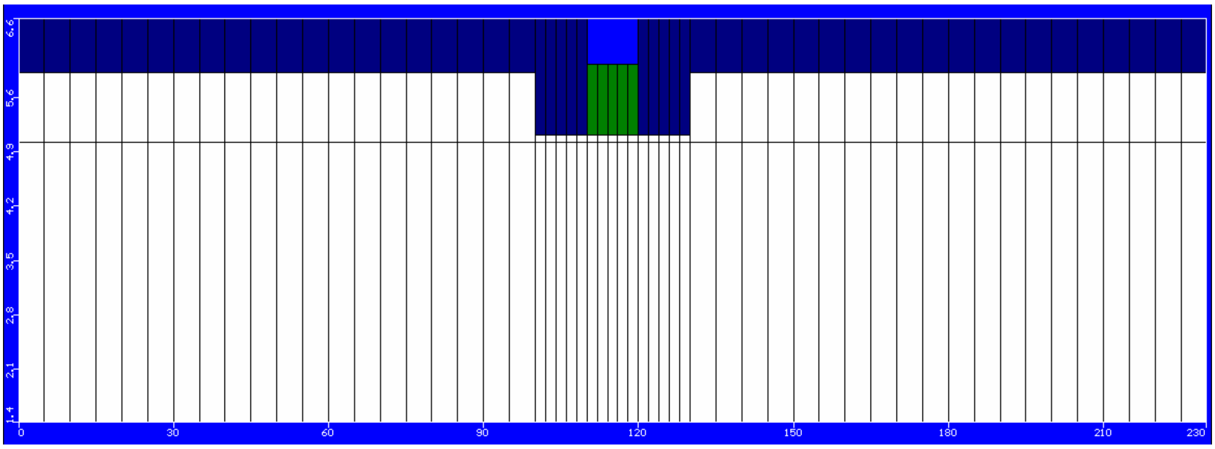

Figure I.1: Cross-section; green = alluvial, bleu = soil, white = granite

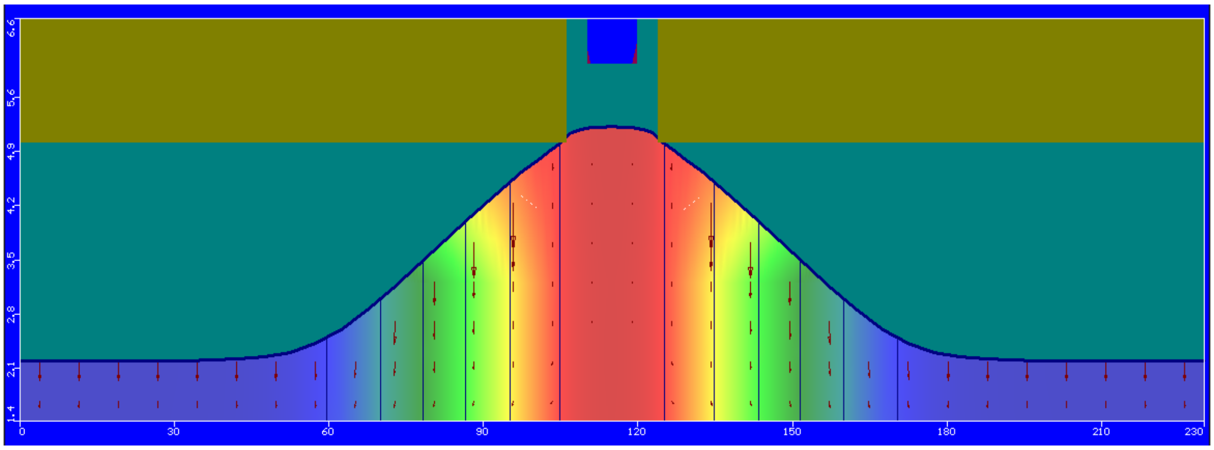

Figure I.2: Cross-section representing the water level after 20 days

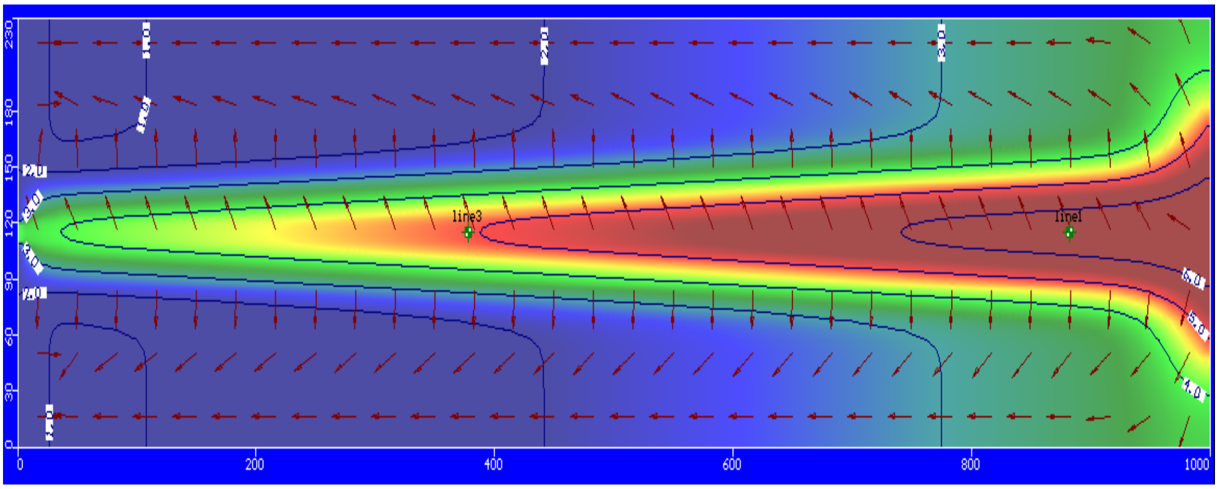

Figure I.3: Top-view water level after 20 days

Appendix II: Satellite image study area

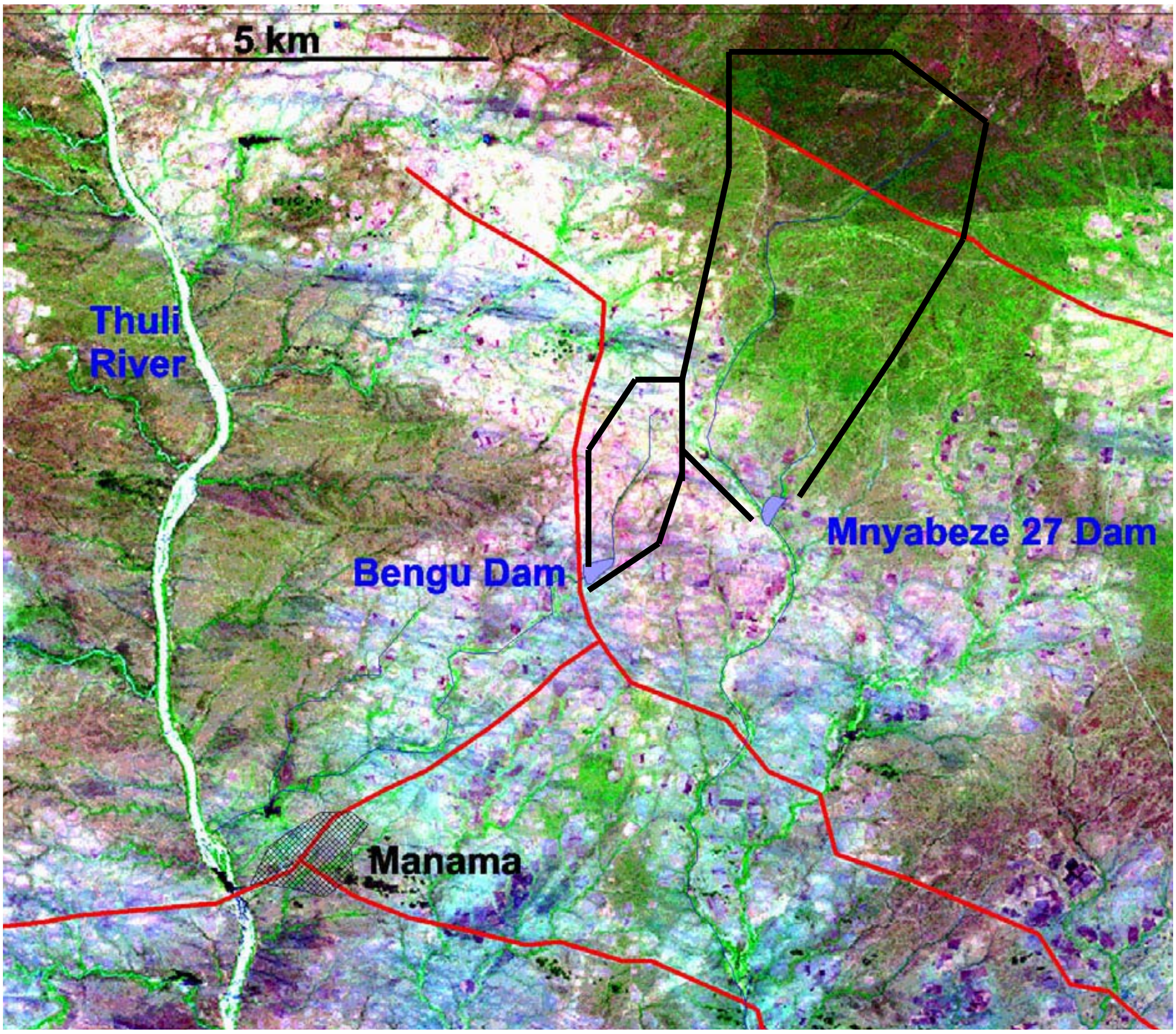

Figure II.1: Satellite image (band 3,4,5 false colour composite of Landsat Scene p170r075, dated 02-06-2000)

Appendix III: Thiessen polygons Mnyabezi catchment

Table III.1: Coordinates rain gauges in the Mnyabezi catchment

Rain gauges Mnyabezi	Name	Latitude	Longitude	Y-projection UTM-grid*	X-projection UTM-grid
1	H. Ncube	S 21°48’99.6’’	E 29°07’32.5’’	76.222.02 N	07.14.794 E
2	K.H. Ndlovu	S 21°28’54.3’’	E 29°03’55.3’’	76.231.23 N	07.139.89 E
3	H. Moyo	S 21°47’92.0’’	E 29°07’50.9’’	76.233.90 N	07.15.000 E
4	N. Moyo	S 21°46’75.2’’	E 29°07’32.9’’	76.246.87 N	07.14.831 E
5	N. Nyathi	S 21°45’98.3’’	E 29°07’59.9’’	76.255.35 N	07.15.122 E
6	“near the river”	S 21°44’07.3’’	E 29°08’33.0’’	76.276.39 N	07.15.909 E
7	“on the tree”	S 21°43’69.8’’	E 29°10’03.1’’	76.280.31 N	07.17.677 E

* the Y-projection is 300 m more south than the official map (BUVUMA 2129 A3) published by the Surveyor-General, Zimbabwe.

