



UNIVERSITY OF ZIMBABWE

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

**RESERVOIR OPERATION UNDER DIFFERENT
CLIMATE CHANGE SCENARIOS: CASE OF ROSWA
DAM, BIKITA DISTRICT, ZIMBABWE.**

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MSc. Thesis in Integrated Water Resources Management

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In collaboration with



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**A thesis submitted in partial fulfilment of the requirements for the Master of Science Degree in
Integrated Water Resources Management**

June 2010

DECLARATION

I, Sifiso P. Ncube declare that this thesis emanates from my own work. All the sources that I have used and quoted have been duly indicated and acknowledged by means of complete citations and references. This thesis has not been submitted before for any degree at any university.

Signed:

Date:.....

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

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LIST OF ABBREVIATIONS AND ACRONYMS

CC	Climate Change
CCC	Canadian Climate Centre
CSO	Central Statistics Office
CV	Climate Variability
DCE	Department of Civil Engineering
DST	Decision Support Tool
FAO	Food and Agriculture Organisation
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
IWMI	International Water Management Institute
IWR	Irrigation Water Requirements
IWRM	Integrated Water Resources Management
MAR	Mean Annual Runoff
MDGs	Millennium Development Goals
NGO	Non-governmental Organisation
SADC	Southern African Development Community
SRES	Special Report on Emissions Scenarios
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
URC	Utility Rule Curve
WEAP	Water Evaluation, Analysis and Planning
WRYM	Water Resources Yield Model
ZINWA	Zimbabwe National Water Authority

DEDICATION

To my mother, Tebina Ncube, thanks for the love and all your efforts. I am finally a master!

To my husband Tafadzwa, it's a great blessing to share this life with you.

*To my nieces and nephews (Mitchell, Nokukhanya, Destiny and Tawananyasha):
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ABSTRACT

The challenge of maintaining or improving the quality of rural livelihoods against the increasing threat of climate change (CC) and climate variability (CV) calls for the development of robust and tested systems, tools and procedures for the management of water resources. The aim of this research was to assess reservoir operation under different climate change scenarios for a medium-sized reservoir in the Bikita District of Zimbabwe. The research tested for trends to confirm climate variability and/or climate change from daily rainfall and temperature data over the period 1954-2000. The CROPWAT model was used to establish crop water requirements for the existing 80 hectare Roswa irrigation scheme. The WAFLEX model was applied to simulate the performance of the system under three scenarios: (1) existing operational rules, (2) reduced water availability due to CC and, and accommodation of projected increased demands for urban use, agriculture, the environment and downstream uses and (3) change in irrigation technology. The results obtained show a general decreasing linear rainfall trend, although the change was not significant at R^2 of 0.009. A clearer cyclic pattern was obtained for the decadal analysis implying that the area is experiencing more of CV than CC. Modelling results show that the reservoir can satisfy current demands but will fail to cope when the planned agricultural expansion is doubled and other demands increase. The conclusions from the research are that the available water resources in the studied system are sufficient to satisfy the current demands. Climate change, together with projected demands will result in shortages of up to 30% for the downstream users. Rationing at 20% would be experienced 24% of the time. The introduction of more efficient irrigation technologies would result in a reduction in these shortages from the current 30% to 24% and 3% for sprinkler and drip irrigation systems respectively. It was therefore concluded that, although the area is experiencing variability in climate, there is enough water in the reservoir to satisfy current demand. Projected changes in climate together with projected demands would lead to shortages, particularly for the downstream users. Policy makers should therefore create awareness in the community so that water users are aware of anticipated consequences of climate change and can adapt accordingly.

Key words: climate change, climate variability, reservoir operation, sustainable livelihoods, water demand

CHAPTER 1

Introduction

1.1. Background

The United Nations Framework Convention on Climate Change (UNFCCC) secretariat, using current information available on existing and projected investment flows and financing, relevant to the development of an effective and appropriate international response to climate change, has estimated that by 2030 developing countries will require US\$ 28–67 billion in funds to enable adaptation to climate change (UNFCCC, 2007). Due to inadequate resources, socially, technologically and financially to adapt, developing countries are the most vulnerable to the impacts climate change. Also, climate change is anticipated to have far reaching effects on the sustainable development of developing countries including their ability to attain the United Nations Millennium Development Goals by 2015 (UN 2007).

In Africa, estimates indicate that one third of the people already live in drought prone areas and 220 million are exposed to drought each year (UNFCCC, 2007). Many areas in Africa have climates that vary a lot on seasonal and decadal time scales. For example, floods and droughts can occur in the same area within months of each other. Senzanje (2006) reported that people living in arid areas with highly variable rainfall, droughts and flood occurrences usually have insecure livelihoods. In order to secure quality livelihoods in these regions, governments and Non-governmental Organisations (NGOs) sponsored the construction of dams. The resultant reservoirs meet water demands for a diversity of competing uses such as domestic water supply, livestock watering, small-scale irrigation, fisheries, brick making and environmental functions such as wildlife support (Andreini et al., 2005).

In 2001, Nijssen et al. affirmed that on a global scale, the hydrological response predicted for most of the basins around the world, as a result of global warming, is a reduction in annual stream flow in the tropical and mid-latitudes. Water authorities in these areas are therefore obliged to cope with uncertainties as to how the climate will change and how water resource planning and management systems have to adapt to these changes. The potential devastation

(flow reductions), which climate change could wreak on medium reservoirs hence the sustainability of water-dependent rural livelihood demand uses, also adds an important dimension to the quest for developing robust and tested decision support systems (Rajasekaram and Nandalal, 2005) for the management of reservoirs. It is paramount therefore, to apply modelling approaches in operating reservoirs and allocating water among competing uses. Numerous models exist for managing reservoirs. These assist in the operation of the reservoir and allocation of water among different users. Some of these include, among others:

- Fuzzy based models which operate on an “if-then” principle, where the “if” is a vector of fuzzy explanatory variables and “then” of fuzzy consequences (Shrestha et al., 1996).
- Stochastic dynamic programming based models in which stationary policies are derived which use the previous period's inflow as a hydrologic state variable (Stedinger et al., 1984).
- Goal programming based models which may be based on physical operating criteria. Pre-emptive goal programming can be applied to the real-time, daily operation of multiple-purpose, multiple-reservoir systems (Can and Houck, 1984).

From the above models or combinations of these, other software models have been developed for water resources management and discussed in this study are the Water Resources Yield Model (WRYM), Water Flow in Excel (WAFLEX) and Water Evaluation and Planning (WEAP21) these are discussed in more detail in Chapter 2.

This research, therefore intended to make a contribution to efforts which focus on achieving improved and secure rural livelihoods through science based decision making, operation and management of medium reservoirs. Focus was on medium reservoirs, which are classified as those having a capacity of between 1 to 3 million cubic meters and height between 8-17 metres (Zimbabwe Water Act, 1998).

1.2. Problem Statement

Generally, there is a primary dependence on the availability of water resources in many civilisations. In Zimbabwe, water has been increasingly becoming a scarce resource (WRMS, 2000). As the trend towards increasing industrialisation continues, water scarcity will certainly increase hence the need to improve water resources management to meet various competing demands (Cleaver and Schreiber, 1994). In this respect, problems of water shortage have globally been alleviated through dam construction since dams have been found to provide a ready and convenient source of water for various uses (Zirebwa et al., 2000). Communities served by these reservoirs tend to be highly dependent on them mainly for domestic and agricultural purposes.

One of the most significant impacts of climate change will be on the hydrological system and hence river flows and available water resources (Alemaw and Chaoka, 2002). With land cover held constant, a decline in rainfall is hypothesized to have a direct declining effect on runoff. In 2005 Kundewicz stated that it is important to establish the effects of climate change or variability on our hydrological systems, as it is fundamental for planning of future water resources and flood prediction. The adverse effects that climate changes may have on surface water resources increase the insecurity of water dependent rural livelihoods.

The importance of reservoirs in sustaining rural livelihoods through provision of water, in light of an absence of appropriate management systems, necessitates a focus on reservoir research and development. There is also the absence of medium multi-purpose reservoir system operating rules that are designed to cope with the threat of climate variability and climate change. This then necessitates the application of modelling techniques to simulate reservoir operation, incorporating the projected effects of climate change to ensure maximum water availability for the communities served.

1.3. Justification of the study

There has generally been increased concern about climate change and variability. Recent explorations of potential climate change done in the Southern African region revealed that a warming of almost 1°C, with high rainfall variability ($\pm 30\%$) accompanied by the recent droughts of 1992 and 1995, has highlighted the sensitivity of the region's water resources to

variations of climate (Hulme et al., 1996). Considering the high dependency on reservoirs, it is imperative, therefore, that water resources management focus on climate change effects on these resources for their sustainability. This is also crucial, since during construction of most of these dams, climate change was not envisaged. This, consequently calls for the management of medium multi-purpose reservoirs through the application of scientifically developed and tested management tools (Rajasekaram and Nandalal, 2005) in light of the acknowledged role of these otherwise marginalized water sources in sustaining rural livelihoods as well as the respective threats posed by climate change. The objectives of the study are outlined in the next section.

1.4. Objectives

Main Objective

To assess reservoir operation under different climate change scenarios focusing on the Roswa dam in the Bikita district of Zimbabwe.

Specific Objectives

- To confirm the existence of variability in climate at a local scale.
- To investigate whether current agricultural water demand is comparable with that calculated based on scientific FAO approaches.
- To apply modelling techniques to simulate reservoir operation under different climate change scenarios.

1.5. Report Layout

The layout of this report of the study is illustrated in Table 1.1

Table 1.1. Report Layout

Chapter 1	Introduction, objectives and problem statement
Chapter 2.	Review of literature.
Chapter 3	Description of the study area
Chapter 4	Research methods.
Chapter 5	Results and analysis
Chapter 6.	Conclusions and recommendations.

CHAPTER 2

Literature Review

Water scarcity (both economic and physical), is increasingly becoming an issue on a global scale. Inocencio et al., (2003) stated that the physically water scarce countries in Southern Africa and regions like North Africa may not have adequate water resources to meet their projected water demands in 2025 although more than a quarter of the world's population will be living in this region. Population dynamics tend to create pressure on freshwater resources through increased demand and pollution (WWAP, 2009). This in turn poses a great threat to the achievement of the Millennium Development Goals (MDGs), particularly Goal 1 of eradicating extreme poverty, in developing countries, which depends largely on improved water supply and sanitation as water is required by all beings for survival and economic growth and development.

FAO (2005), state that in most climates of the world, peak runoff corresponding to a significant part of the total discharge of rivers, occur during a particular season of the year which usually coincide with the least water demands. Reservoir development therefore consists of transferring water from the high supply season to the high demand season (FAO, 1995), usually the dry season. They thus promote improvements in the livelihoods of rural communities and enrich the standards of living by ensuring a year round growing season. Reservoirs also help reduce the effects of droughts and floods (WWAP, 2009), which have caused numerous deaths and resulted in insecure livelihoods, through improved smallholder irrigation and livestock production.

Again, FAO (2006) acknowledges that water is essential for all socio-economic development and for maintaining healthy ecosystems and that as population and economic activities increase, the pressure on water resources is inevitable, leading to tensions, conflicts among users, and excessive pressure on the environment. This increasing stress on freshwater resources brought about by ever increasing demand, brings about the need for a holistic approach to water resources development and management. Managing water has always been about managing naturally occurring variability and climate change threatens to make this

variability greater. This is through shifting and intensifying the extremes and introducing greater uncertainty in the quantity and quality of supply over the long term (WWAP, 2009).

Modelling of reservoir systems has been extensively used in the management of water resources. Water balance modelling can be used to analyze upstream-downstream interactions, dam management options, and water allocation and development options (Love et al., 2008). One such modelling tool is the spreadsheet-based WAFLEX model, (Savenije, 1995), discussed in detail in section 2.6.

2.1. Small-Holder Irrigated Agricultural Production

As a result of the shortcomings of large-scale irrigation systems in African, small-scale irrigation was subsequently advocated (Turner, 1994). Although recent focus has turned towards management and performance improvement, new small-scale irrigation projects continue to be promoted (FAO, 2006). Small-scale farmers must be empowered through, among other issues, providing water through equitable and reliable water allocation processes. This would ensure food security which is mainly hindered by lack of water for crop production.

FAO (2005), states that in most climates of the world, peak runoff, corresponding to a significant part of the total discharge of rivers, occur during a particular season of the year which usually coincides with the least water demand. Dam developments for irrigation have led to a more constant food supply and income generation during the entire year for most rural communities. Small-holder irrigation schemes dependent on these reservoirs have been very successful in improving livelihoods, mainly because they are constructed specifically to the needs of a community, require low maintenance and the community is directly involved in their construction which increases the sense of ownership by the community. Other reasons why these schemes are so successful include (Phillips-Howard, 1996):

- Much lower investment costs than large-scale irrigation schemes.
- They do not use large areas for dams or storage reservoirs, so little or no population displacement is involved.
- Less demanding in terms of management, operation and maintenance.

- They permit farmers to learn irrigation techniques at their own pace and in their own way.

One disadvantage of these schemes is that they usually have low irrigation efficiencies and therefore tend to use more water than other technologies like sprinkler and drip.

2.2. Impacts of Climate Change and Variability

Climate change can be defined as an alteration to measured quantities (e.g. precipitation, temperature, radiation, wind and cloudiness) within the climate system that departs significantly from previous average conditions and is seen to endure bringing about corresponding changes to ecosystems and socio economic activities (Climate Change Information Kit, 2002). Climate variability refers to variations in the average state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events (Bates et al., 2008). It is important to note that, although there is evidence of climate change, different models give varying predictions of how climate will really change. This change in climate is partially attributed to human activities such as the burning of fossil fuels, release of emissions during industrial production, mining processes e.g. blasting and use of chemicals in agricultural production. These activities have led to increased concentrations of greenhouse gases leading to global warming (Climate Change Information Kit, 2002).

According to the Intergovernmental Panel on Climate Change (IPCC, 1995), the warming of the planet is projected to affect precipitation patterns, evapotranspiration rates, the timing and magnitude of runoff, the frequency and intensity of storms and, therefore, both the quality and quantity of surface and groundwater resources. Climate change is therefore a challenge that water managers have to bear in mind when planning and executing water resources programmes.

Bates et al. (2008) state that due to increased water demand, increased populations in Africa are expected to experience water stress (less than 1,000 m³/capita/yr) before 2025, and this will be worsened by climate change when runoff reduces. In some assessments, the population at risk of increased water stress in Africa, for the full range of Special Report on Emissions Scenarios (SRES) scenarios, is projected to be 75–250 million and 350–600

million people by the 2020s and 2050s, respectively (Arnell, 2004). However, the impact of climate change on water resources across the continent is not uniform. Generally, many climate models project declining precipitation in the already-dry regions of Southern Africa, central Asia, the Mediterranean, and Australia (Climate Change Information Kit, 2002). A combination of a decline in precipitation and increased evaporation rates will all culminate in a reduction in runoff. An analysis of summer daily precipitation showed that the amount of rainfall associated with a one-in-twenty-year event may become more extreme over large areas of Mozambique, Zimbabwe, Zambia, Tanzania and the Democratic Republic of Congo, typically associated with an increase in the intensity of rainfall rather than more rain days (Senior, 2002). Intense rainfall will imply that more runoff has to be trapped in reservoirs for later use and therefore the need for operation rules to allow for reduction of the reservoir storage in preparation for possible floods.

Fischer et al., (2005) state that although research confirms that while crops would respond positively to elevated carbon dioxide in the absence of climate change, the associated impacts of high temperatures, altered patterns of precipitation and possibly increased frequency of extreme events such as drought and floods, will probably combine to depress yields and increase production risks in many world regions, widening the gap between rich and poor countries. A decline in agricultural production, which is the backbone of most of these developing countries (Zimbabwe included), will impact negatively on their economies. Also, Fischer et al. (2005) suggested reductions in production in developing countries, in the 5-10% range. They also projected that climate change would result in an additional 15% increase in the number of under-nourished people especially in areas where levels of undernourishment were already high under 'no climate change' conditions.

Assessment of climate change effects allows for management of reservoirs based on predictions to create resilience in rural communities to changes in climate, ultimately leading to reduction in poverty. All this may be a stepping stone in the achievement of the first Millennium Development Goal of reducing poverty. Ragab and Prudhomme, (2002) argue that uncertainties as to how the climate will change and how water resource planning and management systems have to adapt to these changes are issues that water authorities are compelled to cope with. The challenge is to identify short-term strategies to face long-term uncertainties.

In a study done on the sensitivity of Save and Runde catchments' surface water supplies to climate change impacts, Murwira et al. (2009) recommend that Save basin populations be geared for increased variability in the availability of water resources *i.e.* increased frequency of droughts and floods is predicted. As the Rozva Dam is located in the Save catchment, it is therefore important that operation of reservoirs and water allocation be investigated in view of possible changes in climate.

2.3. Stakeholder Participation

In the management of water resources, the Dublin Principles are generally accepted as guiding principles for IWRM. The second and third principles focus on stakeholder participation and gender mainstreaming. Decisions must to be made with full consultation of the community and involvement of users in the planning and implementation of water projects. The participatory approach involves raising awareness of the importance of water among the general public and policy-makers. From principle 3 women also should be involved in the decision-making process as they are the 'providers and users of water'. According to Ziervogel, (2003), the aim is to involve the community in interactive ways that encourage participation of all and enable local stakeholders to drive development processes. A disadvantage stems from power relations that exist where the elite dominate the decision-making process although this does not override the benefits.

