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DEPARTMENT OF CIVIL ENGINEERING

MODELLING MULTIPLE RESERVOIR OPERATION SYSTEM FOR OPTIMUM PRODUCTIVE WATER USE IN THE SAFARI- IGAVA IRRIGATED AREA IN MARONDERA DISTRICT IN ZIMBABWE

By

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ABSTRACT

Zimbabwe undertook a land reform in 2000, where some large scale commercial farms were sub-divided into smaller plots and allocated to new farmers. Reservoirs owned and managed by farmer consortiums were taken over by a state enterprise, the Zimbabwe National Water Authority. A case of one such resettlement area is in the Wenimbi River basin, where 20 large scale commercial farms were sub-divided and allocated to over 600 plot holders. In 2004, a new and larger reservoir, located upstream, was commissioned, mainly to supply water to riparian farmers and a near by town. The changes have brought new water management and farming practices, hence new water supply and demand characteristics, more water users, more competition, shortages and some conflicts.

This research sought to establish the amount of water available, productive water use levels, allocations and underlying causes of shortages and conflict in the Safari-Igava irrigated farms after a major policy changes. A spreadsheet-based simulation model was developed and used in analysis of reservoir operation to help in formulation of water management strategies. The research methods used included gathering of quantitative and qualitative data from the national water authority, government departments and farmers, conducting canals topographic surveys and unstructured questionnaire surveys. Data collected was on water available, water allocation, consumptive water use, crops, irrigation practices, reservoir operations and geographical data of the farms served by the river system.

Results showed that annual water allocations quantities for productive use were not changed for the new setup. Farmers are expanding area under irrigation, on a gravity fed canal system, water measurement structures and reservoirs are not in use and generally in a disrepair condition. Upstream farmers are fully supplied with water while downstream farmers face shortages. Records on water inflow and release are kept at one major reservoir, while there are no records on abstractions from four reservoirs, the river and the canals. Records on current urban water supply, land use and crop production showed that demand is rising, but it is below the maximum allocations. The set up of water abstraction regulations by farmers for the shared water infrastructure was done without outside intervention, checks or controls. The supervision and regulations of water access and distribution by stakeholders like Zimbabwe National Water Authority, the Sub-Catchment Council and government departments of Irrigation and Agricultural Extension are weak. Analysis of different scenarios of water supply by the simulation model showed that there is enough water to meet all demands at current water use levels, but there may not be enough water to meet peak demand.

In order to enhance equity and efficiency, new reservoir operation and reservoir management strategies are required as well as accurate recording of water abstractions for individual users. Also, strict enforcement of water abstraction rules, proper operation and maintenance of infrastructure, accurate billing and management of water supply and distribution are required in order to minimize shortages and occurrence of conflict.

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ABBREVIATIONS

A1:	Small Holder Plots (6ha) For Resettled Farmers
A2:	Large Scale Plots (>20ha) For Resettled Farmers
AREX	Agricultural Research and Extension
CWR	Crop Water Requirement
CV	Coefficient of Variation
DDF	District Development Fund
DOI	Department Of Irrigation
DSC	Dead Storage Capacity
FSC	Full Storage Capacity
GIS	Geographical Information Systems
LBC	Left Bank Canal
MAR	Mean Annual Runoff
MAP	Mean Annual Precipitation
MOL	Ministry Of Lands and Resettlement
MSCC	Macheke Sub-Catchment Council
RBC	Right Bank Canal
UTM	Universal Transverse Mercator
ZINWA	Zimbabwe National Water Authority

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CHAPTER 1

1.0 INTRODUCTION

1.1 General

Water is a finite resource which is under increasing stress as human population and per capita demands increase through the world (IWMI, 2000). The demand for water for agricultural, industrial, power generation, domestic use and sanitation, waste collection, treatment and disposal uses are rising with the growth in the world economies. Flow in most of the rivers of the world are affected by the random and cyclic seasonal fluctuations, hence reservoir storage play a key role in regulating stream flow fluctuations, to develop reliable water supplies, optimal operation of the reservoirs is crucial (Wurbs and James, 2001).