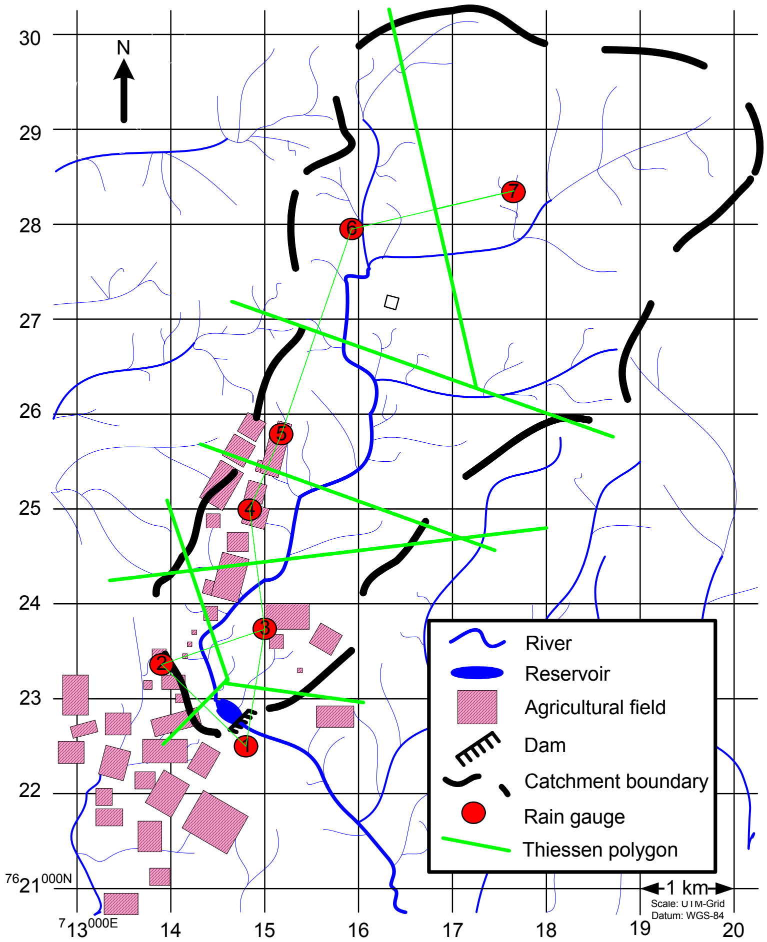

Figure III.1: Polygons Mnyabezi catchment

Appendix IV: Thiessen polygons Bengu catchment

Table IV.1: Coordinates rain gauges in the Bengu catchment

Rain gauges Bengu	Name	Latitude	Longitude	Y-projection UTM-grid*	X-projection UTM-grid
1	Bengu School	S 21°30’39.0’’	E 29°03’01.8’’	76.199.21 N	07.124.07 E
2	K. Ngwenya	S 21°30’19.3’’	E 29°03’40.5’’	76.205.12 N	07.135.28 E
3	N. Denya	S 21°29’48.4’’	E 29°03’31.4’’	76.214.65 N	07.132.79 E
4	K.F. Ndlovu	S 21°29’48.8’’	E 29°03’41.4’’	76.214.49 N	07.135.67 E
5	T. Moyo	S 21°29’35.2’’	E 29°03’29.9’’	76.218.74 N	07.132.42 E
6	F. Nyathi	S 21°29’35.4’’	E 29°03’44.0’’	76.218.63 N	07.136.47 E
7	K.H. Ndlovu	S 21°28’54.3’’	E 29°03’55.3’’	76.231.23 N	07.139.89 E

* the Y-projection is 300 m more south than the official map (BUVUMA 2129 A3) published by the Surveyor-General, Zimbabwe.

Table IV.2: CN-values of Thiessen-polygons in the Bengu catchment

Polygon	Area [ha]	Rangeland [%]	Fields [%]	Farmsteads [%]	Hydrological condition	CN-value [-]
1	50	90	0	10 (5 farms)	Poor	67.1
2	130	76	20	4 (5 farms)	Poor	68.4
3	80	63	31	6 (5 farms)	Poor	68.7
4	100	48	50	2 (2 farms)	Poor	69.8
5	100	36	60	4 (4 farms)	Fair	63.2
6	90	37	60	3 (3 farms)	Fair	63.1
7	150	85	13	2 (3 farms)	Fair	52.2

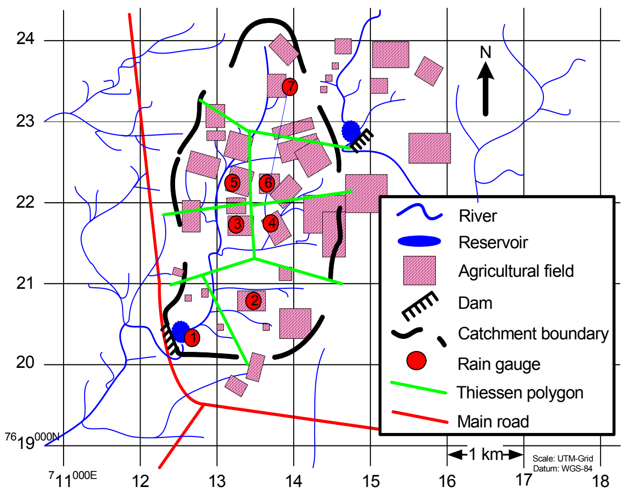

Figure IV.1: Polygons Bengu catchment

Appendix V: Tables for CN-values

Table V.1: Curve numbers for hydrological soil cover complexes for AMC class II (SCS, 1972)

Land use or cover	Treatment or practice	Hydrological condition	Hydrological soil group			
			A	B	C	D
Fallow	Straight row	Poor	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	81	88
	Contoured	Good	65	75	82	86
	Contoured/terraced	Poor	66	74	80	82
	Contoured/terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured/terraced	Poor	61	72	79	82
	Contoured/terraced	Good	59	70	78	81
Close-seeded legumes or rotational meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured/terraced	Poor	63	73	80	83
	Contoured/terraced	Good	51	67	76	80
Pasture range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow (permanent)		Good	30	58	71	78
Woodlands (farm woodlots)		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads			59	74	82	86
Roads, dirt			72	82	87	89
Roads, hard-surface			74	84	90	92

Table VI.2: Seasonal rainfall limits to determine AMC classes (SCS, 1972)

Antecedent Moisture Condition Class	5-day antecedent rainfall (mm)		
	Dormant season	Growing season	Average
1	2	3	4
I	< 13	< 36	< 23
II	13 − 28	36 − 53	23 − 40
III	> 28	> 53	> 40

Table V.3: Conversion table from AMC class II to AMC class I and III (SCS, 1972)

CN AMC II	CN AMC I	CN AMC III	CN AMC II	CN AMC I	CN AMC III
100	100	100	58	38	76
98	94	99	56	36	75
96	89	99	54	34	73
94	85	98	52	32	71
92	81	97	50	31	70
90	78	96	48	29	68
88	75	95	46	27	66
86	72	94	44	25	64
84	68	93	42	24	62
82	66	92	40	22	60
80	63	91	38	21	58
78	60	90	36	19	56
76	58	89	34	18	54
74	55	88	32	16	52
72	53	86	30	15	50
70	51	85	25	12	43
68	48	84	20	9	37
66	46	82	15	6	30
64	44	81	10	4	22
62	42	79	5	2	13
60	40	78	0	0	0

Appendix VI: Tables for hydro-geological characteristics

Table VI.1: Hydraulic conductivity values for different soil types (Dingman, 2002; p. 235)

	Hydraulic conductivity		
Soil type	**K-value [m·day^{-1}]**	**Soil texture**	**K-value [m·day^{-1}]**
Sand	15.21	Sandy clay loam	0.54
Loamy sand	13.48	Silty clay loam	0.15
Sandy loam	3.00	Clay loam	0.21
Silt loam	0.62	Sandy clay	0.19
Loam	0.60	Silty clay	0.09

Table VI.2: Porosity values for different soil types (Dingman, 2002; p. 235)

	Porosity		
Soil type	**Minimum**	**Average**	**Maximum**
Clay	0.34	0.42	0.57
Silt	0.34	0.46	0.61
Fine sand	0.26	0.43	0.53
Medium sand	0.29	0.39	0.49
Coarse sand	0.31	0.39	0.46
Fine gravel	0.25	0.34	0.39
Medium gravel	0.24	0.32	0.44
Coarse gravel	0.24	0.28	0.37

Table VI.3: Specific yield values for different soil types (Dingman, 2002; p. 235)