Stakeholder participation can help improve on the amount produced per unit of water (McCartney and Arranz, 2007). This comes about as a result of more adequate or timely water application and saving of water during the seasons. It also allows greater equity (fairness) of distribution of water from the reservoir. Equitable allocation therefore leads to a reduction in the number of conflicts between farmers. It also encourages a more personal commitment and attachment to the project at hand. Cooperation among farmers enables them to solve many problems by themselves. Uphoff, (1986), stated that to reach sound decisions, there is need to identify problems, gather information, formulate alternative solutions and build consensus. And this has to be done by the farmers facilitated by the water manager.

2.4. Reservoirs

Water is the essential element in rural livelihoods because of the food security and income options it generates in rain-fed and irrigated crop production, industry, domestic processing, aquaculture, livestock, recreation, navigation and transport. Dams therefore provide for water storage to the advantage of these citizens. They, at times, directly support community initiatives that guard against water scarcity by enabling farmers to realize increased food production, reduced poverty and improved rural livelihoods.

A reservoir is a man-made lake which is created when a dam is built on a river or a stream (Hagan, 2007). In Zimbabwe, most reservoirs were constructed through projects funded by the government and various non-governmental organisations. The management of these reservoirs is the duty of ZINWA together with catchment and subcatchment councils and the communities which are benefiting from the reservoirs. These reservoirs are a good avenue for the eradication of poverty if they are properly managed, ensuring equitable allocation and efficient and sustainable use (Hagan, 2007).

In classifying dams, either their height or their capacity, or both is considered and ZINWA classifies dams as in Table 2.1.

Table 2.1: Classification of Dams in Zimbabwe

	<i>Small</i>	<i>Medium</i>	<i>Large</i>	<i>Major</i>
Height (m)	8	8-17	17-30	>30
Capacity Mm ³	<1	1-3	3-20	>20

Source: Adopted from Saunyama (2005)

Reservoir Distribution

Southern Africa has a sizeable number of dams, particularly in South Africa and Zimbabwe (Darwall et al., 2009). This is mainly due to the uneven spatial distribution of precipitation in the region, with a steep gradient from north to south and from east to west, with countries to the south and west being much drier. By 1997 more than 30 large dams had been built in the

Zambezi River basin alone for domestic, industrial and mining water supply, irrigation and power generation (Darwall et al., 2009)

The distribution of reservoirs in Zimbabwe is such that they are concentrated in the stretch from the north-east to the south-west as shown in Figure 2.1.

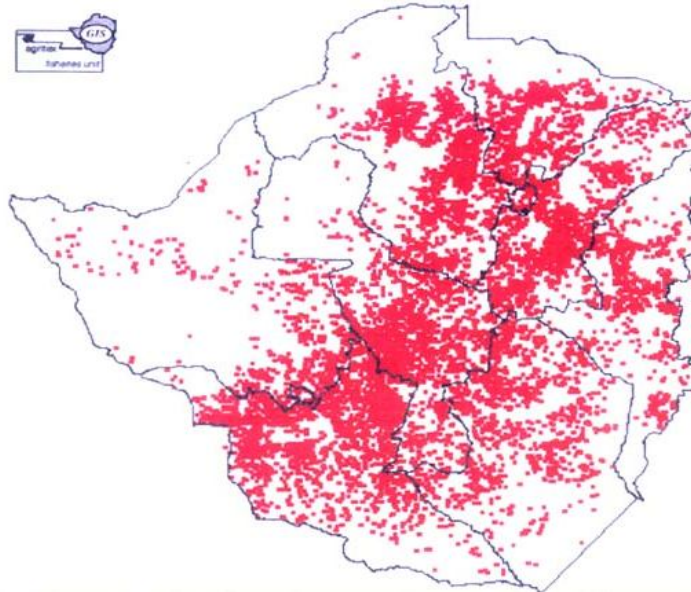


Figure 2.1: Location of dams in Zimbabwe (Chimowa et al., 1993)

The figure shows that most of the dams are located around the central watershed, a generally high altitude area where most rivers start, thereby ensuring the trapping of large amounts of water. There are also higher populations settled around the central watershed. The total number of dams located in the different provinces of the country are given in Table 2.2 (Chimowa et al., 1993). Matabeleland South has the highest number of small dams mainly because it is a low (less than 450 mm/a) rainfall area. Although very important for multi-purpose use, most of these small dams do not adequately meet demand in the water scarce regions. This then leads to a need for medium dams to bridge the gap between small dams and larger dams, which are normally used for enterprises such as urban, industry and mining (McCartney, 2007). Medium reservoirs ensure adequate water supply for such uses as small-scale irrigation, water supply to district and rural service centres, rural domestic use, livestock watering and environmental needs. These are often competing uses hence the need for proper allocation and management of the reservoirs.

Table 2.2.: Number and Capacity of Dams per Province in Zimbabwe (Chimowa et al., 1993)

<i>Province</i>	<i>Total number of dams</i>	<i>Total capacity $\times (10^3 \text{ m}^3)$</i>
<i>Bulawayo</i>	32	9785
<i>Harare</i>	50	13272
<i>Manicaland</i>	679	148656
<i>Mashonaland Central</i>	763	691113
<i>Mashonaland East</i>	1363	292378
<i>Mashonaland West</i>	1413	1334765
<i>Masvingo</i>	1044	2339527
<i>Matabeleland North</i>	611	190498
<i>Matabeleland South</i>	2243	873271
<i>Midlands</i>	1620	2098731

2.5. Reservoir System Operation

Decisions on water quantities to be released from reservoirs and allocation of such water to various users is vital in ensuring sustainability and equity in water use. Water allocation can be done with or without models, but models are more advantageous as they estimate the quantity of water available to different users within a river basin at different times. These models are applied because they help to support the analysis of allocation problems involving complicated hydrological, environmental and socioeconomic constraints and conflicting management objectives (Arranz and McCartney, 2007). Reservoir operation and allocation can be developed from models under varying scenarios.

Scenarios are commonly used to investigate complex systems that are inherently unpredictable or insufficiently understood to enable precise predictions (McCartney and Arranz, 2007). Current water demand needs to be assessed, so that projections for the future under different scenarios can be made, although possible future water needs are uncertain.

It is also important that primary uses i.e. basic human needs and environmental flow requirements are considered a priority over all other uses.. This is in line with the Zimbabwe National Water Act of 1998, to ensure sustenance of human life and maintenance of the proper functioning of the aquatic ecosystem. Water use for primary purposes is defined as reasonable use of water for the subsistence of life i.e. for basic household needs including

drinking, bathing, watering small gardens and a few livestock (Zimbabwe National Water Act, 1998).

The proposed future scenarios should give an idea about possible alternative paths for water resources management in the area although it is imperative to note that they are not the only possibilities. They may be used as a means to aid in planning.

2.6. Reservoir Operation and Allocation Models

The world is fast developing and the problems encountered in the allocation of scarce and limited water resources become even more complex in a rapidly changing society, where policy objectives, interests of stakeholders, economic boundary conditions, and political, financial, and physical constraints change daily (Savenije, 1995). In managing these water resources, water managers have greatly benefitted from models as convenient and effective tools in water resources development and management since they aid to quick decision making. A river basin simulation model simulates the response of the river basin on management strategies and can therefore be used to support decisions. Successive and systematic runs of the model evaluate the responses to the variations in inputs and operating conditions (Khosa et al., 2008). Modelling water demand scenarios can be a powerful tool in water resource system analyses since such models can be used to understand and predict the future performance of water supplies for different users and for the environment.

Models can also help to understand basin-scale river behaviour; to develop basin-scale or national water resources management plans and to evaluate the effect of climate change on a given water resource or supply (Khosa et al., 2008). Modelling water demand scenarios can also be used to plan supply and demand for a particular water use or to examine how policies affect water management, currently, and in the future. The models contribute to a better understanding of the real-world processes and provide quantitative information to support decision-making activities (Khosa et al., 2008). Numerous models have been developed for the management of reservoir systems and some of these include WEAP (McCartney and Arranz, 2007), Ribasim, MikeBasin and spreadsheet based ones like WAFLEX (Savenije, 1995). The choice for application depends on user preference, the intended use and available data. The fundamental logic behind these models can be based on the fuzzy, stochastic programming, goal programming and others.

Fuzzy Rule-Based Modelling of Reservoir Operation

This model operates on an “if-then” principle, where the “if” is a vector of fuzzy explanatory variables or premises and “then” of fuzzy consequences (Shrestha et al., 1996). The reservoir storage level, estimated inflows and demands are used as the hypothesis, while releases from the reservoir are taken as the consequences. Split sampling of historical data (mean daily time series of flow, lake level, demands, and releases) is used to train and then validate the rules. Different performance indices are calculated and two figures of merit, namely, engineering sustainability and engineering risk are developed for evaluating the rules generated by the model (Shrestha et al., 1996).

Stochastic Dynamic Programming Based Models

The model can help in deriving stationary policies which use the previous period's inflow as a hydrologic state variable. A stochastic dynamic programming model which employs the best forecast of the current period's inflow can be used to define a reservoir release policy and to calculate the expected benefits from future operations (Stedinger et al., 1984).

Goal Programming Based Models

Pre-emptive goal programming can be applied to the real-time, daily operation of multiple-purpose, multiple-reservoir systems. A significant advantage of the goal programming approach is that it may be based on physical operating criteria. It does not require the penalty-benefit functions that may be difficult to define but are essential to other real-time operating models and is therefore easier to implement (Can and Houck, 1984)

The above models or their combinations have been used in developing software for use in water resources management. Examples of these are discussed in the following section.

Water Evaluation and Planning (WEAP) Model

The WEAP model was developed for use in evaluating planning and management issues associated with water resources development. It employs a priority-based optimisation linear programming algorithm to allocate water (McCartney and Arranz, 2007). It can be applied to both municipal and agricultural systems and can address a wide range of issues including: sectoral demand analyses, water conservation, water rights and allocation priorities, stream-flow simulation, reservoir operation, ecosystem requirements and cost-benefit analyses (McCartney and Arranz, 2007).

According to Yates et al. (2005), the two primary functions of the model include the simulation of natural hydrological processes (e.g. evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment; and simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

Some limitations of the model are that options of dry, normal and wet years available in WEAP, though very simple and easy to use, may not adequately capture the large variability of hydrologic phenomena in the Southern African context where extremes are very common, even when working with a monthly time-step (McCartney and Arranz, 2007).

Water Flow in Excel (WAFLEX) Model

The (WAFLEX) is a river basin simulation model that uses the spreadsheet environment for the computation of a graphical window to communicate with the user. The WAFLEX model is a spreadsheet simulation model governed by the equation of continuity and the fact that water flows from upstream to downstream. The building blocks are network functions—relations between cells that can be copied to any location in the sheet to mould the network (Savenije, 1995). A model can be built by linking modular system elements together in a directly visible worksheet. The model calculates water balances with monthly time series for each cell. For each time step, WAFLEX calculates the water demands, supply, and therefore the water shortages as a result of the present management of the system based on a schematisation of the river basin. A schematised river basin is duplicated in a demand and

supply mode, with the supply mode calculating the accumulation of water from upstream to downstream. The demand mode on the other hand, calculates the cumulative demand from downstream to upstream. The results are stocked in a database. Future changes in water resources management (e.g. changing reservoir operations, allocation, and new reservoirs) can be estimated on their impact on the total performance of the system and the individual water users. When used together with engineering and economic criteria, the results of these runs allow:

- The systematic comparison of alternative configurations of water resources projects in the basin
- The evaluation of the effect of upstream development on the flows at the outflow and the consequent downstream development (Makurira and Mul, 2007).

Advantages of the WAFLEX Model

The advantages of the WAFLEX model like all other spreadsheet models are that it is accessible, transparent, easy to debug, easy to rerun, give immediate error messages and above all inexpensive and have a ready to use graphical interface (Savenije, 1995). Other benefits of the model are that the graphics guarantee swift and efficient communication with the user and that it requires full understanding of the participant which tends to be good for educational purposes. When the set-up is understood, the participant can understand the underlying equations which are usually hidden in more user-friendly and fool-proof commercial simulation models. The model can also be used for strategic decisions, like what the impact will be of improving the demand management in the towns or irrigation schemes (growing other crops, less irrigation) or change the priority of allocation. The WAFLEX tool was used in the study since it is flexible, easy to access and not costly.

Disadvantages of WAFLEX Model

The disadvantage of spreadsheet models in general is that they are not foolproof and its outcome is as reliable as the person who made it. The model has less confidentiality since it can be tampered, with relative ease; is build on too many assumptions thus oversimplifying

issues and can only be used as a basis for a quick but not conclusive decision-making. The model does not cater for transmission losses and it also prioritises upstream uses implying that shortages will be experienced firstly by downstream users.

WAFLEX application in water management studies in Southern Africa.

The model was applied in studies by Khosa, (2008) in the Thuli catchment, Symphorian *et al.*, (2003) in the Save catchment and Nkomo *et al.*, (2003) in the Komati basin. Khosa (2008) applied the WAFLEX model in the Thuli catchment of Zimbabwe to evaluate the effects of upstream water demand scenarios on downstream users in order to improve on the management of the water resources. The study concluded that at current development levels there are not enough water resources in the basin to meet demands as evidenced by shortages for downstream projects. It was recommended that proposed developments need to be in line with water demand management measures.

Symphorian *et al.*, (2003) applied the WAFLEX model to simulate releases from the Osborne dam for maintaining the minimum environmental flow requirements. The results indicated that the WAFLEX model can generate environmental releases for Odzi River. It was recommended that the model be adopted as an aid to environmental flow allocation by the Save Catchment. However, the study could not take into account the downstream demands from Mozambique due to lack of data.

Another study using the WAFLEX model was conducted by Nkomo and van der Zaag (2003) in the Komati catchment shared by Swaziland and South Africa. The study objective was to investigate water availability and use in the Save catchment and make recommendations on how the water resources in the basin can be managed. A combination of measures were identified which included reducing interbasin transfers, reducing consumption by irrigated agriculture and allocating less flows to the environment.

In this study focus was on the effects of climate change on the operation of Rozva dam, assessing how the water resources available will respond to increase in demand. Since Juizo and Liden. (2008) stated that the choice of model does not per se affect the decision of best water allocation and infrastructure layout of a shared river basin. The chosen allocation and prioritization principles for the specific river basin and the model user's experience and integrity are more important factors to find the optimal and equitable allocation. Most of the models mentioned in section 2.6. have high data requirements which eliminated their use in this study where data availability for medium reservoirs is limited. The WAFLEX model was then employed.

2.7. Concluding Remark

Water resources are under pressure either due to meteorological factors like climate change or anthropological factors like increasing water demands and poor land use practices that accelerate silting up of surface water reservoirs. One approach to address this challenge is proper management through science-based techniques of operating the reservoirs to maximize the efficient use of water resources. This research provides a simulation analysis of water resources in the Roswa Dam under different climate change scenarios. The following chapter therefore provides background information to the research area.

CHAPTER 3

Study Area and Research Methods

3.1. Study Area

The Roswa dam lies in the Lower Save West sub-catchment, in the Save catchment of Zimbabwe (Figure 3.1). It is located in Natural Region III, Sub-zone ES3 with a relatively high average rainfall of about 700 mm/yr and mean annual evaporation of 2000 mm/yr (Mazvimavi, 2005). The area has a warm tropical climate typified by one rainy season of about five months, starting from November to April, and dry weather in the remaining months of the year. Rainfall is mainly due to the passage of the Inter-Tropical Convergence Zone (ITCZ), experienced between December and June. Rainfall is distributed such that areas with higher elevation receive more rainfall than lower lying areas. Rainfall received in the catchment is variable and Table 3.1 illustrates extreme highs and lows, from the thirty year average.

Table 3.1: Years with very low and very high rainfall within Save catchment

<i>Year</i>	<i>Percent below average</i>	<i>Year</i>	<i>Percent above average</i>
1915/16	45	1917/18	93
1921/22	42	1924/25	93
1946/47	51	1928/29	42
1967/68	41	1938/39	52
1972/73	42	1952/53	45
1982/83	45	1980/81	41
1991/92	65	1999/00	71
1994/95	42		

Source: Mazvimavi, 2005

The cropping period for rain fed agriculture in the area is from October-November to March, but irrigated agriculture is throughout the year. The average yield for maize which is the staple food in the area is around 2-3 tonnes per hectare under rain fed agriculture. Irrigated agriculture improves the yield to around 5-8 t/ha.

3.1.1. Roswa Dam

Roswa dam is a multi-purpose reservoir located on the Roswa river adjacent to Nyika Growth point, in Bikita District (Figure 3.1) about 100 km east of Masvingo Town in southern Zimbabwe. The main purpose for the dam is to supply Nyika and Bikita Service Centres with water and to irrigate 80 hectares to the south of Nyika. The dam is located on an irregular granite terrain. Significant evaporation losses occur during the April to December period. Its main demand uses are smallholder irrigated agriculture; water supplies for Nyika and Bikita Growth Points and environmental reserve. Ten percent of the mean annual runoff is released to meet environmental and other downstream needs. Other characteristics of the dam are as in Table 3.2.