In Utah in USA in the Sevier River basin, a semi arid irrigated farming area, agricultural water users identified runoff forecasting as a critical requirement for optimum operation of irrigation diversions and reservoirs, and to optimally use scarce water supply. As a solution a snowmelt-runoff model SRM, was developed as a water management tool that provides runoff forecasts from snow melt and precipitation (Woodruff Miller, 1991).

In South Africa, in Mgeni catchment it was predicted that water would be full utilized and highly polluted by the year 2005 due to increased settlements, industrial and agricultural uses. The hydrological simulation model that combined GIS with an agrohydrological modeling system (called ACRU), on water quality and quantity, helped decision-makers to manage effectively the water resources of the catchment (Tarboton, 1992).

The multipurpose functions of some reservoirs, for example, Mwenje reservoir in the Mazowe catchment in Zimbabwe include urban, mining and irrigated agriculture water supply. These competing users were allocated water on a fractional allocation system under the Water Act of 1976. With the promulgation of the new Water Act of 1998, an analysis of the appropriateness of the fractional allocation system under the new act for the Mazowe catchment was done using a simulation model (Natsa, 1999).

Four reservoirs on Wenimbi River, in the Save catchment, were constructed mainly for urban water supply and irrigated agricultural uses (Luxemburg, 1996). The agricultural or productive water uses have changed in character since the land reform of the year 2000 (AREX, 2005). The water consumption in Marondera Town, has increase since 1996 (ZINWA, 2009). Satisfying the water requirements of the competing users of the four reservoirs on Wenimbi River requires efficient reservoir operations and effective water management strategies.

If the water demand and equitable allocation and distribution is complex computer simulation models are used as analysis tools (Asit, 1976). Several runs of simulation models under various scenarios can be used to come up with optimal strategies for distribution and allocation of water (Wurbs and James, 2001). For a sustainable and equitable water supply from the four dams on Wenimbi River, simulation models can provide the support required in water resources analysis, for management strategies in the reservoirs operation.

1.2 Background

Most of the Safari-Igava farming area that receives erratic rainfall with an average of 880mm per annum (Meteorology Department, 2009). Two main rivers, Wenimbi and Ruzawi Rivers drain through the area into the Macheke River, a tributary of the Save River. Like most rivers in Zimbabwe, flow is mainly during the rainy season, (Mazvimavi, 2003). To mitigate the unreliable rainfall and runoff, 3 reservoirs on Wenimbi River and one on Ruzawi River were constructed by a consortium of large scale commercial farmers to supply water for irrigation and one reservoir was constructed on Wenimbi River by government for Marondera Town water supply (Luxemburg, (1996).

The 5 reservoirs in the Safari-Igava area are the Wenimbi and Safari reservoirs, Eirene farm reservoir 1 and Eirene farm reservoir 2 on Wenimbi River and Gairon reservoir on Ruzawi River. Safari reservoir (capacity 10.4 x 10^6 m^3), is the main reservoir that supplies the irrigated farms and has two canal systems located on either sides of the riparian land of Wenimbi River. The two concrete lined canals convey water for over 12km, were operated and managed by a consortium of large scale farmers, before the land reform of the year 2000. Farmers on the tail end of the right bank canal had access to water from, Gairon (capacity 6.2 x 10^6 m^3) reservoir on Ruzawi River, an interbasin transfer (Macheke Sub-catchment Council, 2006).

1.3 Problem Definition

Resettled farmers are facing water shortages every year and the most affected are tail end farmers relying on the canal system, who are facing problems in planting and irrigating winter crops and providing supplementary irrigation for early summer crops. Presently, the demand for water from the main reservoir for farmers, Safari reservoir, by the resettled farmers seems to be higher than supply, since, the reservoir dries out midway during the dry season (AREX, 2005).