	Specific yield		
Soil type	**Minimum**	**Average**	**Maximum**
Clay	0.01	0.06	0.18
Silt	0.01	0.20	0.39
Fine sand	0.01	0.33	0.46
Medium sand	0.16	0.32	0.46
Coarse sand	0.18	0.30	0.43
Fine gravel	0.13	0.28	0.40
Medium gravel	0.17	0.24	0.44
Coarse gravel	0.13	0.21	0.25

Appendix VII: Rainfall data

Mnyabezi

Table VII.1: Rainfall data Mnyabezi catchment (*estimate)

	Rain gauge number						
Date	**1 [mm]**	**2 [mm]**	**3 [mm]**	**4 [mm]**	**5 [mm]**	**6 [mm]**	**7 [mm]**
11-03-2007	0	0	0	0	0	0	0
…							
27-03-2007	0	0	0	0	0	0	0
28-03-2007	1	3	2	0	0	0	1
29-03-2007	40	39.5	40	48	50	60	70
30-03-2007	10	4	5	10	10	20	20*
31-03-2007	0	5	0	0	0	0	0
01-04-2007	0	0	0	0	0	0	0
02-04-2007	0	0	0	0	0	0	0
03-04-2007	0	4	0	0	0	0	0
04-04-2007	0	3	0	0	0	0	0
05-04-2007	21	15	23	5	20	30	2.5
06-04-2007	0	0	0	0	0	0	0
…							
03-05-2007	0	0	0	0	0	0	0

Bengu

Table VII.2: Rainfall data Bengu catchment

	Rain gauge number						
Date	**1 [mm]**	**2 [mm]**	**3 [mm]**	**4 [mm]**	**5 [mm]**	**6 [mm]**	**7 [mm]**
10-02-2007	9	8	5	4	2	2	0
11-02-2007	2	2	1.5	1.5	1.5	1	0
12-02-2007	0	0	0	0	0	0	0
13-02-2007	0	0	0	0	0	0	0
14-02-2007	0	0	0	0	0	0	0
15-02-2007	0	0	0	0	0	0	0
16-02-2007	0	0	0	0	0	0	0
17-02-2007	0	0	0	0	0	0	0
18-02-2007	0	0	0	0	0	0	0
19-02-2007	5	4.5	7	8	8	8	16
20-02-2007	0	0	0	0	0	0	0

	Rain gauge number						
Date	**1 [mm]**	**2 [mm]**	**3 [mm]**	**4 [mm]**	**5 [mm]**	**6 [mm]**	**7 [mm]**
21-02-2007	0	0	0	0	0	0	0
22-02-2007	0	0	0	0	0	0	0
23-02-2007	0	0	0	0	0	0	0
24-02-2007	0	0	0	0	0	0	0
25-02-2007	0	0	0	0	0	0	0
26-02-2007	0	0	0	0	0	0	0
26-02-2007	26	20	30	30	30	32	40
27-02-2007	1.5	1	1.5	1.5	1.5	1.5	2.5
28-02-2007	0	0	0	0	0	0	0
…							
27-03-2007	0	0	0	0	0	0	0
28-03-2007	2	2	2	2	2	2	3
29-03-2007	32	36	36	36	32	28	39.5
30-03-2007	12	16	19	20	14	15	4
31-03-2007	2	1	2	2	2	3	5
01-04-2007	0	0	0	0	0	0	0
02-04-2007	0	0	0	0	0	0	0
03-04-2007	3	4	4	6	5	6	4
04-04-2007	1.5	1.5	2	1.5	2	2	3
05-04-2007	1.5	10	12	12	15	16	15
06-04-2007	0	0	0	0	0	0	0
…							
03-05-2007	0	0	0	0	0	0	0

Appendix VIII: Open water evaporation data

Table VIII.1: *Open water evaporation data (* rainfall rate ** estimated value before refill pan)*

Date	**Reading evaporation pan [mm]**	**Weather during the day**	**Pan- evaporation [mm·day^{-1}]**	**Evaporation with Pan factor [mm·day^{-1}]**
11-03-2007	46	Clear	10	7.0
12-03-2007	56	Clear	10	7.0
13-03-2007	66	Clear	10	7.0
14-03-2007	76	Clear	10	7.0
15-03-2007	86	Clear	10	7.0
16-03-2007	96	Clear	10	7.0
17-03-2007	106	A few clouds	10	7.0
18-03-2007	116	A few clouds	12	8.4
19-03-2007	128	Totally clouded	2	1.4
20-03-2007	130** - 74	Moderately clouded	9	6.3
21-03-2007	83	Clear	13	9.1
22-03-2007	96	Clear	11	7.7
23-03-2007	107	A few clouds	7	4.9
24-03-2007	114	Clear	12	8.4
25-03-2007	126	Clear	10	7.0
26-03-2007	136	A few clouds	9	6.3
27-03-2007	145** – 74	Heavily cloudy	4	2.8
28-03-2007	76 (2 mm*)	Totally clouded	3	2.1
29-03-2007	47 (32 mm*)	Totally clouded	7	4.9
30-03-2007	42 (12 mm*)	Totally clouded	2	1.4
31-03-2007	42 (2 mm*)	Totally clouded	2	1.2
01-04-2007	44	Totally clouded	4	2.8
02-04-2007	48	Heavily clouded	3	2.1
03-04-2007	48 (3 mm*)	Totally clouded	3.5	2.5
04-04-2007	50 (1.5 mm*)	Totally clouded	5.5	3.9
05-04-2007	53 (1.5 mm*)	Totally clouded	5	3.5
06-04-2007	58	Totally clouded	5	3.5
07-04-2007	63	Totally clouded	6	4.2
08-04-2007	69	Totally clouded	3	2.1
09-04-2007	72	Totally clouded	4	2.8
10-04-2007	76	Moderate clouded	6	4.2
11-04-2007	82	Clear	10	7.0

Date	Reading evaporation pan [mm]	Weather during the day	Pan-evaporation [mm·day^{-1}]	Evaporation with pan factor [mm·day^{-1}]
12-04-2007	92	Moderate clouded	6	4.2
13-04-2007	98	Heavily clouded	4	2.8
14-04-2007	102	A few clouds	5	3.5
15-04-2007	107	Clear	9	6.3
16-04-2007	116	Clear	6	4.2
17-04-2007	122	Clear	9	6.3
18-04-2007	131	A few clouds	8	5.6
19-04-2007	139 – 64	Moderate clouded	8	5.6
20-04-2007	72	Clear	9	6.3
21-04-2007	81	Clear	11	7.7
22-04-2007	92	Clear	7	7.0
23-04-2007	99	A few clouds	6	6.3
24-04-2007	105	Clear	8	5.6
25-04-2007	113	Clear	8	5.6
26-04-2007	121	Clear	14	9.8
27-04-2007	135 – 22	Clear	8	5.6
28-04-2007	30	Heavily clouded	7	4.9
29-04-2007	37	Clear	10	7.0
30-04-2007	47	Clear	8	5.6
01-05-2007	55	Clear	9	7.3
02-05-2007	64	Heavily clouded	6	4.2
03-05-2007	7	A few clouds	8.6***	6.0***

Average evaporation March:	*6.0 mm*
Average evaporation April:	*5.0 mm*
Average evaporation clear sky:	*6.9 mm*
Average evaporation with a few clouds:	*6.0 mm*
Average evaporation moderate clouded:	*5.1 mm*
Average evaporation heavily clouded:	*3.4 mm*
Average evaporation totally clouded:	*2.8 mm*

Appendix IX: Water level reservoir data

Table IX.1: *Water level Mnyabezi and Bengu reservoirs (* estimates)*

Date	Mnyabezi reservoir [cm]	Difference [cm]	Bengu reservoir [cm]	Difference [cm]
11-03-2007	57.8		35.1	
12-03-2007	57.0	- 0.8	34.2	- 0.9
13-03-2007	56.3	- 0.7	33.1	- 1.1
14-03-2007	54.0	- 2.3	32.0*	- 1.1
15-03-2007	52.2	- 1.8	31.1	- 1.1
16-03-2007	50.0	- 2.2	30.8	- 0.3
17-03-2007	48.3	-1.7	29.8	- 1.0
18-03-2007	47.5	- 0.8	28.1	- 1.7
19-03-2007	47.1	- 0.4	27.8	- 0.3
20-03-2007	46.5	- 0.6	27.0	- 0.8
21-03-2007	45.3	- 0.8	26.2	- 0.8
22-03-2007	45.1*	- 0.2	25.3	- 0.9
23-03-2007	44.9*	- 0.2	24.1	- 1.2
24-03-2007	44.0	- 0.9	23.3*	- 0.8
25-03-2007	43.0*	- 1.0	21.8*	- 1.5
26-03-2007	42.0	- 1.0	20.2	- 1.6
27-03-2007	41.5	- 0.5	18.8	- 1.4
28-03-2007	40.0	-1.5	17.5	- 1.3
29-03-2007	76.0	+ 36.0	73.2	+ 65.8
30-03-2007	78.0	+ 2.0	80.0	+ 6.8
31-03-2007	75.0	- 3.0	72.0	- 8.0
01-04-2007	72.1*	- 2.9	68.2	- 3.8
02-04-2007	71.0	- 1.1	66.0	- 2.2
03-04-2007	70.0	- 1.0	65.8	- 0.2
04-04-2007	69.0	- 1.0	64.8	- 1.0
05-04-2007	73.0*	+ 4.0	63.7	- 1.1
06-04-2007	72.0*	- 1.0	62.2*	- 1.5
07-04-2007	71.0*	-1.0	60.7*	- 1.5
08-04-2007	70.0*	-1.0	59.2*	- 1.5
09-04-2007	69.0	-1.0	58.0	- 1.2
10-04-2007	68.0	-1.0	58.8	- 0.8
11-04-2007	67.0	- 1.0	57.9	- 0.9