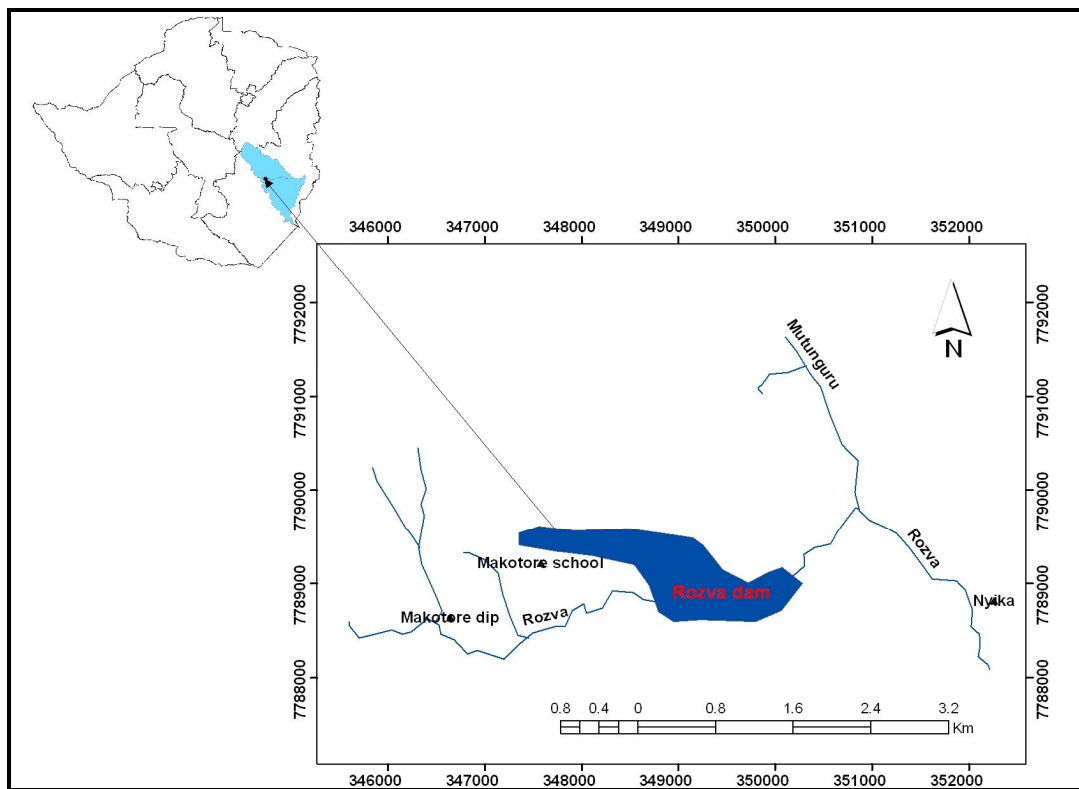


Figure 3.1: Map of the study area

On operating the reservoir, the resident water bailiff carries out the routine operation under the directive of the catchment office. Department of Water Resources (1996) also recommended that the drawdown rate be geared to the downstream requirements i.e. irrigation and water supply.

Table 3.2: Characteristics of Roswa Dam

<i>Characteristic</i>	<i>Quantity</i>
Maximum height of water above the riverbed (m)	17.3
Length at full supply level (km)	1.5
Width at full supply level (km)	0.5
Full supply capacity (Mm ³)	2.8
Catchment area. (km ²)	62
Dead storage (m ³)	60 000
Design yield (Mm ³):	
At 10% risk	1.45
At 4% risk	1.05
Spillway:	
Type	Free overflow masonry weir
Length (m)	50.

Adapted from Ministry of Energy and Water, (1988) and Department of Water Resources, (1996).

3.1.2. Roswa Irrigation Scheme

The scheme was established in 1994 and is 5 km west of Nyika business centre. The 80 hectare scheme supports small-scale farmers, each having either a 1.5 hectare, 1 hectare or a 0.5 hectare plot. Farmers whose agricultural fields were originally located where the scheme

is are the ones with 1.5 hectare plots, while the rest have either 1 hectare or 0.5 hectare. The membership of the scheme was drawn from two villages that are adjacent to each other. The scheme utilizes a drag-hose surface irrigation system with the water being pumped from Roswa dam. Water is applied through polythene pipes connected to hydrants (Plate 3.1). The pipes then feed into furrows in the field.

The scheme is divided into three blocks, with Block A (Chikwadzi) having an area of 12.5 hectare, Block B (Kunedzimwe) with 11.5 hectare and Block C (Roswa) with 56 hectare. From the dam water is pumped into a night storage dam with a capacity of 4000 m³ which was originally constructed to serve Blocks A and B. Some of the crops grown at the scheme include maize, wheat, beans, tomatoes and other vegetables. Produce from the scheme is sold mainly at Nyika service centre, with some being sold in Bikita.



Plate 3.1: A hydrant at the scheme

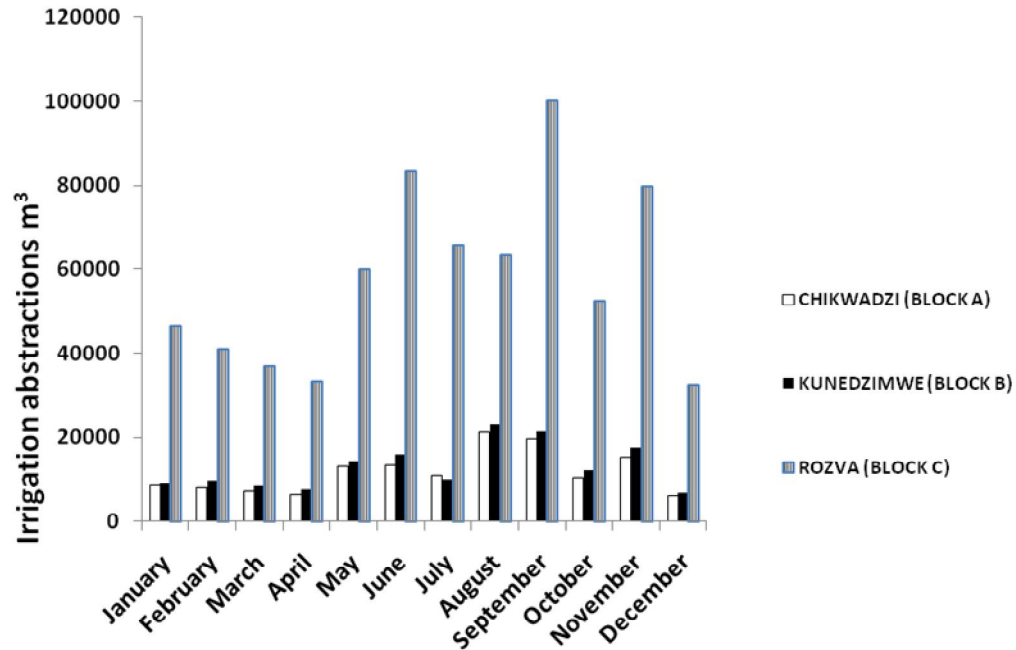


Figure 3.2: Average irrigation abstractions per block

Water from the dam is used to supply the 80 hectare irrigation scheme, domestic use for Bikita and Nyika Growth point, some is lost to evaporation and the rest flows down as environmental flow right down to Siya dam. Figure 3.3 shows monthly average abstractions for domestic water supply for both Nyika and Bikita centres and irrigation.

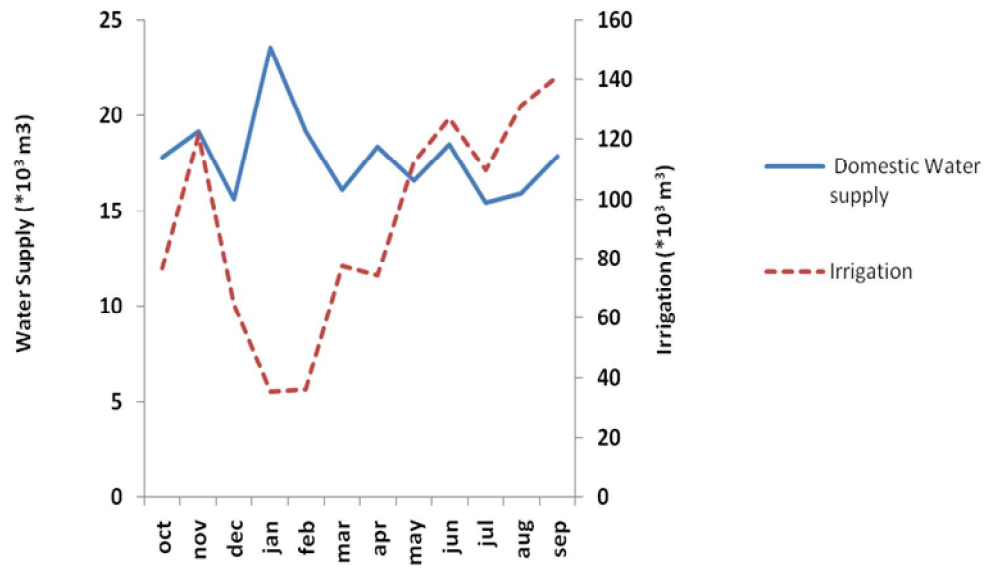


Figure 3.3: Average Monthly uses from Roswa Dam

On average irrigation abstractions from the reservoir are low during the rainy season, being least in February. Also, most of the rainfall is received in December, while evaporation mostly occurs in October.

3.1.3. Criteria for selecting this area

Most studies on reservoir management in Zimbabwe have focused on the much drier Matabeleland South region overlooking other areas with moderate climates, where with the advent of climate change and variability surface water resources may decline, impacting on the livelihoods of the neighbouring communities. The study area was therefore selected to assess the possible impacts of changes in climate on the available water resources and also effects on the small-scale irrigation scheme and the urban communities dependant on the reservoir. The area is one where some subsistence farmers fail to have enough food for the whole year despite readily available water in the perennial river. The following chapter looks into the methods used in the research.

3.2. Research Methods

3.2.1. Introduction

This chapter outlines the procedures used in data collection and analysis with the aim of focusing the study so that adequate data is obtained to answer the research questions of the study. Data for the research was obtained from various institutions which included the Zimbabwe National Water Authority, Meteorological Department, Climate Change Office, Irrigation Department and AREX offices. The data obtained included permitted water abstractions, climatic data (runoff, rainfall, evaporation, temperature) and dam levels together with their corresponding capacities. Other methods employed encompassed interviews, focus group discussions with the farmers (Appendix G) and site visits to the dam and irrigation scheme.

3.2.2. Data Collection

3.2.2.1. Runoff Data

Historical monthly data was collected for the upstream and downstream gauging stations E178 and E179 to input into the model (Appendix A). Simple manual inspections were done but most quality checks were done at ZINWA and Meteorological department offices. The observed runoff record stretched from 1994 when the dam was commissioned to September 2009. In order to obtain a longer stretch of data, runoff was generated from correlating the rainfall data with runoff and obtaining a mathematical relationship between the two. This relationship was then used to generate runoff for the other years dating back to 1953 where only rainfall data was available.

3.2.2.2. Rainfall

Daily and monthly rainfall data was collected from the Harare Meteorological department, Climate Change office and from ZINWA offices in Mutare and Harare. Records for rainfall observed on site had too many gaps and were inadequate for use in the study, so data was obtained for Zaka, a station 100 km from the study site, which has a longer data series. The

data was for the period 1953-2007, years, which made it adequate in assessing whether there are any changes or variability in climate. This was done through trend analyses of the rainfall and temperature data. A regression analysis of the rainfall and runoff data was done to assess the relationship between the two, after which a longer stretch of the runoff was then generated. This was then input into the WAFLEX model as inflow into the reservoir.

3.2.2.3. Temperature

Maximum and minimum temperature was obtained for Zaka for the period 1953-2007. The temperature data was also used in checking for variability and possible change in climate. This was done through the Spearman's Rank Correlation method, which is discussed in section 4.3 and (Appendix C).

3.2.2.4. Evaporation

Average monthly evaporation data (in mm), for Roswa was obtained for the period 2001-2010, from ZINWA. The WAFLEX model was then used to quantify the actual evaporation basing on the corresponding surface area of the reservoir at particular time steps.

3.2.2.5. Water Abstractions

Data on abstractions by permit holders mainly for the purposes of irrigation and domestic use was obtained from ZINWA offices in Mutare. The volumes specified on the water permits were assumed to be the current demand, i.e. not taking into account management issues and transportation losses. This data is shown in Appendix B.

3.2.2.6. Agricultural Water Demand

Crop Water Requirements were computed using the FAO CROPWAT 8.0. software, which uses the Penman-Monteith Method for calculating reference evapotranspiration ET_0 . This was mainly to compare with current abstractions to assess if the crops' water requirements

are being met. The meteorological data (humidity, wind speed, sunshine hours, radiation, ET_0 , rainfall and temperature) utilized in the software for the calculation of reference evapotranspiration was obtained from the FAO database. Rainfall for two stations (Makoholi and Sabi Valley) in the FAO database which were nearest to the study site were regressed linearly with the Zaka rainfall to ascertain which station had a stronger correlation with Zaka (Appendix D). The Makoholi Research station was then used in the computation as it had a slightly higher coefficient of determination. The irrigation water requirements in the model are calculated using the equation:

$$IWR_{gross} = \frac{ET_c - P_e}{\eta} \quad \text{Equation 3.1}$$

Where ET_c is the crop evapotranspiration, P_e being the effective precipitation and η is the irrigation efficiency.

$$ET_c = k_c * k_p * E_0 \quad \text{Equation 3.2}$$

Where k_c is the crop coefficient, k_{pan} , the pan coefficient and E_0 the open pan evaporation. The k_c values are obtained by constructing the k_c curves taking into consideration the planting date, the crop growth stages and duration and the cropping pattern. An example of such a curve is as in Figure 3.4.

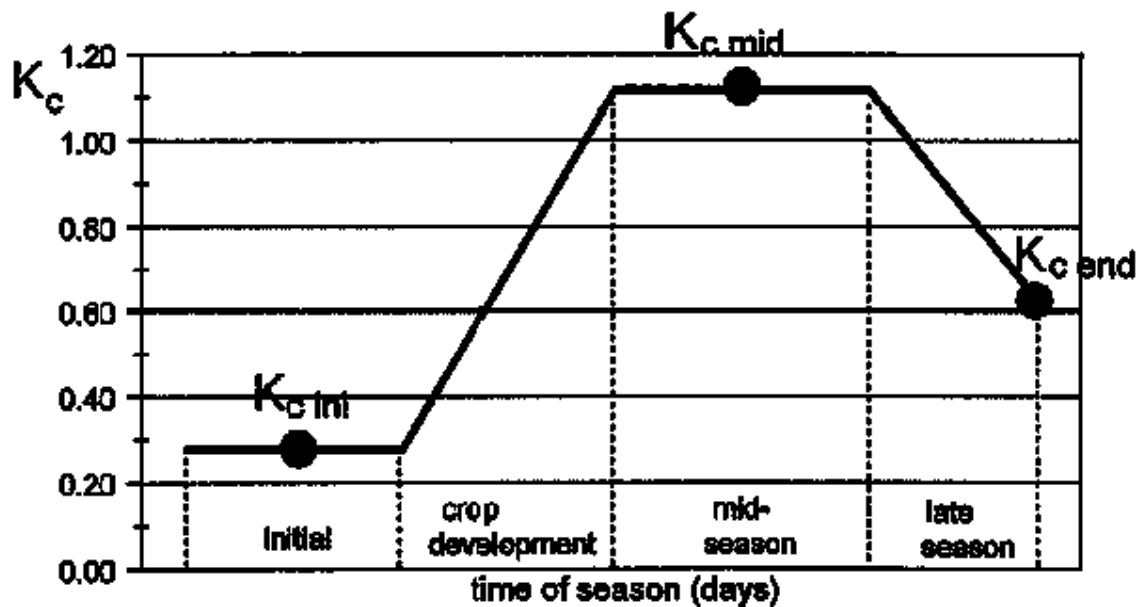


Figure 3.4: A typical crop coefficient (k_c) curve (Source: FAO, 1998)

CROPWAT 8.0. is a tool to help agro-meteorologists, agronomists and irrigation engineers to carry out standard calculations for evapotranspiration and crop water use studies, and more specifically the design and management of irrigation schemes. Through the input of crop data (growth stages, k_c factors, root zone depth and allowable soil moisture depletion factor), the programme calculates the crop water requirements on a decade (10-day) basis. The programme is interactive in nature. In addition, it allows the development of irrigation schedules for different management conditions and the estimation of scheme water supply for varying cropping patterns.

3.2.2.7. Dam Capacity

The monthly capacities of the dam (Appendix E), together with the levels were obtained from ZINWA and these were used in modelling reservoir storages and allocations made.

3.2.3. Trend Analysis

In order to understand the temporal dynamics in rainfall and temperature in the area, the Spearman's Rank Correlation test was used. Specifically, rainfall and temperature were tested to confirm whether they showed a significant decreasing or increasing trend. Trend tests are important in understanding the trajectory of surface water resources in the area. This method was used in analyzing for trend because the data is distribution free i.e. it does not require the assumption of an underlying statistical distribution, unlike methods such as linear regression and the t and F tests. Another advantage of the method is its nearly uniform power for linear and non-linear trends (Dahmen et al., 1989). The method is based on the Spearman's rank-correlation coefficient, R_{sp} , which is defined as:

$$R_{sp} = 1 - \frac{6 \sum_{i=1}^n D_i^2}{n(n^2 - 1)} \quad \text{Equation 3.3}$$

Where n is the total number of data, D is the difference between the rankings, and i is the chronological order number. The difference between the rankings is computed as

$$D_i = kx_i - ky_i \quad \text{Equation 3.4}$$

Where kx_i is the rank of the variable, x , which is the chronological order number of the observations. The series of observations, y , is transformed to its rank equivalent ky_i , by assigning the chronological order number of an observation in the original series to the corresponding order number in the ranked series, y . The null hypothesis tested was:

$H_1: R_{sp}=0$ (there is no trend against an alternative hypothesis $H_1: R_{sp}< \text{or} > 0$ (there is a trend).