Date	Mnyabezi reservoir [cm]	Difference [cm]	Bengu reservoir [cm]	Difference [cm]
12-04-2007	66.0	- 1.0	56.3	- 1.3
13-04-2007	65.0	- 1.0	54.8	- 1.5
14-04-2007	64.0	- 1.0	53.8	- 1.0
15-04-2007	64.3	- 0.7	53.1*	- 0.7
16-04-2007	63.0	- 1.3	52.9	- 0.2
17-04-2007	61.9	- 1.1	51.8	- 1.1
18-04-2007	61.0	- 0.9	50.5	- 1.3
19-04-2007	60.0	- 1.0	49.5	- 1.0
20-04-2007	59.0	- 1.0	48.6	- 0.9
21-04-2007	58.0	- 1.0	47.8	- 0.8
22-04-2007	57.0	- 1.0	46.0	- 1.8
23-04-2007	56.0	- 1.0	45.0	- 1.0
24-04-2007	55.0	- 1.0	44.7	- 0.3
25-04-2007	54.0	- 1.0	43.9	- 1.2
26-04-2007	53.0	- 1.0	42.3	- 1.6
27-04-2007	52.0*	- 0.7	42.8	- 0.5
28-04-2007	51.3*	- 0.7	41.6	- 1.2
29-04-2007	50.6*	- 0.7	41.0	- 0.6
30-04-2007	49.9*	- 0.7	40.4	- 0.6
01-05-2007	49.2*	- 0.7	39.0	- 0.5
02-05-2007	48.5*	- 0.7	38.3*	- 0.7
03-05-2007	47.9	- 0.6	37.6	- 0.7

Appendix X: Abstractions Mnyabezi reservoir

Table X.1: Abstractions by cattle from the Mnyabezi reservoir

	Name	Cows	Calves	Goats	Kids	Donkeys	Water use livestock
		[-]	[-]	[-]	[-]	[-]	[l·day^{-1}] *
1	D. Dube	8	3	12	1	9	472
2	T. Madzikiti	11	2	11	4	3	418
3	M. Mdlongwa	10	3	6	5	4	400
4	H. Moyo	8	2	10	5	9	460
5	Ja. Moyo	4	1	14	2	5	284
6	Jo. Moyo	2	0	30	0	11	420
7	K. Moyo	4	1	15	1	4	267
8	M. Moyo	3	1	7	4	9	308
9	N. Moyo	7	1	9	1	2	272
10	Sa. Moyo	3	0	5	0	5	200
11	Sh. Moyo	2	1	9	0	2	145
12	O. Nare	30	3	20	1	10	1,082
13	T. Nare	1	1	29	30	9	420
14	H. Ncube	5	1	13	5	4	290
15	W. Ncube	3	1	4	2	0	109
16	J. Ndlovu	9	3	15	0	5	430
17	M. Ndlovu	34	10	32	10	12	1,370
18	G. Ndlovu	5	1	12	3	6	321
19	S. Ngulube	5	2	5	0	3	230
20	M. Ngwenya	9	2	15	3	6	446
21	O. Ngwenya	10	3	20	4	6	508
22	El. Nyathi	8	1	32	15	4	480
23	Ep. Nyathi	16	6	20	10	6	700
24	F. Nyathi	2	2	24	0	5	290
25	K. Nyathi	1	1	8	7	4	169
26	N. Nyathi	4	3	4	2	4	234
27.	P. Nyathi	20	6	30	10	7	870
	Total	**224**	**61**	**411**	**125**	**153**	**11,595**

* *1 cow uses 25 l·day^{-1}* *1 calve uses 10 l·day^{-1}*
1 donkey uses 20 l·day^{-1} *1 kid uses 2 l·day^{-1}*
1 goat uses 5 l·day^{-1}

Appendix XI: Abstractions Bengu reservoir

Table XI.1: Abstractions by cattle from the Bengu reservoir

	Name	Cows [-]	Calves [-]	Goats [-]	Kids [-]	Donkeys [-]	Water use livestock [l·day^{-1}] *
1	T. Bedza	0	0	8	3	2	86
2	E. Chinamure	10	3	32	12	4	544
3	N. Denya	0	0	15	6	6	207
4	B. Dube	6	2	25	10	3	375
5	El. Dube	1	0	10	2	6	199
6	Ev. Dube	6	2	10	2	5	324
7	P. Dube	5	2	15	5	2	270
8	A. Homela	0	0	5	2	0	29
9	D. Khumalo	0	0	10	3	0	56
10	C. Mabetha	5	2	8	2	4	269
11	M. Mabetha	1	0	4	4	3	113
12	S. Mabhena	0	0	13	2	0	69
13	E. Malutha	0	0	14	6	7	222
14	T. Malutha	0	0	15	7	0	89
15	H. Magaya	13	0	38	21	0	557
16	K. Magaya	0	0	15	4	5	183
17	G. Maphosa	0	0	6	1	6	152
18	Nd. Maphosa	0	0	8	2	2	84
19	Nk. Maphosa	0	0	8	2	0	44
20	G. Mapfumo	5	2	39	11	7	502
21	V. Masendeke	2	1	2	0	0	70
22	K. Masiane	0	0	12	4	0	68
23	S. Masiane	0	0	15	5	3	145
24	M. Masiane	0	0	10	3	4	136
25	L. Masuku	10	4	28	5	6	560
26	E. Mathe	20	4	35	10	1	755
27	M. Mathe	3	3	3	4	3	188
28	S. Mathnodi	0	0	10	3	3	116
29	N. Mbedzi	0	0	15	5	7	225
30	Al. Moyo	31	10	44	12	4	1,199
31	Au. Moyo	0	0	10	0	0	50
32	A. S. Moyo	5	1	20	5	5	345

	Name	Cows [-]	Calves [-]	Goats [-]	Kids [-]	Donkeys [-]	Water use livestock [l·day^{-1}] *
33	G. Moyo	0	0	10	0	0	50
34	L. Moyo	8	2	28	6	6	492
35	M. Moyo	4	2	29	9	6	403
36	O. Moyo	35	5	46	21	10	1,397
37	P. Moyo	0	0	12	2	3	124
38	S. Moyo	22	10	46	12	9	1,084
39	T. Moyo	12	3	21	6	4	527
40	S. Mpofu	15	3	32	10	6	705
41	S. Mtembo	6	2	21	7	8	449
42	A. Nare	0	0	2	0	0	10
43	B. Nare	0	0	9	1	0	47
44	E. Nare	0	0	28	12	4	244
45	L. Nare	2	1	5	1	6	207
46	Ma. Nare	10	3	22	6	7	542
47	Me. Nare	4	0	10	3	4	236
48	S. Nare	6	2	39	12	8	549
49	Th. Nare	0	0	8	2	0	44
50	Ti. Nare	5	2	12	3	8	371
51	Ts. Nare	0	0	13	4	6	193
52	B. Ncube	28	7	52	12	6	1,174
53	D. Ncube	8	4	35	6	8	587
54	H. Ncube	12	4	38	12	9	734
55	K. Ncube	0	0	38	9	6	328
56	Lu. Ncube	0	0	5	1	0	27
57	Le. Ncube	0	0	9	10	3	125
58	N. Ncube	0	0	7	3	4	121
59	O. Ncube	8	2	15	6	6	427
60	R. Ncube	0	0	15	5	4	165
61	S. Ncube	0	0	21	7	0	119
62	Ma. Ndlovu	6	2	12	3	0	236
63	Mi. Ndlovu	10	3	20	6	6	512
64	E. Ndlovu	0	0	28	8	6	276
65	Joi. Ndlovu	0	0	15	5	5	185
66	Jon. Ndlovu	0	0	12	4	0	68
67	N. Ndlovu	6	2	21	6	6	407
68	Sim. Ndlovu	8	3	24	9	6	488
69	Sip. Ndlovu	1	0	5	2	0	54
70	Sit. Ndlovu	0	0	15	6	6	207

	Name	Cows [-]	Calves [-]	Goats [-]	Kids [-]	Donkeys [-]	Water abstraction [l·day^{-1}] *
71	T. Ndlovu	3	1	0	0	0	85
72	G. Ngulube	0	0	6	3	0	36
73	L. Ngulube	0	0	15	5	0	85
74	K. Ngwenya	6	2	24	9	12	548
75	T. Ngwenya	0	0	10	3	0	56
76	P. Nkala	7	3	0	0	6	325
77	F. Nkomo	0	0	5	1	0	27
78	L. Ntini	0	0	18	6	3	162
79	A. Nyathi	0	0	8	3	4	126
80	B. Nyathi	0	0	10	1	0	52
81	Md. Nyathi	41	12	52	15	12	1,675
82	Mi. Nyathi	28	8	45	15	8	1,195
83	O. Nyathi	58	15	30	10	9	1,950
84	P. Nyathi	0	0	9	3	2	91
85	T. Nyathi	0	0	30	12	16	494
86	M. Nyoni	0	0	10	2	3	114
87	B. Sibanda	0	0	30	10	3	230
88	E. Sibanda	0	0	16	6	0	92
89	H. Sibanda	0	0	4	1	0	22
90	S. Sibanda	0	0	15	4	0	83
91	R. Sebata	31	11	42	18	10	1,331
92	T. Sijiye	0	0	15	4	6	203
93	K. Sithole	0	0	15	8	3	151
94	D. Tlou	0	0	52	15	8	450
95	P. Zhou	0	0	6	1	0	32
	Total	**513**	**150**	**1,749**	**555**	**379**	**31,760**

* *1 cow uses 25 l·day^{-1}*
1 donkey uses 20 l·day^{-1}
1 goat uses 5 l·day^{-1}
1 calve uses 10 l·day^{-1}
1 kid uses 2 l·day^{-1}

Appendix XII: Abstractions people

Table XII.1: *Pump abstractions for domestic use in the Mnyabezi catchment*

	Name	Water use 11 April [l·day^{-1}]	Water use 24 April [l·day^{-1}]	Water use 27 April [l·day^{-1}]	Water use 28 April [l·day^{-1}]	Water use 30 April [l·day^{-1}]	Average water use [l·day^{-1}]
1	D. Dube	120	140	120	140	140	132
2	T. Madzikiti	200	200	200	120	120	168
3	M. Mdlongwa	80	100	160	30	60	86
4	H. Moyo	120	160	140	160	160	148
5	Ja. Moyo	40	80	80	210	200	122
6	Jo. Moyo	160	100	160	140	140	140
7	K. Moyo	100	100	100	200	200	140
8	M. Moyo	240	140	240	140	80	168
9	N. Moyo	100	160	120	200	80	132
10	Sa. Moyo	200	200	200	180	180	192
11	Sh. Moyo	80	80	180	160	160	132
12	O. Nare	120	120	120	160	160	136
13	T. Nare	60	120	80	40	80	76
14	H. Ncube	140	120	140	130	120	130
15	W. Ncube	120	100	120	80	80	100
16	J. Ndlovu	100	130	130	140	140	128
17	M. Ndlovu	200	200	200	140	180	184
18	G. Ndlovu	120	80	180	120	180	136
19	S. Ngulube	130	80	80	40	40	74
20	M. Ngwenya	180	200	100	200	70	150
21	O. Ngwenya	100	100	80	210	200	138
22	El. Nyathi	160	140	120	120	40	116
23	Ep. Nyathi	160	180	200	100	120	152
24	F. Nyathi	180	180	130	180	180	170
25	K. Nyathi	80	60	90	60	60	70
26	N. Nyathi	120	120	200	80	80	120
27	P. Nyathi	120	200	200	100	100	144
	Total	**3,530**	**3,590**	**3,870**	**3,580**	**3,350**	**3,584**

Table XII.2: *Pump abstractions for gardening in the Bengu catchment (* gardens are 100 m²)*

	Name	Water use [l·day^{-1}]*
1	N. Denya	380
2	N. Mabetha	540
3	L .Magaya	160
4	A. Masuku	200
5	E. Mathe	400
6	E. Nare	600
7	Sip. Ndolvu	100
8	Sit. Ndlovu	320
9	C. Phiri	460
10	B. Sibanda	460
11	H. Sibanda	200
Average		**347**

Appendix XIII: Sieving tests soil

The sieving was done by a sieve shaker model A. The used sieves are US standard sieves with sizes 4000, 2800, 2000, 1000, 500, 250, 180, 125 and 32 µm. Unfortunately, the 64 µm sieve is not available, which gives slightly higher values for the 32 µm. The samples are electronically weighted (accuracy 0.001 g). For the soil in the Mnyabezi catchment three ground samples are analysed.

Table XIII.1: Results soil sample (1)

US standard sieve number [µm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	9.44	2.57	6.87	2.77	100.00
2800	11.86	2.56	9.3	3.75	97.23
2000	15.86	2.54	13.32	5.37	93.48
1000	35.5	2.55	32.95	13.28	88.11
500	49.67	2.69	46.98	18.94	74.83
250	66.23	2.42	63.81	25.72	55.89
180	32.07	2.54	29.53	11.90	30.17
125	26.16	2.35	23.81	9.60	18.26
32	22.83	2.47	20.36	8.21	8.66
< 32	3.84	2.71	1.13	0.46	0.46
Total			**248.06**	**100**	

Table XIII.2: Results soil sample (2)

US standard sieve number [µm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	0	2.57	0	0.00	100.00
2800	4.87	2.56	2.31	0.93	100.00
2000	13.67	2.54	11.13	4.50	99.07
1000	41.43	2.55	38.88	15.71	94.57
500	72.25	2.69	69.56	28.10	78.86
250	62.52	2.42	60.1	24.28	50.76
180	28.86	2.54	26.32	10.63	26.48
125	14.02	2.35	11.67	4.71	15.85
32	29.03	2.47	26.56	10.73	11.13
< 32	3.71	2.71	1	0.40	0.40
Total			**247.53**	**100**	

Table XIII.3: Results soil sample (3)

US standard sieve number [µm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	0.00	2.57	0.00	0.00	100.00
2800	6.60	2.56	4.04	1.61	100.00
2000	12.7	2.54	10.16	4.06	98.39
1000	44.21	2.55	41.66	16.65	94.32
500	67.97	2.69	65.28	26.09	77.67
250	72.21	2.42	69.79	27.89	51.58
180	24.93	2.54	22.39	8.95	23.69
125	15.19	2.35	12.84	5.13	14.74
32	25.11	2.47	22.64	9.05	9.61
< 32	4.11	2.71	1.40	0.56	0.56
Total			**250.20**	**100**	

Table XIII.4: Results samples alluvial material

US standard sieve number [µm]	Average of total weight [%]	Cumulative [%]
4000	0.92	100.00
2800	2.10	99.08
2000	4.64	96.98
1000	15.21	92.34
500	24.38	77.12
250	25.97	52.74
180	10.50	26.78
125	6.48	16.28
32	9.33	9.80
Total	**100.00**	

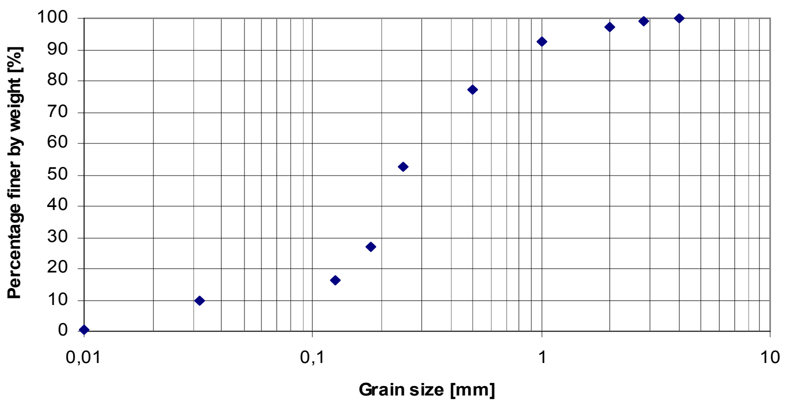

Figure XIII.1: Distribution grain sizes soil Mnyabezi catchment

Appendix XIV: Sieving tests alluvial material

The sieving was done by a sieve shaker model A. The used sieves are US standard sieves with sizes 4000, 2800, 2000, 1000, 500, 250, 180, 125 and 32 μm. Unfortunately the 64 μm sieve is not available, which gives slightly higher values for the 32 μm. The samples are electronically weighted (accuracy 0.001 g). For the alluvial material from the Mnyabezi River four ground samples are analysed.

Table XIV.1: *Results sample alluvial material (1)*

US standard sieve number [μm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	25.85	2.57	23.28	9.00	100.00
2800	23.02	2.56	20.46	7.91	91.00
2000	27.95	2.54	25.41	9.83	83.08
1000	62.08	2.55	59.53	23.02	73.26
500	67.58	2.69	64.89	25.10	50.23
250	51.19	2.42	48.77	18.86	25.14
180	14.63	2.54	12.09	4.68	6.27
125	5.25	2.35	2.9	1.12	1.60
32	3.7	2.47	1.23	0.48	0.48
Total			**258.56**	**100.00**	

Table XIV.2: *Results sample alluvial material (2)*

US standard sieve number [μm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	40.57	2.57	38	15.04	100.00
2800	29.47	2.56	26.91	10.65	84.96
2000	33.53	2.54	30.99	12.27	74.30
1000	72.62	2.55	70.07	27.74	62.04
500	60.34	2.69	57.65	22.82	34.30
250	26.88	2.42	24.46	9.68	11.48
180	5.1	2.54	2.56	1.01	1.79
125	3.42	2.35	1.07	0.42	0.78
32	3.37	2.47	0.9	0.36	0.36
Total			**252.61**	**100.00**	

Table XIV.3: *Results sample alluvial material (3)*

US standard sieve number [µm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	48.49	2.57	45.92	17.88	100.00
2800	25.37	2.56	22.81	8.88	82.12
2000	29.78	2.54	27.24	10.60	73.24
1000	64.96	2.55	62.41	24.30	62.64
500	62.1	2.69	59.41	23.13	38.34
250	33.44	2.42	31.02	12.08	15.22
180	7.68	2.54	5.14	2.00	3.14
125	4.43	2.35	2.08	0.81	1.14
32	3.32	2.47	0.85	0.33	0.33
Total			**256.88**	**100.00**	

Table XIV.4: *Results sample alluvial material (4)*

US standard sieve number [µm]	Measured weight [g]	Weight paper [g]	Real weight [g]	Percentage of total weight [%]	Cumulative [%]
4000	65.62	2.57	63.05	24.89	100.00
2800	30.9	2.56	28.34	11.19	75.11
2000	31.5	2.54	28.96	11.43	63.93
1000	52.8	2.55	50.25	19.83	52.50
500	49.76	2.69	47.07	18.58	32.66
250	31.51	2.42	29.09	11.48	14.09
180	6.62	2.54	4.08	1.61	2.60
125	4.06	2.35	1.71	0.67	0.99
32	3.28	2.47	0.81	0.32	0.32
Total			**253.36**	**100.00**	

Table XIV.5: Results samples alluvial material

US standard sieve number [µm]	Average of total weight [%]	Cumulative [%]
4000	16.70	100.00
2800	9.66	83.30
2000	11.03	73.64
1000	23.72	62.61
500	22.41	38.88
250	13.03	16.48
180	2.33	3.45
125	0.76	1.13
32	0.37	0.37
Total	**100.00**	