With the test statistic:

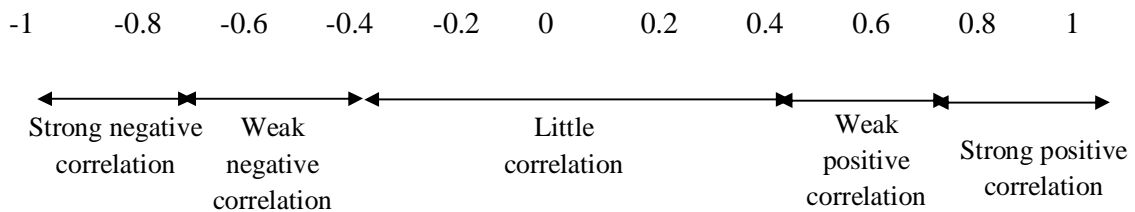
$$t_t = R_{sp} \left[\frac{n-2}{1-R_{sp}^2} \right]^{0.5} \quad \text{Equation 3.5}$$

Where t_t has Student's t-distribution with $v = n-2$ degrees of freedom. At a significance level of 5% (two tailed), the two-sided critical region, U , of t_t is bounded by (Dahmen et al., 1989)

$$\{-\infty, t\{v, 2.5\}\} \cup \{t\{v, 97.5\}, +\infty\}$$

The method was used to analyse trends in rainfall and maximum (Appendix C) and minimum temperature.

Interpreting the Size of the Correlation Coefficient



3.2.4. Modelling Approaches

A model is the replica of the actual existing system, behaving in respect to certain properties and functions as the prototype. It formulates the input-response relation in mathematical terms, thereby simulating system behaviour. The role of the modelling process in water management is as illustrated in Figure 3.5. The modelling process used in the study was also almost similar and is discussed in the following section.

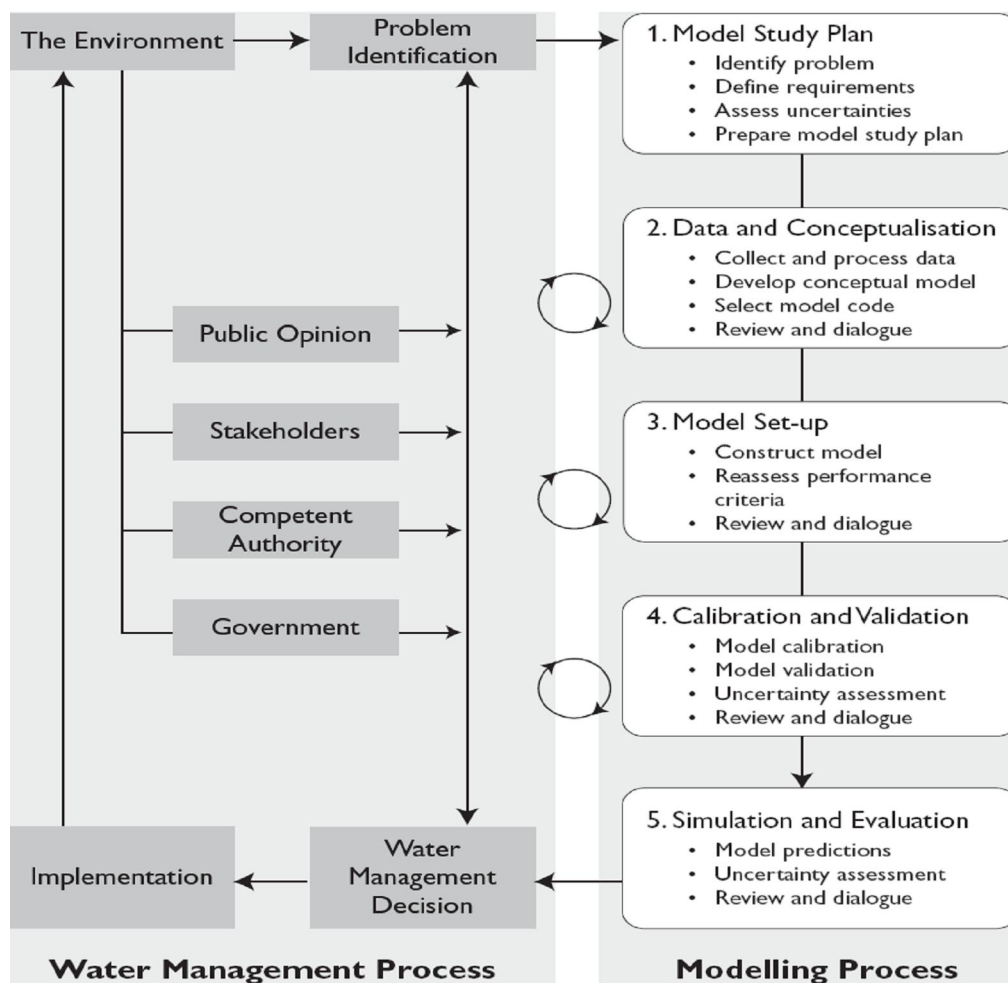


Figure 3.5: The role of the modelling process and the water management decision process. (Pascual et al. 2003)

3.2.4.1. Configuration of the WAFLEX Model

The WAFLEX model has been developed to help in solving water allocation problems by examining the water demand versus the water availability in the reservoir. The configuration of the model was aimed at applying the model to simulate the reservoir response to different water demand scenarios on a monthly time step. A conceptual representation of the Roswa River with the inflows and water uses is as in Figure 3.6, from which networks of spreadsheet cells which are interlinked are developed. Its network functions are based on the equation of continuity and the fact that water flows from upstream to downstream. For each time step, the flow is calculated in each cell adding up the flows of adjacent cells.

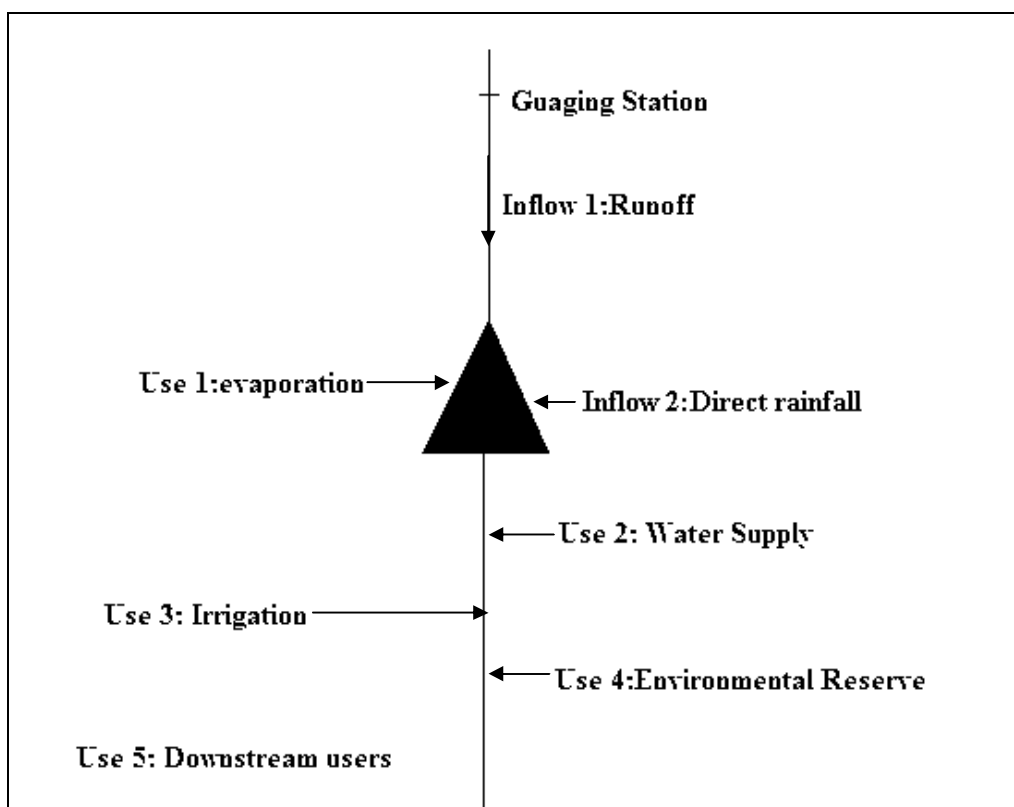


Figure 3.6: Conceptualisation of the Roswa river system

3.2.4.2 Steps in Developing The Model

This section gives a brief description of how the system variables like water demand, inflows and outflows were incorporated into the model. The steps followed in developing the model are as follows:

Step 1: Schematisation of the river was done in the supply sheet where flows are calculated in the downstream direction. A demand sheet was also created where a schematisation of the river was done and the demands calculated by adding them in the upstream direction. A reservoir sheet was also included. Abstraction points were represented in the network as nodes.

Step 2: Interlinking of the cells was done to form the river system including all inflows and outflows.

Step 3: A series sheet was created where; the inputs i.e. observed runoff and all the demands were copied to the respective columns. VLOOKUP functions were also defined which vertically lookup for each time step calculation.

Step 4: The supply and series sheets were linked using the =INDIRECT function. A logical operation was put on each node to allow abstraction.

Step 5: Macros were written in the macro sheet using Visual Basic Program in MS Excel (Appendix I)

The model was then run for different scenarios to simulate the performance of the system and the outputs noted for any shortages.

Table 3.3: Scenario Development for Roswa

<i>Scenario</i>	<i>Description</i>	<i>Comment</i>
1	Current system operation with its normal inflows and outflows to assess water availability under current demand.	Assessment of current situation i.e. base case scenario.
2	Basing on climate change with effects of 50% reduction in runoff (Ministry of Mines, Environment and Tourism, 1998), while accommodating projected increased demands for water supply, agriculture, and downstream users	The scenario seeks to assess what the effects of climate change and future increases in demand would be on water availability and allocations, basing on results obtained by the Ministry of mines, of a 50% runoff reduction.
3	Change surface irrigation technology to a more water efficient technology e.g. sprinkler while retaining the scenario with climate change impacted inflows.	If the runoff were to reduce by 50%, one mitigation measure would be to improve the irrigation technology used. The irrigation method used at the study area is surface, which has low irrigation efficiencies. Therefore this scenario is for assessing the effects of improved irrigation technologies under scenario two.

Scenario 2 considers a reduction in inflows due to climate change. This is based on the Canadian Climate Centre (CCC) second-generation atmospheric general circulation model simulation of current temperatures, particularly in the Gwayi, Odzi and Sebakwe catchments

for the doubling of CO₂ case. Rainfall-runoff simulation for the doubling of CO₂ scenario showed that a 15%-19% decrease in rainfall and a 7.5%-13% increase in potential evapotranspiration will result in a 50% decrease in runoff by the year 2075. The difference in climate change impact on runoff among the three representative catchments considered was a 50% decrease. Therefore, a 50% decrease was assumed a reasonable estimate for the whole country (Ministry of Mines, Environment and Tourism, 1998).

Water balance calculations using Equation 3.5 were used to monitor the errors in the model to ensure that all of the water within the system was accounted for.

$$I_t - O_t = \Delta S_t \quad \text{Equation 3.5}$$

Where I_t is the sum of all inflows into the system at time t , O_t is the sum of all withdrawals from the system at time t and ΔS is the change in storage time t . The inflow is runoff and rainfall, and outflows include environmental reserve, abstractions and evaporation.

For a given reservoir, the change in storage is

$$\Delta S = S_t - S_{t-1} \quad \text{Equation 3.6}$$

Where: ΔS is change in storage, S_t is storage at time t and S_{t-1} is storage at time $t-1$.

Although the determination of environmental flow requirements EFR is quite complex, current planning by ZINWA allocates a simple 5% of the runoff in the river basin to the environment (Zimbabwe National Water Authority, 2006). From WAFLEX, operation and allocation of water will be developed under the different scenarios. Allocation should prioritise primary, secondary and then tertiary water use.

3.2.5. Interviews and Focus Group Discussions

As stated in chapter two, water resources management should incorporate the water users' preferences. In light of this, the initial processes included unstructured interviews and focus group discussions with ZINWA authorities and farmers (irrigators). This was initially to assess how water from the Roswa dam was being used, and to establish their preferences. The ZINWA authorities are responsible for managing the reservoirs. Guiding questions used are as in Appendix F together with photos in Appendix G

3.2.6. Population and Demand Projections

Population growth was assumed to follow Equation 3.7

$$P_n = (1 + r)^n P_0 \quad \text{Equation 3.7}$$

Where P_n is population at time n , P_0 is population at time 0 and r is the population growth rate (%).

The above methods provided inputs into the WAFLEX model and the results obtained are discussed in the next chapter.

CHAPTER 4

Results and Discussion

From the methods discussed in the previous chapter, the following results were obtained starting with the assessment of the existence of climate change at a local scale to the running of the WAFLEX model in reservoir operation.

4.1. Climate Change and Variability

The first objective was to assess the changes in climate at a local scale and this was done through analysis of two parameters normally used in climate change studies i.e. rainfall and temperature, using MS Excel and the Spearman's Rank Correlation Method.

4.1.1. Rainfall

Time series rainfall data from 1953 to 2008 was used in the analysis and its characteristics for the different months are as shown in Table 4.1. Generally, most of the rainfall is received in December and February, with the highest being almost 590 mm/month. From the data obtained for Zaka, the annual average was found to be 744.6 mm/month. From April to October the area is generally dry, with no rain recorded in the dry months. From the standard deviation it is clear that the data are spread out over a large range of values.

Table 4.1: Characteristics of Rainfall Data from 1953-2008.

	<i>Oct</i>	<i>Nov</i>	<i>Dec</i>	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>Jun</i>	<i>Jul</i>	<i>Aug</i>	<i>Sep</i>
MEAN(mm)	29.6	93.6	180.2	138.0	134.0	84.0	31.5	15.8	11.5	8.3	5.0	12.9
MAX (mm).	140.6	274.4	586.5	375.0	589.2	387.9	165.3	111.7	98.0	58.9	23.2	109.9
MIN.(mm)	0.0	3.5	16.1	12.7	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0
ST.DEV	27.3	57.0	117.1	89.2	114.5	81.4	31.6	23.7	17.3	11.5	6.3	17.6

Annual totals of the rainfall data were then plotted for the period 1953-2008 with trend-lines showing the direction of the trend (Figure 4.1). The linear trend line shows a generally declining trend in total rainfall over the years, although it is not significant at a coefficient of determination (R^2) of 0.009. The effect of which would be a corresponding decline in runoff if land-use and land cover remain constant and ultimately in the amount of surface water available. The 5 year moving averages show variability in the rainfall with peaks between 1974-1980 and 1998-2002. The years 1954, 1968, 1974, 1983, 1992, 2005 received low rainfall, with the year 1992 receiving the lowest rainfall. On average, this shows a 10-year cycle in the minimum rainfall received in the area. The 10 year moving average (MA) curve follows a similar trend with more refined crests (giving values lower than those for 5- year MA) and troughs.

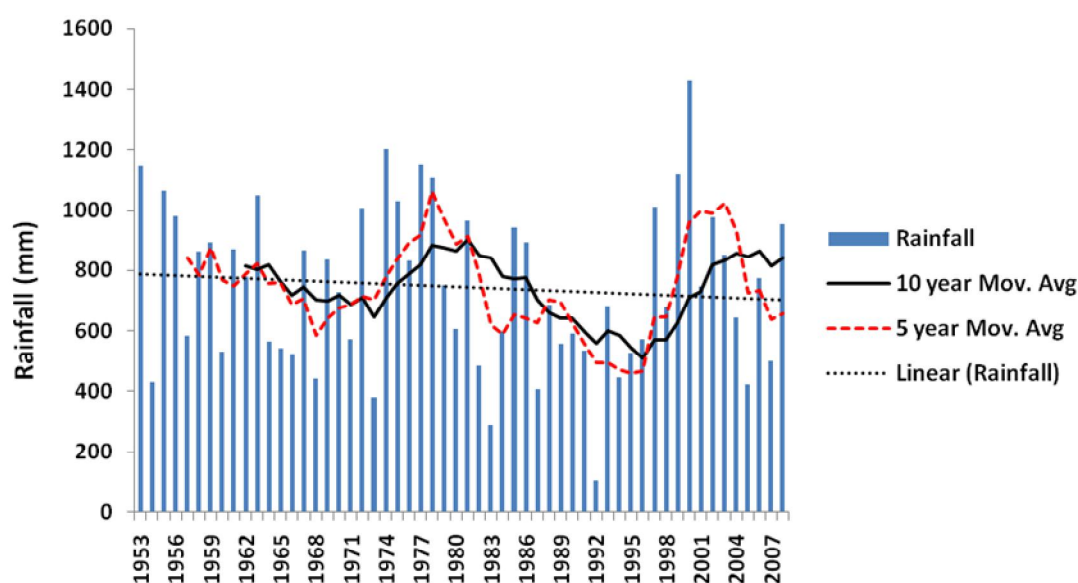


Figure 4.1: Total Annual Rainfall (1953-2008)

Having ascertained a declining trend in rainfall, a trend analysis was then done to confirm if there is change in rainfall and if it is significant. This was done through the Spearman's Rank Correlation method and the student t-test and the results are shown in Table 4.2. In testing the null hypothesis $H_0: R_{sp}=0$ implying no trend against $H_1: R_{sp} \neq 0$ (there is trend). The Spearman's rank-correlation coefficient (R_{sp}) was not equal to zero meaning that there is a trend

(implying a change) and the negative value showing that the trend is decreasing. From the Student t-test the change was found to be insignificant at 5% level of significance. In conclusion, from analysis of the rainfall data it is evident that there is a declining trend in rainfall, showing a change from the mean, although this is not statistically significant at a 5% level of significance. While trend is insignificant, cyclic trends (variability) are more pronounced with 5 and 10 year moving averages.