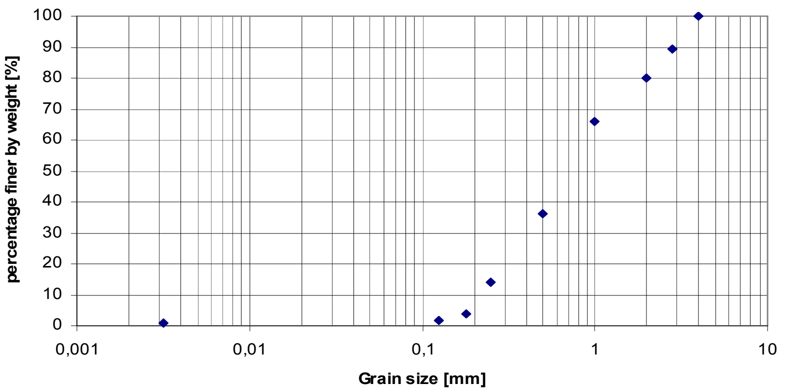

Figure XIV.1: Distribution grain sizes soil Mnyabezi catchment

Appendix XV: Dimension Mnyabezi reservoir

Table XV.15: Coordinates of the Mnyabezi reservoir

GPS-point	Latitude	Longitude	Y-projection UTM-grid*	X-projection UTM-grid
1	S 21°48’73.2’’	E 29°07’21.7’’	76.22.495 N	07.14.686 E
2	S 21°48’73.8’’	E 29°07’25.5’’	76.22.488 N	07.147.26 E
3	S 21°48’68.9’’	E 29°07’32.8’’	76.22.542 N	07.14.801 E
4	S 21°48’61.5’’	E 29°07’36.2’’	76.22.623 N	07.14.838 E
5	S 21°48’53.6’’	E 29°07’33.6’’	76.22.710 N	07.14.812 E
6	S 21°48’47.0’’	E 29°07’27.6’’	76.22.785 N	07.14.751 E
7	S 21°48’38.3’’	E 29°07’19.8’’	76.22.882 N	07.14.672 E
8	S 21°48’40.1’’	E 29°07’05.8’’	76.22.864 N	07.14.526 E
9	S 21°48’57.7’’	E 29°07’07.9’’	76.22.668 N	07.14.545 E
10	S 21°48’71.6’’	E 29°07’20.3’’	76.22.514 N	07.14.672 E
11	S 21°48’71.9’’	E 29°07’23.2’’	76.22.509 N	07.14.701 E
12	S 21°48’64.5’’	E 29°07’15.1’’	76.22.592 N	07.14.619 E
13	S 21°48’59.2’’	E 29°07’14.7’’	76.22.651 N	07.14.616 E
14	S 21°48’65.7’’	E 29°07’24.1’’	76.22.578 N	07.14.588 E
15	S 21°48’56.5’’	E 29°07’26.7’’	76.22.680 N	07.14.842 E
16	S 21°48’58.8’’	E 29°07’13.3’’	76.22.654 N	07.14.787 E
17	S 21°48’60.3’’	E 29°07’36.4’’	76.22.636 N	07.14.840 E

** the Y-projection is 300 m more south than the official map (BUVUMA 2129 A3) published by the Surveyor-General, Zimbabwe.*

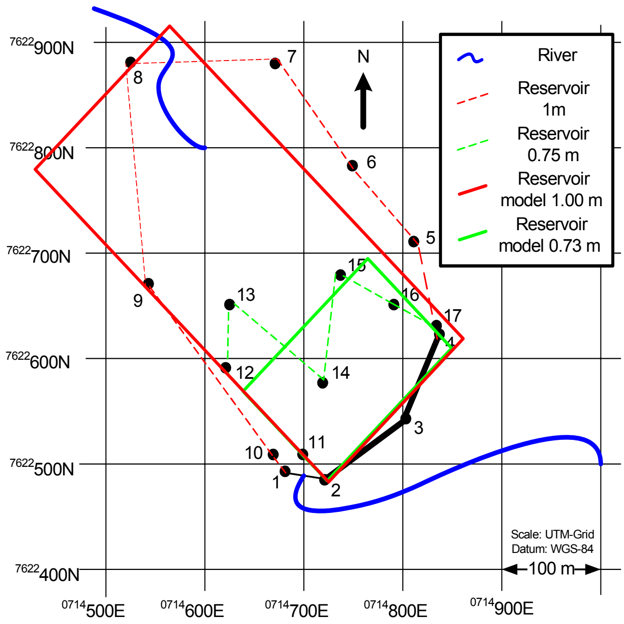

Figure XV.1: Dimensions of the Mnyabezi reservoir

Appendix XVI: Dimension Bengu reservoir

Table XVI.1: Coordinates of the Bengu reservoir

GPS-point	Latitude	Longitude	Y-projection UTM-grid*	X-projection UTM-grid
1	S 21°30’304’’	E 29°02’586’’	76.20.187 N	07.12.317 E
2	S 21°30’289’’	E 29°02’595’’	76.20.232 N	07.12.344 E
3	S 21°30’295’’	E 29°03’013’’	76.20.215 N	07.12.394 E
4	S 21°30’329’’	E 29°03’022’’	76.20.110 N	07.12.420 E
5	S 21°30’361’’	E 29°03’004’’	76.20.010 N	07.12.367 E

* *the Y-projection is 300 m more south than the official map (BUVUMA 2129 A3) published by the Surveyor-General, Zimbabwe.*

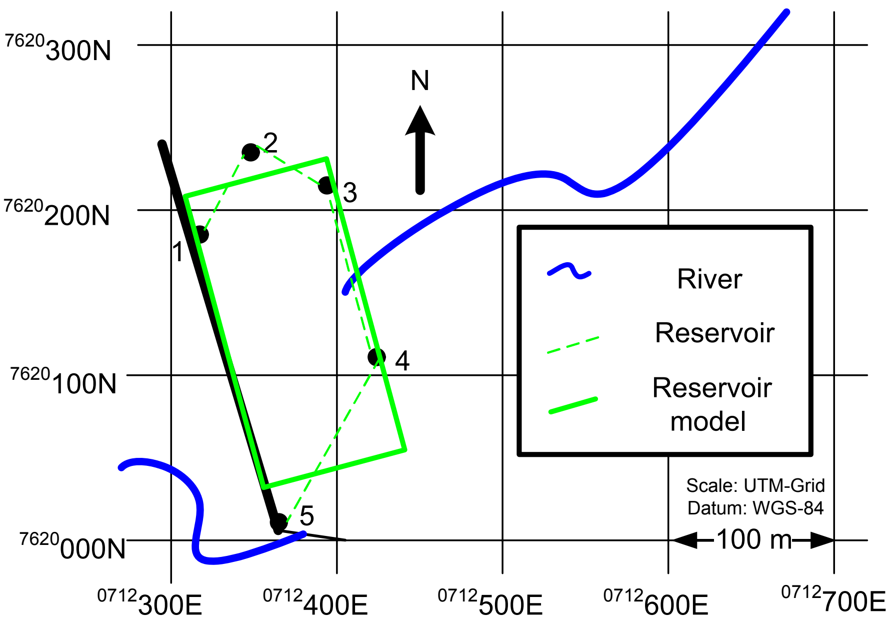

Figure XVI.1: Dimensions Bengu reservoir

Appendix XVII: Dimensions of the alluvial aquifer

XVII.1 Shape

The shape of the alluvial aquifer is determined with a GPS-device. The red dots indicate the locations of the physical probing, which are the locations of the piezometers as well.

Table XVII1: Coordinates of the alluvial aquife

GPS-point	Latitude	Longitude	Y-projection UTM-grid*	X-projection UTM-grid
1	S 21°29’159’’	E 29°04’276’’	76.22.446 N	07.14.910 E
2	S 21°29’166’’	E 29°04’317’’	76.22.423 N	07.15.028 E
3	S 21°29’178’’	E 29°04’332’’	76.22.385 N	07.15.069 E
4	S 21°29’181’’	E 29°04’354’’	76.22.375 N	07.15.134 E
5	S 21°29’189’’	E 29°04’367’’	76.22.348 N	07.15.170 E
6	S 21°29’210’’	E 29°04’393’’	76.22.283 N	07.15.245 E
7	S 21°29’228’’	E 29°04’411’’	76.22.228 N	07.15.294 E
8	S 21°29’260’’	E 29°04’444’’	76.22.127 N	07.15.390 E
9	S 21°29’276’’	E 29°04’448’’	76.22.077 N	07.15.400 E
10	S 21°29’287’’	E 29°04’455’’	76.22.044 N	07.15.419 E
11	S 21°29’312’’	E 29°04’474’’	76.21.968 N	07.15.472 E
12	S 21°29’320’’	E 29°04’484’’	76.21.940 N	07.15.501 E
13	S 21°29’336’’	E 29°04’491’’	76.21.894 N	07.15.522 E
14	S 21°29’348’’	E 29°04’508’’	76.21.855 N	07.15.571 E

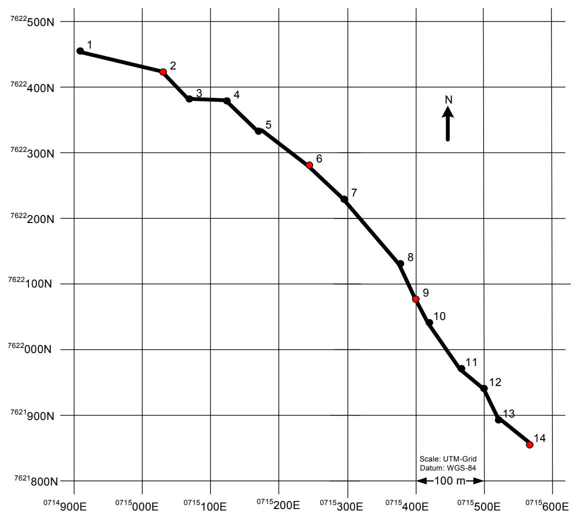

Figure XVII.1: Shape of the alluvial aquifer (* the Y-projection is 300 m more south than the map (BUVUMA 2129 A3) published by the Surveyor-General, Zimbabwe.)

XVII.2 Physical Probing

The physical probing is done at four lines along the alluvial aquifer. The probing started on the right bank, while looking downstream.

Table XVI.2: Physical probing line 1

Point [m]	Depth [m]	Point [m]	Depth [m]
0	0.00	5	0.97
2	1.02	6	0.85
3	1.30	7	1.00
4	1.30	9	0.00
Location line 1	120 m downstream dam	Width of line 1	9 meter

Table XVII.3: Physical probing line 2

Point [m]	Depth [m]	Point [m]	Depth [m]
0	0.00	6.5	0.66
0.5	0.42	8.5	0.63
2.5	0.98	10.5	0.00
4.5	0.87		
Location line 2	370 m downstream dam	Width of line 2	10.5 m

Table XVII.4: Physical probing line 3

Point [m]	Depth [m]	Point [m]	Depth [m]
0	0.00	6	0.82
2	1.16	8	0.75
4	1.12	10	0.00
Location line 3	620 m downstream dam	Width of line 3	10 m

Table XVII.5: Physical probing line 4

Point [m]	Depth [m]	Point [m]	Depth [m]
0	0.00	5	0.89
1	0.64	7	1.00
3	0.89	9	0.00
Location line 4	900 m downstream dam	Width of line 9	9 m

XVII.3 Resistivity test

The resistivity test is done at the same four lines along the alluvial aquifer as the physical probing. Unfortunately, the reading for line 1 and 3 gave unrealistic results, so these are not presented here. The location is measured from the right riverbank, while looking downstream.

Table XVII.6: Resistivity test line 2

Line	2	Location	2m	Line	2	Location	4m
AB/2 [m]	MN/2 [m]	ρ [Ω·m]	s.d. [%]	AB/2 [m]	MN/2 [m]	ρ [Ω·m]	s.d. [%]
1.5	0.5	257.22	0.1	1.5	0.5	123.33	0.1
2	0.5	158.05	0.1	2	0.5	78.94	0.2
2.5	0.5	97.43	0.1	2.5	0.5	52.54	0.0
3	0.5	71.73	1.1	3	0.5	44.58	0.1
5	0.5	55.30	0.2	5	0.5	40.98	0.0
7	2.0	50.18	0.3	7	2.0	49.25	0.5
10	2.0	70.83	1.1	10	2.0	52.36	0.2
15	2.0	81.88	3.1	15	2.0	60.93	1.9

Table XVII.7: Resistivity test line 4

Line	4	Location	3m	Line	4	Location	7m
AB/2 [m]	MN/2 [m]	ρ [Ω·m]	s.d. [%]	AB/2 [m]	MN/2 [m]	ρ [Ω·m]	s.d. [%]
1.5	0.5	397.48	0.3	1.5	0.5	529.09	0.3
2	0.5	74.39	7.7	2	0.5	280.07	0.1
2.5	0.5			2.5	0.5	124.39	0.1
3	0.5	87.80	0.7	3	0.5	62.01	0.7
5	0.5	79.27	1.1	5	0.5	67.16	1.2
7	2.0	147.72	0.0	7	2.0	61.14	0.9
10	2.0	158.42	0.5	10	2.0	78.89	2.2
15	2.0	142.44	4.3	15	2.0	56.59	6.6

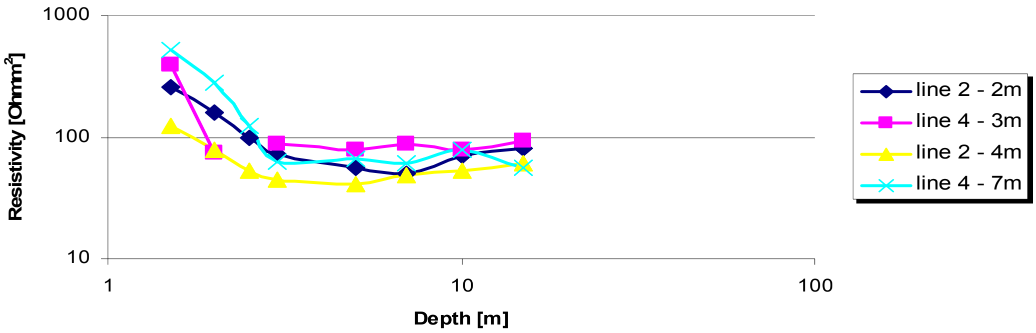

Figure XVII.2: Results resistivity test

XVII.4 Slope

The slope of the alluvial aquifer is determined with a dumpy level and a tape measure. The heights are measured from the reference level 99.000, which represents the top of the gauging plate in the reservoir.

Table XVII.8: Slope of the alluvial aquifer

Measuring Point	Distance [m]	Measured height [m]	Difference in height [m]	Slope [%]
1	0.00	95.043	0.082	0.259
2	31.65	94.961	0.090	0.424
3	21.25	94.871	0.070	0.307
4	22.80	94.801	0.048	0.162
5	29.61	94.753	0.150	0.595
6	25.22	94.603	- 0.009	- 0.035
7	25.44	94.612	0.120	0.490
8	24.50	94.492	0.060	0.002
9	30.00	94.432	0.068	0.273
10	24.90	94.364	0.038	0.141
11	26.93	94.326	0.110	0.409
12	26.93	94.216	0.047	0.173
13	27.10	94.169	0.082	0.259
Total	**316.33**		**0.874**	**0.276**

Appendix XVIII: Groundwater table data alluvial aquifer

Two piezometers per physical probing line were dug into the alluvial aquifer on the deepest points according to the physical probing. Due to the pointed end of the piezometers the tapeline can not reach the end of the piezometer, see Figure XVIII.1 and XVIII.2 for a representation of the field situation. So a few cm per piezometer have to be added to calculate the water level. It was often not possible to dig the piezometers in until the granite layer. The difference between the physical probing (the real physical depth) and the depth of the piezometers is recorded. So, this height difference have to be added to the water level as well. Piezometers 1, 2, 3, 4, 7 and 8 were pulled out of the alluvial aquifer by kids on the 3rd of April. The piezometers were dug in on the 4th of April again. Due to this the depth of the piezometers were changed. All the data according to the depth is given in Table XVIII.1. The location is measured from the right riverbank, while looking downstream.

Figure XVIII.1: Piezometer (1)

Figure XVIII.2: Piezometer (2)

Table XVIII.1: Depth of the piezometers (from surface area of the alluvial aquifer)

Piezometer	Location [m]	Real depth aquifer [cm]	Depth piezometer until 3rd of April [cm]	Depth piezometer after 3rd of April [cm]
1	3.0	130	109	104
2	7.0	100	70.5	75.5
3	2.5	98	91.5	93.5
4	4.5	87	71.5	67.5
5	4.0	82	77	77
6	6.0	112	93	93
7	3.0	89	86	80
8	7.0	100	97	89

The results of the measurements are given in Table XVIII.2. Some days are missing, because the field assistant was not able to do the readings these days.

Table XVIII.2: Rough data from the piezometers in the alluvial aquifer

	Number piezometer							
Date	**1 [cm]**	**2 [cm]**	**3 [cm]**	**4 [cm]**	**5 [cm]**	**6 [cm]**	**7 [cm]**	**8 [cm]**
11-03-2007	8	2.4	20	22	29	0	30	0
12-03-2007	5	2.2	14.2	10	18	0	20	0
13-03-2007	3	1.2	13	7.5	13.6	0	15	0
14-03-2007	3	1	12.2	5	8.2	0	10	0
15-03-2007	0	0	5	1	2	0	3	0
16-03-2007	0	0	0	0	0	0	0	0
…								
28-03-2007	0	0	0	0	0	0	0	0
29-03-2007	flow	flow	flow	flow	flow	flow	flow	flow
30-03-2007	90	70	80	86.4	60.3	50.2	80	79
31-03-2007	80	65	69	70	50.5	49.3	72	70.2
01-04-2007	70	50	70.5	55.1	50	70	78	55
02-04-2007	-	-	-	-	-	-	-	-
03-04-2007	-	-	-	-	-	-	-	-
04-04-2007	40	60	58	28	30	20	11	39
05-04-2007	-	-	-	-	-	-	-	-
06-04-2007	-	-	-	-	-	-	-	-
07-04-2007	-	-	-	-	-	-	-	-
08-04-2007	-	-	-	-	-	-	-	-
09-04-2007	-	-	-	-	-	-	-	-
10-04-2007	-	-	-	-	-	-	-	-
11-04-2007	-	-	-	-	-	-	-	-
12-04-2007	10	8	missing	missing	9.3	16.2	6.3	16.2
13-04-2007	5	4.2	missing	missing	5.1	10	3.1	11.1
14-04-2007	2	1	missing	missing	3.1	4	2.1	5.3
15-04-2007	0	0	missing	missing	2	3.1	2	1
16-04-2007	0	0	missing	missing	0	0	0	0
17-04-2007	0	0	missing	missing	0	0	0	0
18-04-2007	0	0	missing	missing	0	0	0	0
19-04-2007	0	0	missing	missing	0	0	0	0
20-04-2007	0	0	missing	missing	0	0	0	0
21-04-2007	0	0	missing	missing	0	0	0	0
…								
04-05-2007	0	0	missing	missing	0	0	0	0

In Table XVIII.3 the calculated results of the groundwater depth are given for the period from the 28th of March until the 16th of April. In Figure XVIII.3 the data is visualized in a graph. Piezometer 3 and 4 are not presented, because the data suggest some reading errors and besides the last part is missing.