Table 4.2: Summary of Spearman's rank correlation analysis for rainfall.

<i>Parameter</i>	<i>Rsp</i>	<i>t_r</i>	<i>t{v,2.5}</i>	<i>t{v,97.5}</i>	<i>Conclusion at 5% significance level</i>
Rainfall	-0.11	-0.82	-2	2	Decreasing trend, Not significant

4.1.2. Temperature

The same analysis as that for rainfall was done for temperature data and the results obtained are shown in Tables 4.3, 4.4 and Figure 4.2. From Table 4.3, average maximum temperature is approximately 28⁰C, which is slightly above the country's average of 26⁰C, while the minimum is 14.8⁰C. The maximum temperature recorded in the area during this period was 41.5⁰C. The figure shows an increasing trend (change) from the mean in an ascending direction in both maximum and minimum temperature over the years.

Table 4.3: Characteristics of Temperature Data

	Maximum Temperature (⁰ C)	Minimum Temperature (⁰ C)
MEAN	27.9	14.8
MAX.	41.5	28.6
MIN.	8.5	0.1
ST.DEV	4.9	4.6

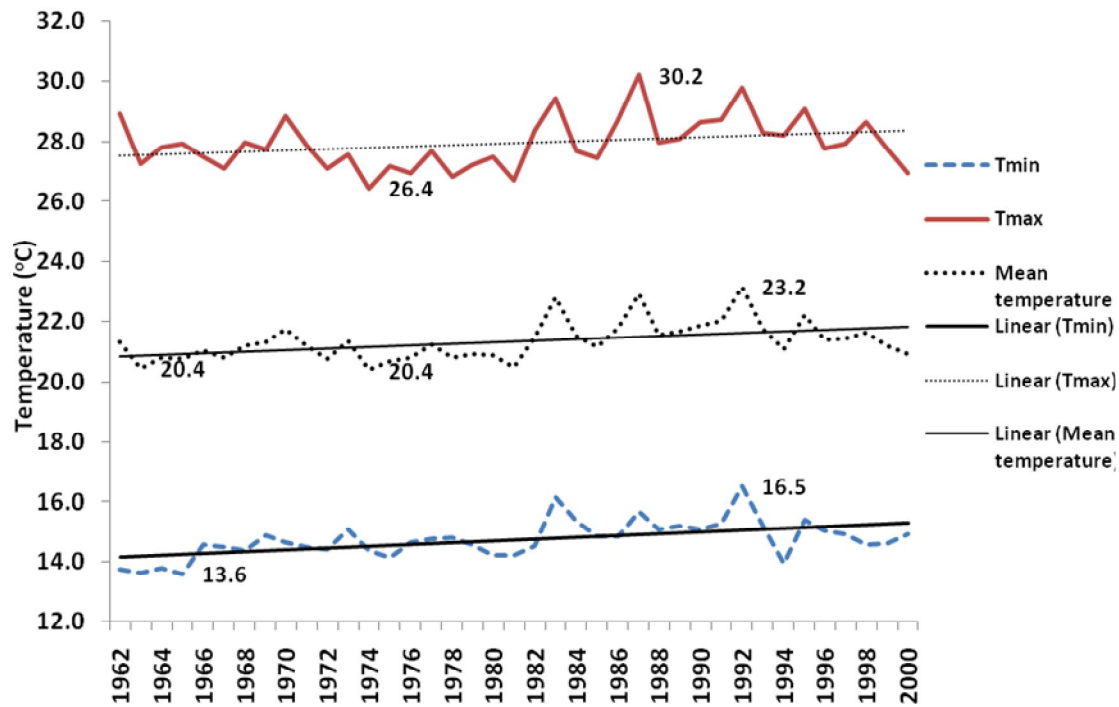


Figure 4.2: Annual Temperature (1962-2008)

The changes observed in Figure 4.2 were also tested for significance using the Spearman's Rank correlation method. An example on the calculation procedure for maximum temperature is outlined in Appendix C and a summary of the results is in Table 4.4.

Table 4.4: Summary of Spearman's rank correlation analysis for temperature

Parameter	R_{sp}	t_t	$t\{v,2.5\}$	$t\{v,97.5\}$	Conclusion at 5% significance level
Tmax	0.16	1.11	-2	2	Increasing trend, not significant
Tmin	0.32	2.22	-2	2	Increasing trend, significant(weak)

Calculated t_t values for rainfall and maximum temperature lie within the critical region $\{-\infty, t\{v,2.5\}\} \cup \{t\{v,97.5\}, +\infty\}$ implying a non-significant change, while the t_t value for minimum temperature shows significant change, although the significance is weak at R_{sp} below 0.5. Although above results show no significant change in the climate, the fact that

there is a certain level of trend, particularly increasing temperatures and decreasing rainfall, it is paramount that water resources management be geared towards possible changes in climate. It is in line with this argument that a scenario was run, effecting a 50% decrease in runoff as a result of climate change based on a study done in the country by Ministry of Mines, Environment and Tourism (1998).

4.2. Water uses from the dam

Water allocation in the basin is based on the ZINWA guidelines of prioritising primary use, followed by the environment, urban, industry, mining, agriculture and finally future reserve. Currently, at the site, the environment and downstream users together are allocated 10% of the mean annual runoff and water allocation is through the permit system. Current mean water demand from Roswa was estimated to be 264 000 m³/a and Figure 4.3 shows how the water is currently distributed.

Worldwide, the agricultural sector is the largest consumer of freshwater (Rani and Moreira, 2009) and Roswa dam is no exception as the major consumer of water from the dam is agriculture at 40% of the total. This water was for irrigating the 80 hectare Roswa irrigation scheme. In line with the foregoing statement, the research also assessed optimum irrigation water requirements for the scheme using the CROPWAT 8.0. model and compared these with current irrigation applications.

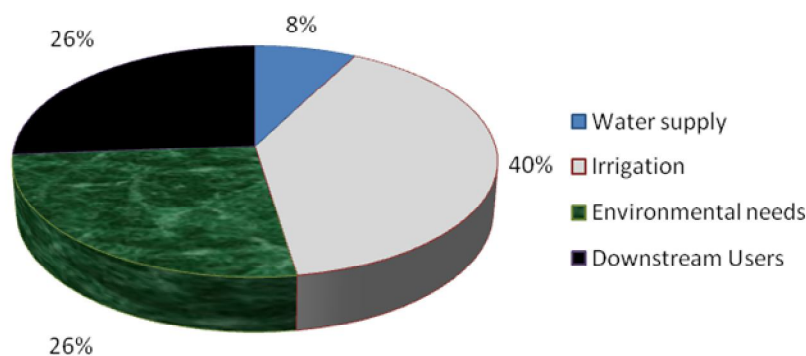


Figure 4.3: Water use by sector

4.3. Irrigation Water Requirements

The CROPWAT model requires rainfall, temperature, wind speed, humidity, and sunshine hours climatic data so in calculating the irrigation water requirements, the first step involved acquiring data for inputting in the CROPWAT model and thus a station near to the study area was selected from the FAO database. The Makoholi research station was selected because it had a strong coefficient of determination (R^2) of 0.985, from the regression analysis results as shown in Figure 4.4. Climatic data for Makoholi was then used in the model with confidence.

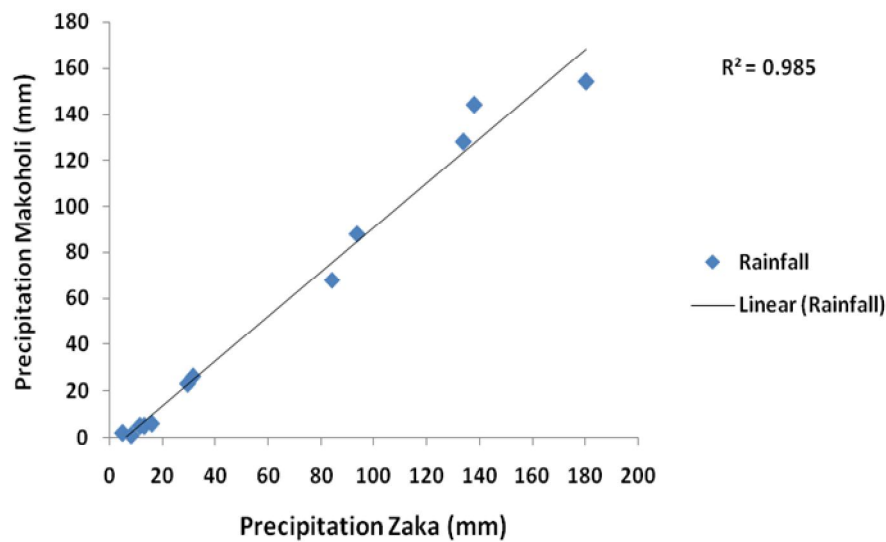


Figure 4.4: Regression analysis between Zaka and Makoholi rainfall data

Other climatic data used included, temperature, humidity, wind speed, number of sunshine hours and radiation, from which crop evapotranspiration was calculated. Figure 4.5 show values for some of these parameters. The crop evapotranspiration is highest in the drier months of September and October, when temperatures are at their peak.

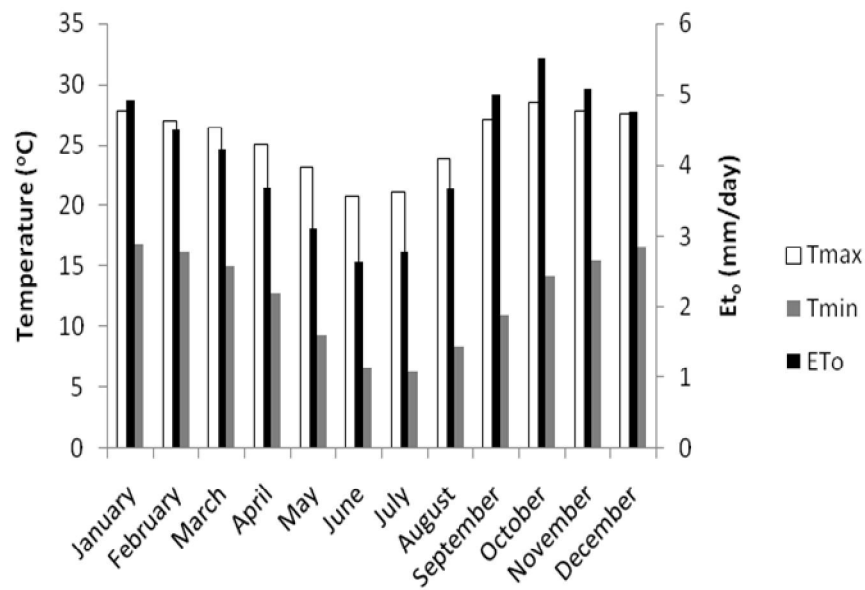


Figure 4.5: Crop Evapotranspiration and Temperature from CROPWAT 8.0.

Soil characteristics were obtained from the FAO CROPWAT database (FAO, 2010) and a red loamy soil, with an infiltration rate of 30 mm/day and a total available soil moisture of 180mm/m. Crops used in the analysis included maize, beans, winter wheat, tomatoes and vegetables which are the crops grown at the Roswa irrigation scheme. These are shown in Figure 4.6, with the length of growing season and K_c values. There was no staggered planting for any of the crops. The planting date for vegetables was placed at mid July but these are grown whenever the field is fallow. Maize is grown in August to be sold as green mealies in December, when the crop is at a higher market demand therefore fetching higher returns. Some of the crops grown are shown in Appendix G.

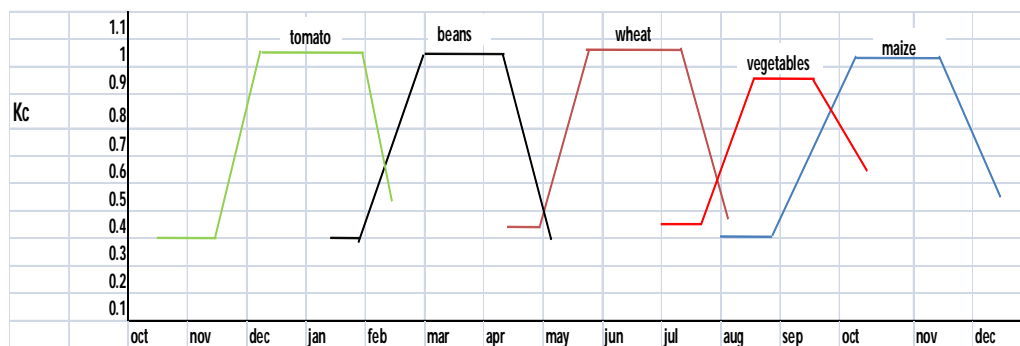


Figure 4.6: Cropping pattern at Rozva irrigation scheme

From the above data the crop water requirements and also the irrigation water requirements at 60% efficiency were then calculated and are shown in Figure 4.7. Although the farmers use surface irrigation which usually has efficiencies of around 40-50%, the irrigation efficiency for the scheme was taken as 60% since the technology employed is partially piped, with hoses being used from the hydrants to direct water onto the farrows where the crops are planted. Gross irrigation water requirements calculated using CROPWAT 8.0. was then plotted against current average monthly abstractions (Figure 4.7) and differences between the two were observed. The later was observed to be lower than the ideally required irrigation water, although these averaged out throughout the year. Considering that the current irrigation abstractions were recorded at the master meter into the night storage dam, if spills, conveyance, distribution and application losses are considered it can be concluded that the farmers are applying less water than what the crops require, which may adversely impact on their crop yields. These low application rates may be due to the fact that water application is not flexible i.e. although different crops are grown on the scheme at a time, water releases and application rates are constant. Since a variety of crops are grown at the scheme, the crops therefore has to adapt to the water applied, which then compromises on the performance of the crop, which is largely a function of the amount of water applied.

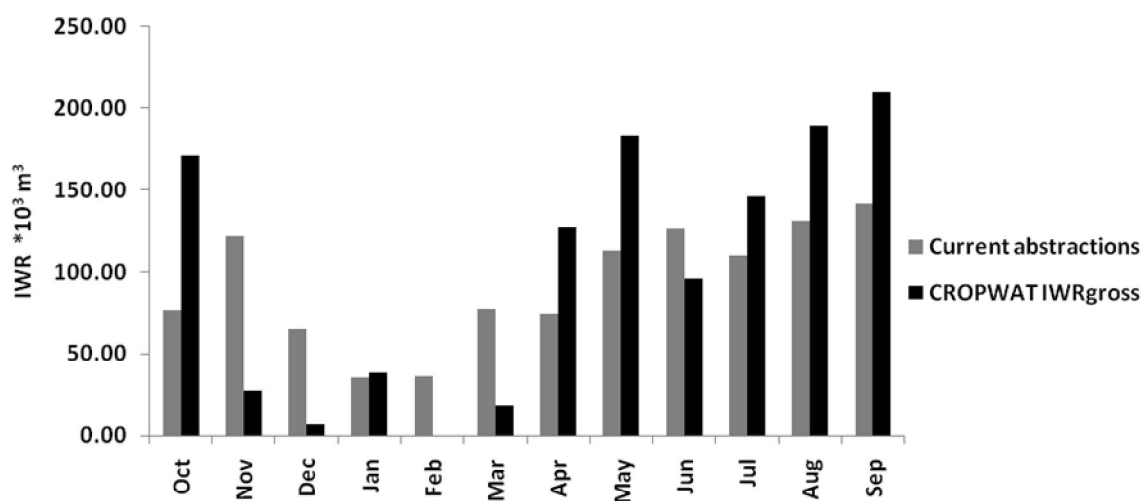


Figure 4.7: Irrigation Water Requirements

4.4. WAFLEX Modelling of Roswa Reservoir System

In simulating reservoir performance, values for inflows, outflows and storages were collected for the reservoir. For the inflow into the reservoir, monthly runoff data measured at the upstream gauging station was used to generate longer flow data (Figure 4.8). This then constituted the inflows into the reservoir, in the model.

4.4.1. Generated Runoff

The runoff acquired from ZINWA was from 1994-2008, so to obtain a longer stretch of data, existing runoff data was regressed with rainfall data for the same timeframe to generate data for the same as rainfall. The results are shown in Figure 4.8. The differences observed may be as a result of uncertainties in nature, which are difficult to incorporate into the model. Some inconsistencies may have come as a result of the use of data from another station, which have different terrains compared to the study site.