Table XVIII.3: Groundwater level in the alluvial aquifer (* estimates)

	Number piezometer							
Date	**1 [cm]**	**2 [cm]**	**3 [cm]**	**4 [cm]**	**5 [cm]**	**6 [cm]**	**7 [cm]**	**8 [cm]**
28-03-2007	0	0	0	0	0	0	0	0
29-03-2007	130	100	98	87	82	112	89	100
30-03-2007	116	94.5	84.5	105.9	65.3	69.2	89	90
31-03-2007	106	89.5	73.5	89.5	55.5	68.3	81	81.2
01-04-2007	96	74.5	75	74.6	55	59*	77*	66
02-04-2007	-	-	-	-	-	-	-	-
03-04-2007	-	-	-	-	-	-	-	-
04-04-2007	66	64.5*	62.5	47.5	35	39	40*	50
05-04-2007	-	-	-	-	-	-	-	-
06-04-2007	-	-	-	-	-	-	-	-
07-04-2007	-	-	-	-	-	-	-	-
08-04-2007	-	-	-	-	-	-	-	-
09-04-2007	-	-	-	-	-	-	-	-
10-04-2007	-	-	-	-	-	-	-	-
11-04-2007	-	-	-	-	-	-	-	-
12-04-2007	36	32.5	missing	missing	14.3	35.2	15.3	27.2
13-04-2007	31	28.7	missing	missing	10.1	29	12.1	22.1
14-04-2007	28	25.5	missing	missing	8.1	23	11.1	16.3
15-04-2007	26	24.5	missing	missing	7	22.1	11	12
16-04-2007	24	23.5	missing	missing	5	19	9	11

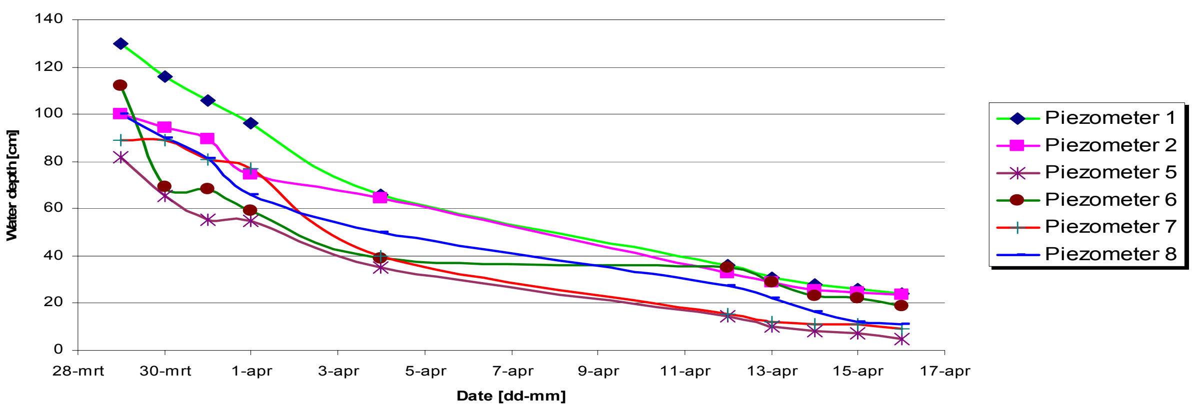

Figure XVIII.3: Groundwater level in the alluvial aquifer

Appendix IXX: Results dam overflow

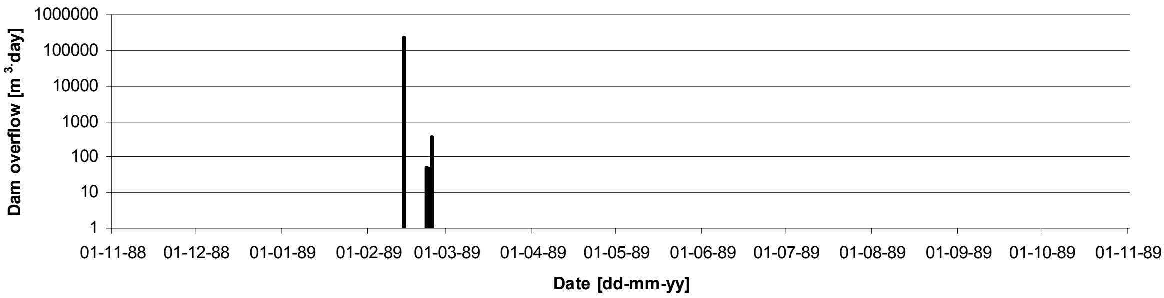

Figure IXX.1: Days over dam overflow for the Mnyabezi reservoir for the dry year '88/'89

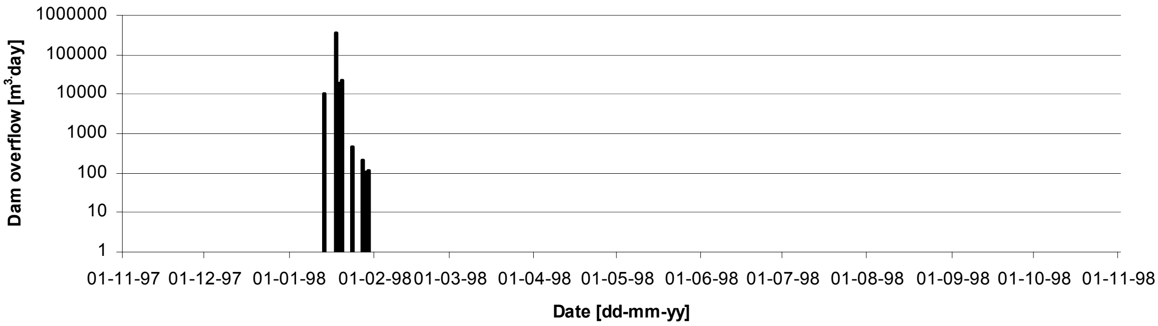

Figure IXX.2: Water level for the Mnyabezi reservoir for the normal year '97/'98

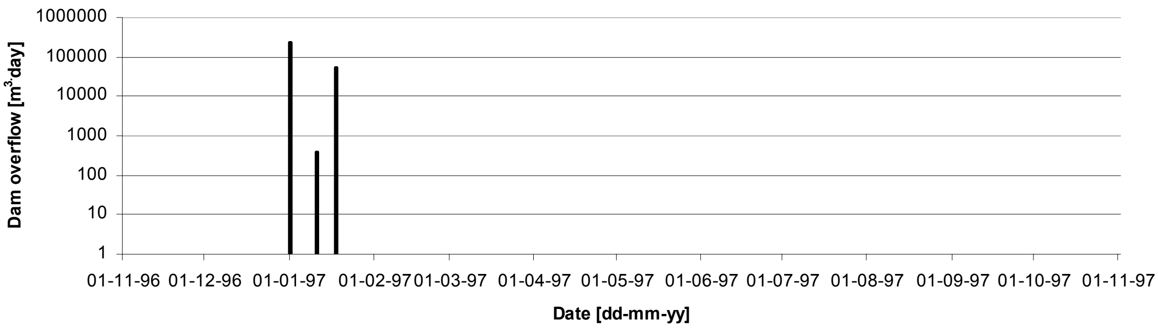

Figure IXX.3: Days over dam overflow for the Mnyabezi reservoir for the wet year '96/'97

Appendix XX: Qualitative uncertainty analyses

Table XX.1: Uncertainty matrix rainfall-runoff model

Location		**Level** **Statistical uncertainty**	**Scenario uncertainty**	**Recognised ignorance**	**Nature** **Epistemic / variability uncertainty**
Model	**Model structure**		Lumped relation between initial abstraction, CN-value and precipitation to calculate discharge		Epistemic uncertainty
	Technical structure				
Inputs	**Driving forces**				
	System data	- Measured precipitation (spatial non-homogeneous) - Surface area Thiessen-polygons	Precipitation from meteorological station (spatial non-homogeneous)		Epistemic uncertainty
Parameters	**A priori chosen parameters**	- Hydrological soil group - Land use - Land treatment - Hydrological conditions			Epistemic uncertainty
	Calibrated parameters	Initial abstraction			Epistemic uncertainty

Table XX.2: Uncertainty matrix reservoir model

Location		**Level** **Statistical uncertainty**	**Scenario uncertainty**	**Recognised ignorance**	**Nature** **Epistemic / variability uncertainty**
Model	**Model structure**	Relation water level, surface and volume of the reservoir with heightened spillway	Relation water level, surface and volume of the reservoir with heightened spillway		Epistemic uncertainty
	Technical structure				
Inputs	**Driving forces**				
	System data	- River inflow - Dimensions reservoir			Epistemic uncertainty
Parameters	**A priori chosen parameters**	- Measured precipitation - Measured open water evaporation - Amount of cattle drinking from the reservoir - Water use livestock unit	- Precipitation data from meteorological station Thuli Estate - Evaporation data from meteorological station Beitbridge		Epistemic uncertainty
	Calibrated parameters	Seepage			Epistemic uncertainty

Table XX.3: Uncertainty matrix groundwater model

Location		**Level** **Statistical uncertainty**	**Scenario uncertainty**	**Recognised ignorance**	**Nature** **Epistemic / variability uncertainty**
Model	**Model structure**	- Relation between depth and amount of evapotransiration - River leakage (at the first day) into the alluvial aquifer	Relation between seepage and the impermeable layer of the sand storage dam		Epistemic uncertainty
	Technical structure	The numerical way (layers divided into parts with the same hydrogeological characteristics) of modelling water flows			Variability uncertainty
Inputs	**Driving forces**				
	System data	- Calculated evapotranspiration - Measured open water evaporation - Input and output head boundary condition	Meteorological data from meteorological station Beitbridge		Epistemic uncertainty
Parameters	**A priori chosen parameters**	- Crop coefficient - Evaporation depth - Dimensions alluvial aquifer - Dimensions soil layer - Slope riverbed - Streambed conductance - Hydrogeological characteristics aquifer - Hydrogeological characteristics soil - Specific storage granite layer - Amount of domestic water use	Days of river inflow		Epistemic uncertainty
	Calibrated parameters	- Hydraulic conductivity granite layer - Porosity granite layer			Epistemic uncertainty