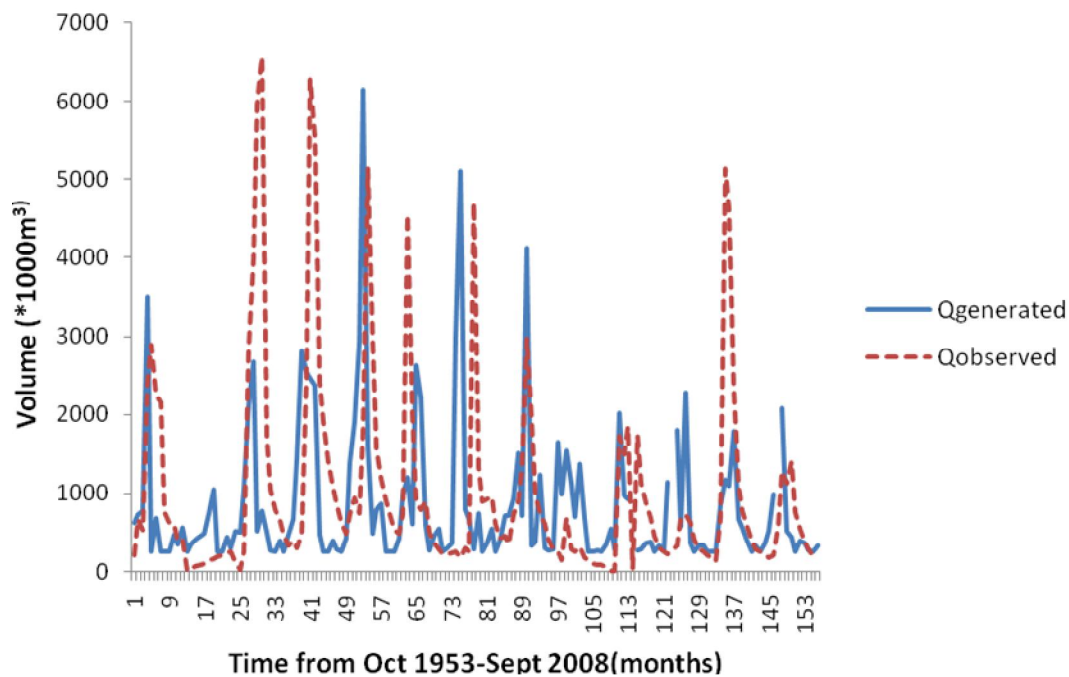


Figure 4.8: Observed and generated runoff into the reservoir

4.4.2. Model Evaluation

To evaluate the model, the simulation of the observed runoff was analysed. Figure 4.9 shows the simulated and observed flows. Inconsistencies may be due to losses that were not accounted for.

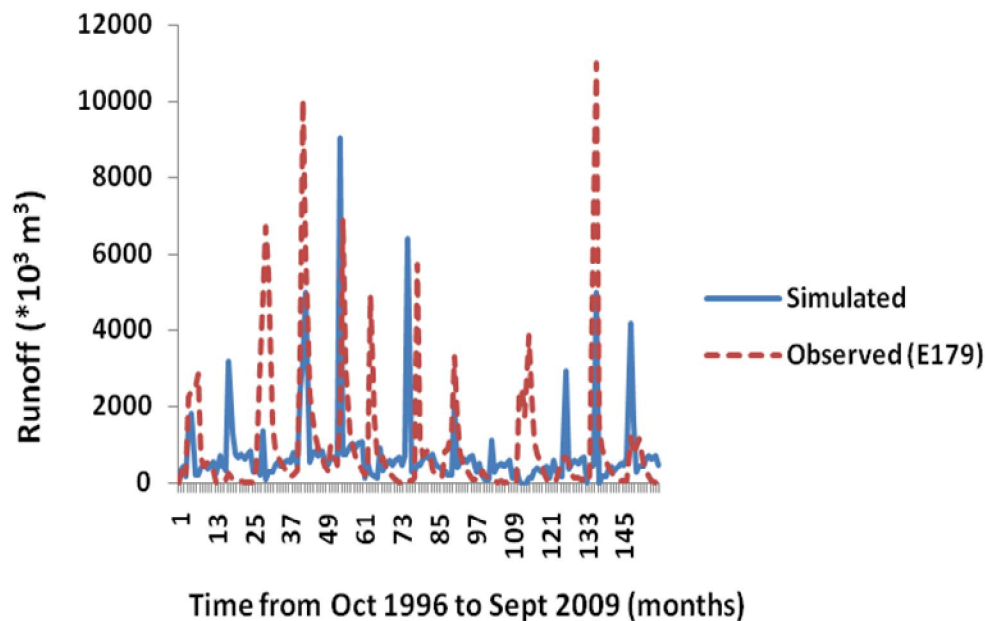


Figure 4.9: Simulation of the observed flows (1996-2009)

The differences noted in the Figure 4.9 may also be due to underestimation of floods that may happen during recording. Complex base-flow values were also not incorporated into the model. There are also issue of uncertainties which are very difficult to incorporate into a model.

4.4.3. Reservoir Operation and Water Allocation

In running the WAFLEX model to assess various operation and allocation options, the scenarios discussed in Chapter 4 were instituted with a starting dam capacity of $500 \times 10^3 \text{ m}^3$ for all scenarios. For the second and third scenarios, utility rule curves (URC) were introduced at $1500 \times 10^3 \text{ m}^3/\text{month}$ and $800 \times 10^3 \text{ m}^3/\text{month}$ for URC1 and URC2 respectively. The implication is that when the reservoir is drawn-down to $1500 \times 10^3 \text{ m}^3$ (URC1), rationing

should be instituted at 20% and at 40% when the level reaches $800 \times 10^3 \text{ m}^3$ (URC 2). Values for the URC were chosen arbitrarily, mainly as a management measure under the second and third scenarios i.e. if there is to be shortages as a result of climate change.

The main focus in the study was on the frequency of shortages rather than volumetric shortages. This was mainly because high shortage frequencies lead to dry spells especially if the shortages occur over the same period. Volumetric shortages would have less impact on ultimate yields since water is in abundance.

Scenario 1: Base Case Scenario

The model was run first for all existing water demands with environmental flow requirements and downstream users allocated 5% of the Mean Annual Runoff (MAR) each. When no rationing was instituted, there was 100% satisfaction level for both current and projected demands. Thus the dam can supply even the projected increased demand. The model showed (Table 4.5) that when water is rationed, shortages were experienced in environmental flows and by the downstream users. These were minimal at 2% and 5% respectively. Shortages were considered to occur if the amount of water required by a user was not supplied in totality.

Table.4.5: Percent Level of satisfaction for the main users under current water demand

Scenario	Use	Percentage	
		Current demand	Projected demand with rationing
1	Water supply	100	100
	Irrigation	100	100
	Environmental flows	100	98
	Downstream users	100	95

The storage graph (Figure 4.10), illustrated that the reservoir is at full capacity most of the years. The figure shows total abstractions at below $500\,000 \text{ m}^3/\text{month}$, which is

approximately one fifth of the full supply capacity of 2.8 Mm^3 . A reason for the small abstractions could be attributed to low populations and power outages faced in the country, since there is no pumping without power. The large difference between storage and the requests imply that there is possibility for future expansion in irrigation and other uses. This possibility of expansion was analysed for irrigation and the results are discussed below.

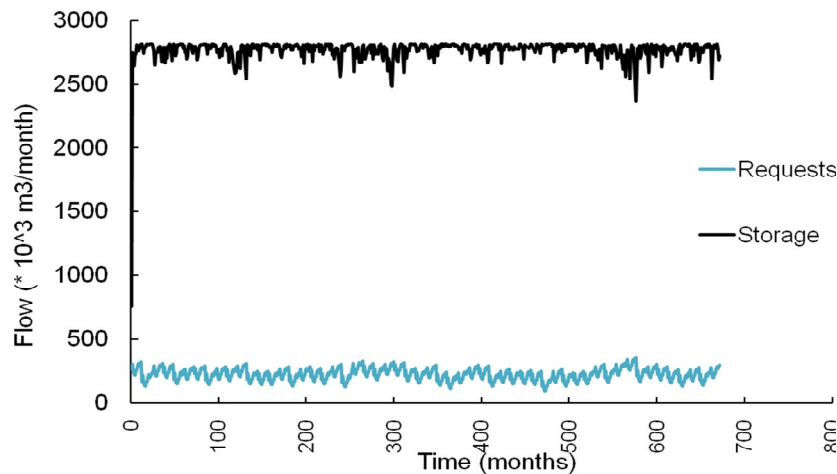


Figure 4.10: Current storages and requests for Roswa dam

The model was also run under the current situation, holding inflows and other demands constant while varying irrigation water demand. This was to assess how much increase in irrigation the reservoir could take under the current scenario. Results showed that irrigation could be increased to 320 hectares (i.e. four-fold) before any shortages are encountered. At 5 times the current irrigation demand, satisfaction levels would be in the order of 99%, 98%, 98% for irrigation, environmental water requirements and downstream users, respectively. The 99% satisfaction levels for irrigation are acceptable at 10% risk. For urban water supply, the satisfaction level would be 100%. From this analysis it can be concluded that the reservoir is under-utilised, with a possible expansion in irrigation of up to 4 times the original area. This is with the same crops being grown under the current farming practices.

Due to the large difference between inflows and requests an investigation was done to assess if the dam was necessary in the area, at its present location. Here the requests including evaporation were subtracted from inflows as generated from observed river flows. The results show that most of the demands can be met from the inflows without the presence of a dam

(Figure 4.11). A maximum demand of $200 \times 10^3 \text{ m}^3/\text{month}$ cannot be supplied from the inflows, therefore the need for the dam to cater for such shortages when they arise. With the advent of climate change, inflows will decrease (Bates et al., 2008), therefore the dam will serve an important purpose in ensuring water availability for the communities.

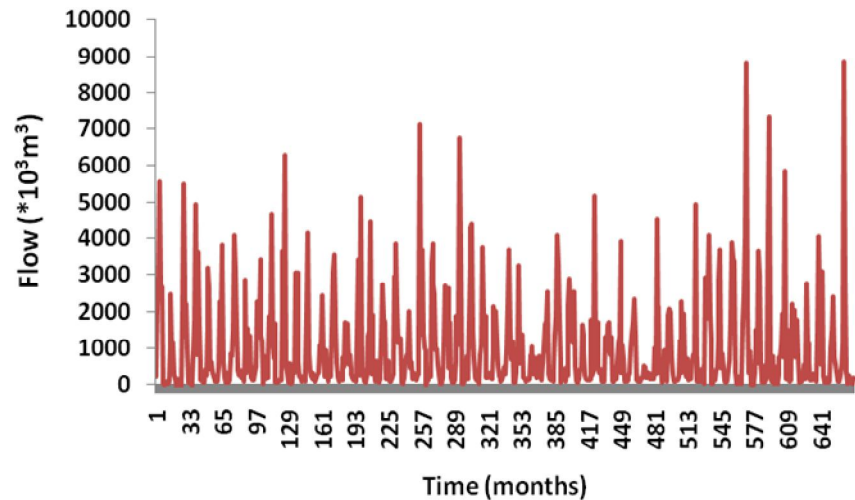


Figure 4.11: Excess water when demands are subtracted directly from inflows under scenario 1

Scenario 2(a): Climate Change Effects Leading to 50% Runoff Reduction

In this scenario runoff into the reservoir was reduced by 50% as described for scenario 2 in Chapter 4 but current demands were maintained. Since future projections, present a certain level of uncertainty, the possibility of a stable or declining population, and hence, demands cannot be totally ignored. The scenario was therefore run with current demands. The scenario also served to show if there is any under-utilisation of the water in the reservoir compared to the storages which were found to be high in comparison to the demands (Figure 4.10). Table 5.6 confirms that even with a 50% reduction in the current inflows there is enough water to satisfy the current demand. A 100% satisfaction rate was obtained for all demands as shown in Table 4.6. Figure 4.10 shows a graph similar to the one obtained in this run. An analysis was then done of the percentage reduction in runoff at which shortages would start to occur and this was found to be at 70%.

Table 4.6: Percent Level of satisfaction for the main users under climate change with no increased demand

Scenario	Use	Percentage at		
		50 % runoff reduction	70% runoff reduction	80% runoff reduction
2	Water supply	100	100	100
	Irrigation	100	100	100
	Environmental flows	100	100	96
	Downstream users	100	98	57

The satisfaction levels at 70% reduction runoff reduction are as shown in Table 4.6. At this level, 2% shortages are experienced only by the downstream users, who have a fairly high satisfaction level of 98%. The frequency of rationing at 70% inflow reduction was found to be 11 times for 20% rationing and once for 40% rationing. As a percentage of the total number of runs, these amount to 2% and 0% respectively, which is acceptable. Figure 4.12 (a) shows the reductions in storage against the demands at 70% runoff reduction, while Figure 4.12 (b) shows these at 80% runoff reduction.

At 80% runoff reduction, the satisfaction levels for downstream users go down to 57%. In terms of rationing, rationing at 40% would have to be done 3% of the total time, while 20% rationing occurs 309 times and this is 46% of the total time, which implies 20% rationing would be done for approximately half the time. These are high as the users would not have full access to water approximately half the time.

Possibilities of a reduction in inflow/runoff in the order of 70% and 80% are generally not logical, but in extreme cases of consecutive severe drought years, brought about by variability in climate, such reductions may be possible. An example would be the 1991/1992 drought where a 65% reduction from the mean rainfall was experienced in the Save catchment (Mazvimavi, 2005). Increased losses to evaporation will imply reduced runoff generation.

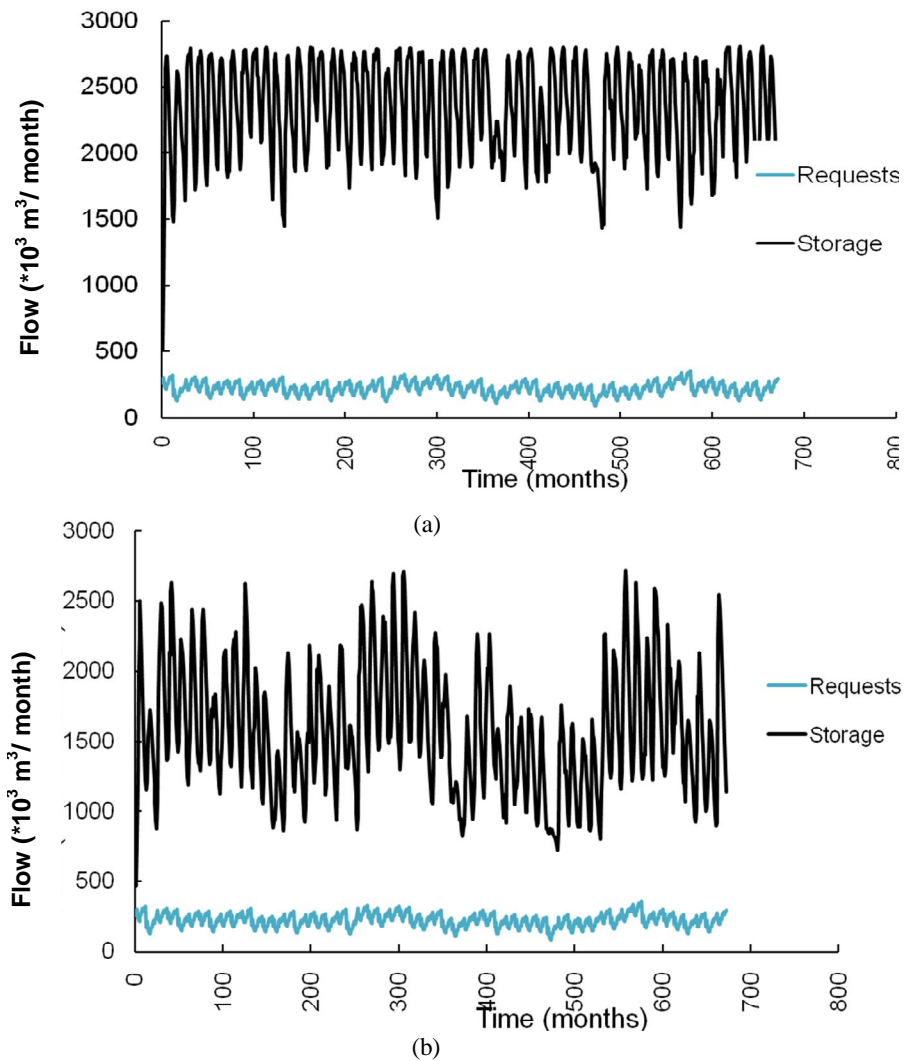


Figure 4.12: Storages and requests at (a) 70% and (b) 80% runoff reduction

A more 'logical' analysis was done where future increased demands were projected for agriculture, water supply and downstream users.

Scenario 2(b): Accommodation of future increases in demand under climate change.

The scenario probed into the effects of projected increased demands for urban use, agriculture and downstream uses, while maintaining 50% runoff reduction as a result of climate change. A report by the Central Statistics Office (CSO) on the 2002 census in Zimbabwe, stated that at a population growth rate of 1.1%, the population will double in almost 70 years (CSO, Reservoir Operation Under Different Climate Change Scenarios: Case Of Roswa Dam, Bikita District, Zimbabwe.

2002).this doubling of the population would therefore lead to an increased demand. The demand for water supply, irrigation and downstream users were increased as discussed in the following sections.

Urban water supply

Increases in urban water supply are mainly as a result of population growth. Assumptions made in the population were that the rate of growth for the area is constant. The population growth rate for Masvingo in 2002 was 1.3% (CSO, 2002). Since population census is often done on administrative boundaries and Nyika and Bikita are located in this province, the same growth rate was therefore assumed for the study area. The population was projected using Equation 4.7. Minimum domestic water requirement of 50 l/c/d, as proposed by Gleick (1996) was used to calculate domestic water use. The population of Bikita was 9801 and 8298 for Nyika in the 2002 census. Calculations for water supply under increased demand are shown in Appendix H.

Irrigation water requirements

The irrigation water requirements were calculated for a 100% increase in area calculated using CROPWAT 8.0. The 100% figure was chosen arbitrarily to assess the effects, on the reservoir, of doubling the irrigated area. The irrigated area was only doubled and not quadrupled, since the other uses were also increased in line with future projections. This is based on an assumption that for most irrigation schemes, the limiting factor is not land, but water availability. There was a 60% increase in the gross irrigation water required if the area irrigated is increased from 80 hectares to 160 hectares. The gross irrigation water requirements for both areas are shown in Figure 4.13.

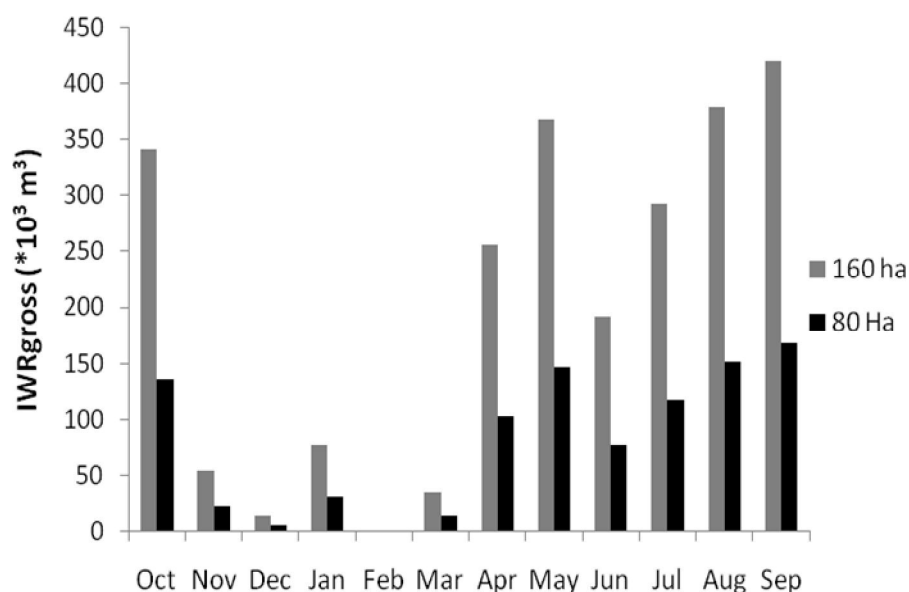


Figure 4.13: Increase in IWR_{gross} with 100% increase in area cultivated

Environmental Water Requirements.

For the environment no increases were incorporated i.e. 5% of MAR was maintained.

Table 4.7: Percent Level of satisfaction for the main users under increased demand

Scenario	Use	Percentage satisfaction
3	Water supply	100
	Irrigation	98
	Environmental flows	82
	Downstream users	70

Due to the projected demand increases, water allocation will be such that the frequency of rationing at 40% will be 51 times, which was equivalent to 8% of the total time. The frequency of 20% rationing would be 163 times, which is 24% (approximately one-quarter) of the time. In total, 32% of the time, full allocations are not realised. Figure 4.14 shows increased fluctuations in storage as the demands increase, illustrating more use of the water in the reservoir, as compared to the current uses demonstrated in Figure 5.10.

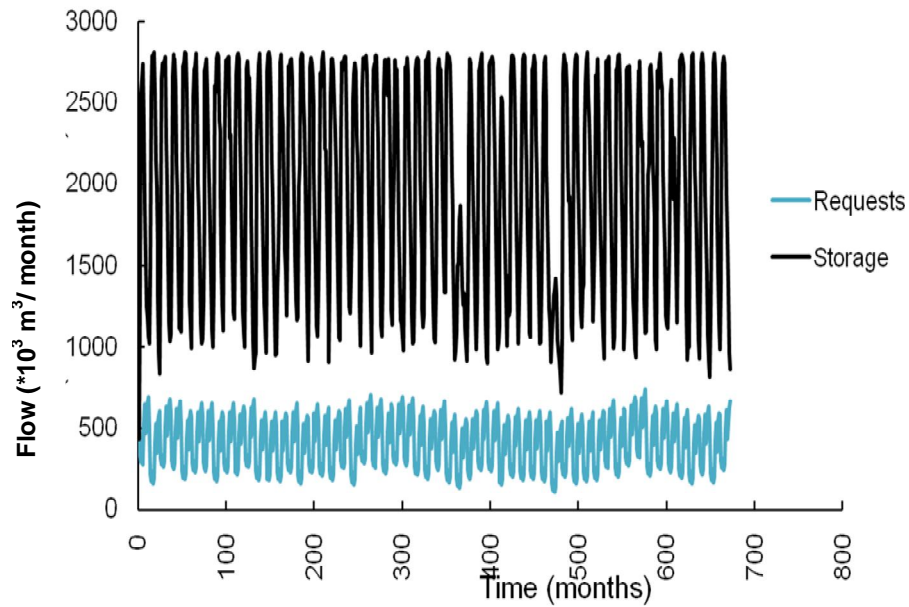


Figure 4.14: Storages and increased requests

Scenario 3: Change in irrigation technology

Since agricultural demand is the greatest consumer of water; one mitigation strategy in reducing the shortages identified in scenario 2(b) would be to introduce a more efficient irrigation technology. This scenario, therefore, explored the possible effects that may be brought about by a change in the irrigation technology employed, to a more water efficient technology e.g. sprinkler or drip, while retaining the scenario with climate change impacted inflows and increased demand. Figure 4.15 shows the projected gross irrigation water requirements at 60%, 75% and 90% irrigation efficiencies, representing efficiencies for the partially piped surface, sprinkler and drip irrigation system technologies respectively.

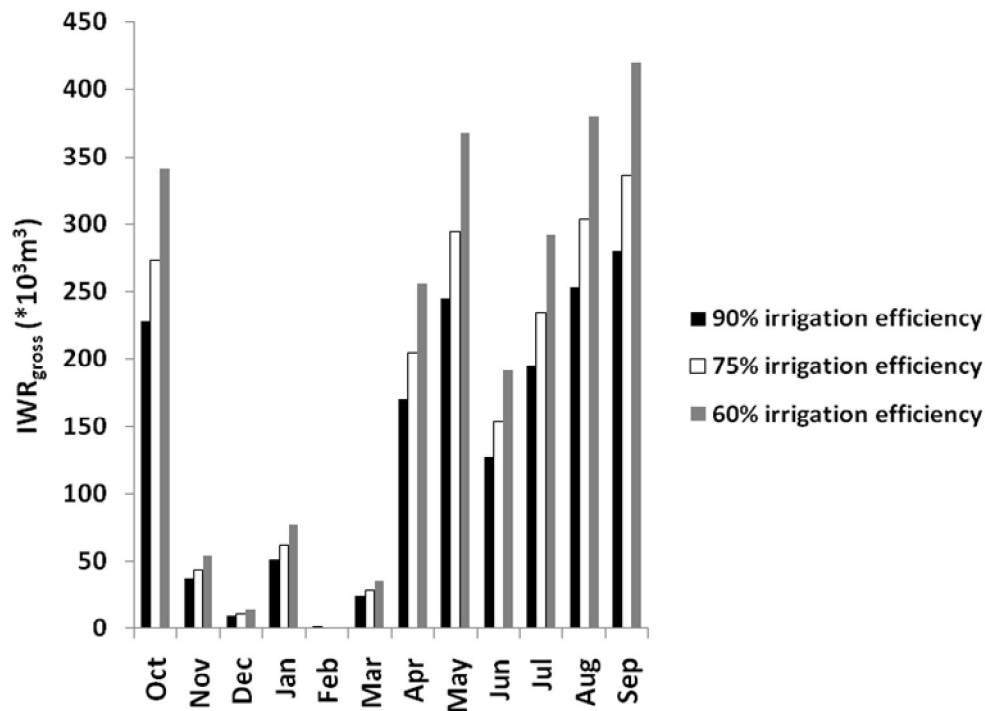


Figure 4.15: Gross irrigation water requirements

The demands shown in Figure 4.15 were input into the model to assess satisfaction levels if more efficient irrigation methods were to be employed at the irrigation scheme. Table 5.8 shows an increased satisfaction levels from surface to drip irrigation methods. Thus drip irrigation method recommended at the scheme especially since the farmers showed a keen interest in more efficient irrigation systems during the focus group discussions. A reduction in irrigation abstractions implies less cost for the farmers; but loss of returns to the water supply authority.

Table 4.8: Percentage level of satisfaction for the main users under different irrigation efficiencies.

Scenario	Description	Use	Percentage satisfaction
3a	60% irrigation efficiency	Water supply	100
		Irrigation	98
		Environmental flows	82
		Downstream users	70
3b	75% irrigation efficiency	Water supply	100
		Irrigation	100
		Environmental flows	91
		Downstream users	76
3c	90% irrigation efficiency	Water supply	100
		Irrigation	100
		Environmental flows	97
		Downstream users	85

At 60% irrigation efficiency, the frequency of the need for rationing at 40% is 51, would be 8% of the total time while that for rationing at 20% would be 163 amounting to 24% of the total time. Moreover at 75% irrigation efficiency, the frequency of rationing at 40% is 10 which is 1% of the total time, while that for 20% rationing is 158 amounting to 24% of the total time. At 90% irrigation efficiency and 50% runoff reduction, the frequency of 40% rationing is 4 and 1% as a percentage of the time frame, while 20% rationing would have to be done 105 times amounting to 16% of the total time. The combined effect of climate change and increased demands on water availability will be shortages for most of users. In conclusion, it is also noteworthy that improving the water application technique does not necessarily remove shortages but minimises them. For example, changing from surface to drip irrigation would imply an increase in satisfaction levels from 70% to 85%.

Since satisfaction levels are closely linked to the production yield (Rani and Moreira, 2009) the shortages observed in the model results may therefore imply non feasibility of doubling the irrigated area. A much smaller increase e.g. 40 hectare may be a better option, because

percent satisfaction levels for 120 hectares would be 100%, 100%, 98% and 90% for water supply, irrigation, environmental flows and downstream users, respectively. As stated above, possibilities of a decline in population, leading to decline in demands for both water supply and irrigation and introduction of water demand management techniques may cause a reduction in the computed shortages. However, considering the target area, suitability of irrigation system for different crops and farmer preferences the sprinkler irrigation becomes the most feasible option for Rozva irrigation scheme. The option of using pressurised systems (drip or sprinkler) can only be promoted if power can be guaranteed and if the additional power costs will not negatively affect productivity.

In conclusion, it was observed that currently, the reservoir has adequate water to meet all of its demands and still has excess flows. Under climate change and projected demands, shortages would be experienced, especially by the downstream users if allocations are not adjusted in accordance with equity principles. There would be no shortages for water supply i.e. the community is assured water for primary use.

CHAPTER 5

Conclusions and Recommendations

This chapter gives conclusions and recommendation based on the objectives.

Conclusions

- From the results of the study it can be concluded that at a local scale, there is evidence of changes in climate basing on temperature and rainfall data for 54 years. Generally rising temperatures were observed, while rainfall is decreasing. This observed change was not statistically significant at 5% level of significance.
- Less volumes of water are applied by the irrigators at the Rozva irrigation scheme compared to the recommended CROPWAT volumes, which may compromise on crop productivity.
- There are currently no shortages experienced by the water users. However, with 50% runoff reduction as a result of climate change, shortage would be experienced, particularly by the downstream users. Thus rationing should be done on upstream water users so that there is equity in allocation. Water supply always had 100% satisfaction levels, which is line with the requirements of the Water Act, for prioritising water for primary use.
- Limits to expanding irrigated land include power-cuts, additional power costs if pressurised systems are to be employed and additional cost of piping and possibly pumping if the current surface irrigation system is to be maintained.

Recommendations

- Although at a local scale there was no significant change in climate, the Rozva community still needs to be geared towards changes in climate. This is because, for doubling carbon emissions scenario, significant changes in climate were projected for

Gwayi, Odzi and Sebakwe in the order of 50% reduction in runoff. One adaptation mechanism could be growing drought resistant or tolerant crops.

- Since the dam is currently being under-utilised, the farmers can consider growing more high value crops until such a time that demands meet supply.
- Due to the effects of climate change together with increased demands imply that the farmers should set up measures to deal with reductions water resources availability. One option would be to introduce more sustainable irrigation practices and where possible, the farmers should grow the same crop at a given time to ensure adequate irrigation application. This would also ensure that their produce is easily marketable, as they can cooperatively transport it to the markets.
- Under climate change scenarios, it would be imperative to adopt the drip irrigation technology to minimise on losses but if funds are limiting, sprinkler irrigation can be adopted which is not as capital intensive as drip. Water demand management measures such as retrofitting can also be legally enforced at Nyika and Bikita.
- Further research and refinement of the model could incorporate land-use changes and their effects on water availability. Transmission and seepage losses, together with siltation levels could also be factored in. The model can also be refined to equitably allocate the water, since it prioritised upstream abstractions.
- Policy makers should also institute awareness creation mechanisms to educate communities such as Rozva on climate change and its effects on water resources and crop production, so that they may not be found vulnerable to these effects and set up adaptation mechanisms.

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APPENDICES

Appendix A: Runoff data used in the study

RIVER: ROSWA

LOCATION : ROSWA D/S FLUME

DATE OPENED: 29/11/94

R/T CODE NO.:5178 01

NOTCH CAPACITY : 7.4 m³/s

STATION NUMBER: E178

ZONE: ES 3

LATITUDE: 1955 S

LONGITUDE: 3211 E

AREA: 1.81km²

MONTHLY RUNOFF (*10³ m³)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	Total	Max	Days no flow
1994-1995	50	32	69	1090	234	209	156	195	101	87	52	22	2297	1269.1	7.12	9
1996-1997	205	662	522	2419	2887	2244	2157	762	625	607	391	411	13891	7674.8	7	0
1997-1998	13	37	63	89	102	138	158	188	207	240	245	119	1601	884.5	0.1	16
1998-1999	16	248	2850	3986	5958	6567	1712	1051	789	657	472	322	24629	13607.3	4.43	27
1999-2000	384	302	470	2450	6286	5548	2408	1909	1402	1080	865	622	23725	13108	4.05	0
2000-2001	488	734	943	738	1808	5134	2933	1574	1189	912	738	526	17717	9788.5	3.95	0
2001-2002	482	727	4558	2006	899	796	904	500	353	276	228	216	11944	6598.9	6.96	0
2002-2003	239	255	175	291	250	4704	1321	905	931	956	607	429	11063	6112	7.71	0
2003-2004	455	352	722	892	1331	2970	1935	987	746	604	402	276	11674	6449.4	3.06	0
2004-2005	245	149	679	289	245	317	183	143	106	91	78	49	2576	1423	0.65	0
2005-2006	7	0	1734	1503	1845	7559	1736	1126	878	688	450	297	17823	9846.7	13.7	56
2006-2007	249	216	198	327	682	732	625	404	285	259	214	178	4369	2413.9	1.95	0
2007-2008	134	678	5132	4630	2326	1096	773	575	389	279	252	229	16493	9112.1	9.8	0
2008-2009	179	208	184	1281	1132	1403	765	543	368	285	194	*	6543	3615	1.49	0
MEAN	185	271	1077	1294	1529	2319	1045	639	492	413	305	217	9785			
MAX.	488	734	5132	4630	6286	7559	2933	1909	1402	1080	865	622	24629			
MIN.	0	0	0	0	0	0	0	0	0	0	0	0	0			
DAYS	496	480	496	496	451	507	510	527	510	527	495	450	5945			
ST.DEV	180	271	1601	1402	1940	2580	949	562	435	356	260	198	8352			
SKEW	0.549	0.763	1.835	1.248	1.714	0.887	0.532	0.801	0.66	0.527	0.709	0.543	0.37			
C.V.	0.971	1.002	1.487	1.084	1.269	1.113	0.908	0.88	0.883	0.862	0.853	0.912	0.854			

Mean Flow m ³ /s	0.073	0.111	0.427	0.513	0.667	0.9	0.403	0.239	0.19	0.154	0.121	0.095	0.324
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Data collected and processed at the Research and Data Division of The Zimbabwe National Water Authority (Z.I.N.W.A.) Data processed on 03-29-10 at 10:42:33

RIVER: ROSWA

LOCATION : ROSWA U/S FLUME

DATE OPENED: 29/11/94

R/T CODE NO.:5179 01

NOTCH CAPACITY : 5.1 m³/s

STATION NUMBER: E179

ZONE: ES3

LATITUDE: 1959 S

LONGITUDE: 3211 E

AREA: 55.13km²

MONTHLY RUNOFF (*10³ m³)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	Total Unit R/off	Max flood	Days no flow
1991-1992	*	*	*	*	*	0	0	0	0	0	0	0	0	0	0	194
1992-1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	365
1993-1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	365
1994-1995	0	5	38	422	251	118	36	62	62	69	104	44	1210	22	1.53	60
1996-1997	15	491	260	2260	2389	2486	2840	691	450	558	447	322	13208	239.6	4.69	0

1997-1998	16	0	0	108	232	92	79	54	36	27	27	26	697	12.6	0.15	111
1998-1999	27	380	3145	4860	6719	5515	1518	882	681	579	361	190	24857	450.9	11	1
1999-2000	171	204	330	3505	10039	6000	2315	1692	1211	913	696	456	27532	499.4	17.1	1
2000-2001	314	955	789	496	1774	6916	3048	1356	986	729	589	331	18283	331.6	8.05	0
2001-2002	206	395	4914	1628	665	545	686	352	260	152	104	26	9932	180.2	7.22	0
2002-2003	30	80	34	34	134	5721	1169	721	848	820	348	203	10142	184	13.5	30
2003-2004	199	187	820	856	1334	3289	1704	788	443	340	200	91	10250	185.9	5.68	3
2004-2005	86	38	325	204	115	145	111	23	53	18	0	3	1121	20.3	0.53	82
2005-2006	0	30	2354	2455	1756	3839	2303	1054	769	506	237	110	15413	279.6	9.89	56
2006-2007	19	72	83	363	629	684	522	200	131	134	82	87	3006	54.5	1.78	24
2007-2008	51	40	7155	10989	1487	928	586	395	277	178	100	35	22220	403.1	10.5	15
2008-2009	48	53	1192	752	967	1168	549	337	175	68	6	*	5314	96.4	8.68	36
MEAN	69	172	1261	1702	1676	2203	1027	506	375	299	194	113	9599			
MAX.	314	955	7155	10989	10039	6916	3048	1692	1211	913	696	456	27532			
MIN.	0	0	0	0	0	0	0	0	0	0	0	0	0			
DAYS	496	480	496	496	451	507	510	524	505	527	523	480	5995			
ST.DEV	94	255	2042	2774	2693	2491	1062	518	389	318	220	140	9343			
SKEW	1.524	2.107	0.04	2.669	2.479	0.8	0.746	0.926	0.869	0.756	1.114	0.336	0.635			
C.V.	1.357	1.482	0.62	1.63	1.607	1.131	1.034	1.023	1.035	1.061	1.135	0.237	0.973			
Mean Flow m3/s	0.028	0.071	0.5	0.675	0.731	0.855	0.396	0.19	0.146	0.112	0.073	0.046	0.315			

Data collected and processed at the Research and Data Division of The Zimbabwe National Water Authority (Z.I.N.W.A.)

Data processed on 03-29-10 at 10:31:04

Appendix B: Permitted water abstractions

WATER SUPPLY FOR NYIKA AND BIKITA (*10³ m³)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual average
2002	16.64	11.64	16.56	27.09	26.41	14.96	16.21	16.26	16.65	10.64	15.18	10.62	16.57
2003	18.72	19.39	14.63	17.52	18.53	16.97	15.55	16.85	17.13	11.33	10.51	17.20	16.19
2004	15.23	16.71	18.72	14.43	15.66	12.87	17.43	16.16	16.30	13.54	15.24	17.16	15.79
2005	22.90	23.75	17.16	17.75	22.03	18.07	18.30	21.00	20.80	21.63	22.97	26.08	21.03
2006	17.68	22.31	18.22	64.51	16.57	14.66	15.17	12.36	16.70	17.61	16.30	18.94	20.92
2007	19.51	24.76	12.01	18.93	21.71	19.90	25.09	23.52	22.30	20.61	19.36	22.93	20.89
2008	18.41	22.78	18.10	12.26	15.03	15.81	15.00	15.91	25.88	15.76	14.47	16.34	17.15
2009	13.49	12.16	9.56	16.06	17.35	15.79	24.29	10.78	12.46	12.34	13.61	13.73	14.30
Monthly average	17.82	19.19	15.62	23.57	19.16	16.13	18.38	16.60	18.53	15.43	15.96	17.87	

IRRIGATION ABSTRACTIONS (*10³ m³)

Month	October	November	December	January	February	March	April	May	June	July	August	September
2007	75.12	113.06	45.70	64.30	58.56	52.64	47.76	87.53	112.51	86.45	107.71	141.17
2008		130.19	83.87	6.44	14.15	102.56	101.11	137.50	141.36	133.20	154.80	
2009	81.95	92.04	41.04	40.56	5.75	30.69	30.40	56.40	72.03	42.05	90.40	106.09

IRRIGATION CONSUMPTION PER BLOCK(*10³ m³)

	BLOCK	January	February	March	April	May	June	July	August	September	October	November	December
2007	A:CHIKWADZI	8.6	8.1	7.2	6.6	13.2	13.3	10.9	21.4	19.7	10.3	15.4	6.2
	B:KUNEDZIMWE	9.2	9.5	8.6	7.8	14.4	15.8	9.9	23.1	21.4	12.2	17.7	7.0
	C:ROZVA	46.5	41.0	36.8	33.4	60.0	83.3	65.7	63.2	100.1	52.6	79.9	32.5
2008	CHIKWADZI	1.0	2.1	14.1	14.3	18.9	19.4	18.3	21.3	19.7	18.9	18.1	11.6
	KUNEDZIMWE	0.9	2.0	16.7	16.2	22.6	23.0	21.6	25.2	22.5	21.1	19.8	13.2
	ROZVA	4.5	10.0	71.8	70.6	96.0	99.0	93.2	108.4	100.3	96.3	92.3	59.1
2009	CHIKWADZI	5.6	0.9	1.0	4.2	7.8	10.0	5.3	15.8	18.6	14.3	14.0	6.7
	KUNEDZIMWE	6.6	4.7	9.0	4.9	9.2	11.3	7.9	17.0	19.9	15.4	16.3	7.2
	ROZVA	28.4	0.2	20.7	21.3	39.5	50.7	28.8	57.6	67.6	52.3	61.7	27.2
2010	CHIKWADZI	10.2											
	KUNEDZIMWE	11.0											
	ROZVA	37.3											

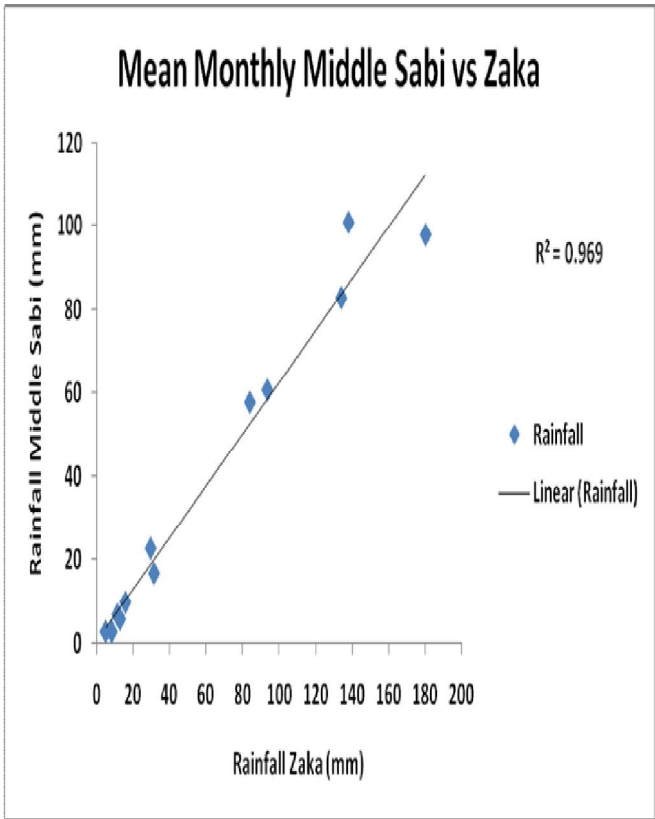
Appendix C: Trend Analysis On Maximum Temperature Data Using Spearman's Rank Correlation Method

Year	Avrg Tmax	y=ranked Tmax	kxi	kyi	Di	Di2	Year	Avrg Tmax	y	kxi	kyi	Di	Di ²		
1962	28.9	26.3	1	46	-45	2025	1987	30.2	27.9	26	10	16	256		
1963	27.3	26.4	2	13	-11	121	1988	28.0	27.9	27	36	-9	81		
1964	27.8	26.7	3	20	-17	289	1989	28.1	28.0	28	7	21	441		
1965	27.9	26.8	4	17	-13	169	1990	28.7	28.0	29	27	2	4		
1966	27.5	26.9	5	15	-10	100	1991	28.7	28.1	30	28	2	4		
1967	27.1	26.9	6	39	-33	1089	1992	29.8	28.1	31	45	-14	196		
1968	28.0	27.0	7	44	-37	1369	1993	28.3	28.2	32	33	-1	1		
1969	27.7	27.1	8	6	2	4	1994	28.2	28.2	33	41	-8	64		
1970	28.8	27.1	9	11	-2	4	1995	29.1	28.3	34	32	2	4		
1971	27.9	27.2	10	14	-4	16	1996	27.8	28.4	35	21	14	196		
1972	27.1	27.2	11	18	-7	49	1997	27.9	28.6	36	37	-1	1		
1973	27.6	27.2	12	40	-28	784	1998	28.6	28.6	37	43	-6	36		
1974	26.4	27.3	13	2	11	121	1999	27.8	28.7	38	25	13	169		
1975	27.2	27.5	14	5	9	81	2000	26.9	28.7	39	29	10	100		
1976	26.9	27.5	15	19	-4	16	2001	27.2	28.7	40	30	10	100		
1977	27.7	27.5	16	24	-8	64	2002	28.2	28.8	41	9	32	1024		
1978	26.8	27.6	17	12	5	25	2003	27.7	28.9	42	1	41	1681		
1979	27.2	27.7	18	8	10	100	2004	28.6	29.1	43	34	9	81		
1980	27.5	27.7	19	16	3	9	2005	27.0	29.4	44	22	22	484		
1981	26.7	27.7	20	23	-3	9	2006	28.1	29.8	45	31	14	196		
1982	28.4	27.7	21	42	-21	441	2007	26.3	30.2	46	26	20	400		
1983	29.4	27.8	22	3	19	361	Total Di ²						13546		
1984	27.7	27.8	23	35	-12	144								R _{sp} = 0.164601	
1985	27.5	27.8	24	38	-14	196								t= 1.106936	
1986	28.7	27.9	25	4	21	441									

$$R_s = 0.164601$$

$$t = 1.106936$$

Appendix D: Linear Regression between Middle Sabi and Zaka



Appendix E: Reservoir Capacities

ROSWA DAM CAPACITIES (STORAGE) IN Mm³

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
October	2.48	2.82	2.82	2.82	2.78	2.83	2.82	2.12	2.80	2.53	2.70	2.57	
November	2.46	2.82	2.82	2.83	2.81	2.82	2.74	2.12	2.71	2.43	2.57	2.44	
December	2.76	2.83	2.82	2.84	2.71	2.83	2.78	2.71	2.71	2.83	2.51	2.71	
January	2.70	2.81	2.84	2.83	2.81	2.68	2.84	2.82	2.83	2.81	2.93	2.84	2.67
February	2.81	2.83	2.93	2.84	2.83	2.76	2.84	2.82	2.84	2.83	2.84	2.84	2.56
March	2.81	2.83	2.84	2.84	2.82	2.84	2.85	2.82	2.87	2.83	2.83	2.84	
April	2.81	2.83	2.84	2.84	2.83	2.84	2.84	2.80	2.84	2.83	2.83	2.83	
May	2.81	2.82	2.83	2.83	2.83	2.83	2.83	2.72	2.83	2.82	2.82	2.84	
June	2.78	2.82	2.83	2.82	2.83	2.83	2.83	2.62	2.83	2.82	2.82	2.83	
July	2.76	2.82	2.83	2.82	2.83	2.83	2.83	2.62	2.83	2.82	2.78	2.82	
August	2.69	2.82	2.83	2.83	2.82	2.83	2.82	2.47	2.82	2.77	2.82	2.79	
September	2.63	2.82	2.82	2.82	2.81	2.83	2.82	2.32	2.82	2.65	2.78	2.72	

NB: Full Supply Capacity = 2.8 Mm³

Appendix F: Guiding Questions for Interviews and Focus Group Discussions

Reservoir operation:

- ✓ What is (sub) catchment council policy?
- ✓ What is policy of dam management policy?
- ✓ How is the reservoir managed on the ground? i.e. release for downstream uses, release to immediate users e.g. agriculture, urban, etc? At what reservoir levels do they effect interventions?
- ✓ How do they cater for environ flows?
- ✓ When do they start rationing? What are the effects
- ✓ Were there ever any shortages? How severe? What solutions are used?
- ✓ Are there supplemental boreholes? Capacity? When are they used?
- ✓ Why was the dam built? Benefits?
- ✓ What improvements need to be made as far as operation of the reservoir is concerned?
- ✓ What are the sentiments to any suggested changes in reservoir mgt

Allocation:

- ✓ How is the water allocated? Who gets priority? When?
 - ✓ Possibilities of future shortages? solutions to curb these shortages
 - ✓ Is there a possibility for future increase in irrigated area? Urban expansion? Downstream demands?
 - ✓ What is the cost of water for water supply and for irrigation? and how is water charged? Where does the money go?
 - ✓ What other demands are there? How are they factored in?
- Records of allocations and dam levels.
- Conflict resolution mechanisms?
- Stakeholder involvement e.g. AREX, DA, Physical Planning, ZINWA, etc.

Farmers:

- ✓ How is the water managed from the inlet @ the scheme?
- ✓ Which crops are grown? hectarage? What are the other preferences?
- ✓ When are crops grown? Summer and winter crop? three crops?

- ✓ When do they request for water? who does?
- ✓ What are the sentiments to any increases/ reduction in irrigated land?
- ✓ Proceeds from the crops (\$)?
- ✓ How is the water paid for? How much?
- ✓ Hectarage per farmer?
- ✓ Total hectarage per sub-section?
- ✓ Irrigation method used. Is there potential for improvement to e.g. low cost drip?

Water supply:

Find the populations served per year, and the growth rate?

Appendix G: Photos of Crops Grown and Focus Group Discussion

(a)



(b)



(a)Hose that transport water from the hydrants to furrows in the fields, (b)Mixed cropping of maize, wheat and vegetables



Focus Group Discussion

Appendix H: Calculation of increased demand in Water supply

Population	Bikita	9801	$P_n = (1+r)^n \cdot P_o$
	Nyika	8298	
	Total	18099	
Water use		50L/capita/day	

Water supply	Total population(P_o)	18099	
	year	2030	2075
	n	20	65
	r	0.013	0.013
	P_n	23434	41905
	ln L	35150762	62857888
	ln 10^3 m^3	35.2	62.9

Appendix I: Macros for Rozva Dam

Sub Computation()

'Defining initial values of reservoirs

Range("Stor1").Value = Range("Start_a").Value

Range("Stor1").Value = Range("Start_a").Value

For Count = 1 To Range("end").Value

Range("Count").Value = Count

calculatetimestep

Next Count

End Sub

Sub calculatetimestep()

'computation of one time step. Each time step results in the range "OUTPUT" are copied down into the output section

Res

Range("output").Copy

Range("output").Offset(Range("Counter").Value + 4, 0).PasteSpecial (xlPasteValues)

End Sub

Sub Res()

Range("infl1").Value = Range("inflow").Value

Range("Req1").Value = Range("Req").Value

$\text{Stor1} = \text{Range}(\text{"Stor"}).\text{Value}$

$\text{Range}(\text{"Stor1"}).\text{Value} = (\text{Range}(\text{"Stor1"}).\text{Value} + \text{Range}(\text{"infl1"}).\text{Value} - \text{Range}(\text{"req1"}).\text{Value})$

$\text{Range}(\text{"rel1"}).\text{Value} = \text{Range}(\text{"req1"}).\text{Value}$

$\text{Stor1} = \text{Range}(\text{"Stor1"}).\text{Value}$

If $\text{Stor1} \geq \text{Range}(\text{"FRC"}).\text{Value}$ Then

$\text{Range}(\text{"Rel1"}).\text{Value} = \text{Range}(\text{"Rel1"}).\text{Value} + \text{Stor1} - \text{Range}(\text{"frc"}).\text{Value}$

$\text{Range}(\text{"Stor1"}).\text{Value} = \text{Range}(\text{"FRC"}).\text{Value}$

End If

If $\text{Stor1} < \text{Range}(\text{"URC1"}).\text{Value}$ Then

$\text{Range}(\text{"Stor1"}).\text{Value} = (\text{Range}(\text{"Stor1"}).\text{Value} + \text{Range}(\text{"Rat1"}).\text{Value} * 1 / 100 * \text{Range}(\text{"Req1"}).\text{Value})$

$\text{Range}(\text{"Rel1"}).\text{Value} = (1 - \text{Range}(\text{"Rat1"}).\text{Value} / 100) * \text{Range}(\text{"Req1"}).\text{Value}$

End If

If $\text{Stor1} < \text{Range}(\text{"URC2"}).\text{Value}$ Then

$\text{Range}(\text{"Stor1"}).\text{Value} = (\text{Range}(\text{"Stor1"}).\text{Value} + \text{Range}(\text{"Rat2"}).\text{Value} * 1 / 100 * \text{Range}(\text{"Req1"}).\text{Value})$

$\text{Range}(\text{"Rel1"}).\text{Value} = (1 - \text{Range}(\text{"Rat2"}).\text{Value} / 100) * \text{Range}(\text{"Req1"}).\text{Value}$

End If

If $\text{Range}(\text{"Stor1"}).\text{Value} < \text{Range}(\text{"DSC"}).\text{Value}$ Then

$\text{Range}(\text{"Rel1"}).\text{Value} = \text{Range}(\text{"stor1"}).\text{Value} + \text{Range}(\text{"infl1"}).\text{Value} - \text{Range}(\text{"dsc"}).\text{Value}$

$\text{Range}(\text{"Stor1"}).\text{Value} = \text{Range}(\text{"DSC"}).\text{Value}$

End If

If Range("Rel1").Value < 0 Then

 Range("Rel1").Value = 0

End If

"{recalc \$areax_mupf}

Application.Calculate

Range("evaploss").Value = ((Range("p").Value - Range("e").Value) / 1000 * Range("area").Value) / 1000

Range("stor1").Value = Range("Stor1").Value - Range("evaploss").Value

Range("Stor").Value = Range("Stor1").Value

Range("rel").Value = Range("Rel1").Value

End Sub