The land reform in the year 2000 sub-divided 20 irrigated large scale commercial farms into 600 plots of various sizes. The resettled farmers have diverse cropping patterns and irrigation schedules, hence new water demand characteristics. Management and operation of the Safari, Gairon reservoirs, Eirene farm reservoir1 (capacity of 2.3 x 10^6 m^3) and Eirene farm reservoir 2 (capacity of 0.5 x 10^6 m^3), which were previously owned and operated by the large scale commercial farmers, were taken over by the national water authority, the Zimbabwe National Water Authority (ZINWA), as published in the Government Gazette (2006). In 2004 a larger reservoir (Wenimbi reservoir with capacity 21.3 x 10^6 m^3) was commissioned. It was constructed for urban water supply of Marondera Town (with a population of 80 000), and the water supply pipeline and pumping system is currently under construction. Records for Wenimbi reservoir show that farmers have been purchasing water from the reservoir as from the year 2005.

Farmers resort to purchasing water from ZINWA's Wenimbi reservoir after using up water in the Safari reservoir (ZINWA, 2009).

The increase in the number of users and new water demand characteristics have brought more competition for water which have resulted in conflicts among farmers (upstream and downstream), and between ZINWA and the farmers (AREX, 2005). The problem might escalate when Marondera starts abstracting water from Wenimbi reservoir, therefore careful operation of the reservoirs becomes crucial. The changes in management and operation of reservoir, and water demand characteristics may have a huge impact on availability of water to the urban and productive water users in the Wenimbi River basin.

1.4 Justification

Changes in operation of the multiple reservoirs, water distribution and water demand under the new cropping and irrigation practices seems to be the cause of shortages and conflict in the Wenimbi River basin. Equitable distribution and management of water resources for optimum productive use of water is vital for conflict prevention in the Safari-Igava farming community. For equity and sustainable use of water, new strategies may be required for operation and management of the multiple reservoirs. Therefore formulation of management strategies that enhance efficient management and equitable distribution of water resources for optimum productive water use is crucial for conflict prevention in the Wenimbi river basin.

The impact of construction of Wenimbi reservoir on availability of water for productive use was evaluated by a ZINWA hydrologist who found out that release from Wenimbi reservoir of normal flow and shortfalls in downstream reservoirs could satisfy all demands (Luxemburg 1996). The analysis was done before the land reform and when the Water Act of 1976 was in operation. A new Water Act of 1998 was promulgated in 1999, hence the establishment of the national water authority, catchment councils and sub-catchment councils which manages all water resources in Zimbabwe. There were no further studies and evaluation of water management of the multiple reservoirs in the Safari-Igava area after the land reform of the year 2000.

1.5 Objectives

1.5.1 Main objective

To develop a simulation computer model as a management tool that helps in development and analysis of water management strategies so as to minimizes shortages and equitably allocate water for urban users and irrigated farms in the Safari-Igava area, after the land reform.

1.5.2 Specific Objectives

The specific objectives for this study were:

1. To determine the quantity of water available, present water allocation, distribution and demand in the Safari-Igava system.

2. To develop a spreadsheet based simulation computer model based on a Waflex package, which can be used as a tool for analysis of operational strategies of multiple reservoirs for different water demand scenarios.

3. To use the model as a decision support tool that helps in formulation and analysis of water management strategies that enhance efficient productive water use, and reduce shortages and conflict in the Wenimbi River basin.

1.6 Hypothesis

The study is based on the hypothesis that simulation models can be used as management tools in formulation and analysis of water management strategies for operation of multiple reservoir systems in order to reduce water shortages.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

There is a general acceptance that models can be useful simplified decision support tools for understanding complex hydrological systems (Wurbs and James, 2001). In water resources planning and management there is often a need for simulation models that describe water flows, water quality, ecology and economy to support water management decisions. Once such models have been calibrated (if necessary) and validated they can be extremely useful to examine the effects of changes such as upstream land use, gross water requirements or the operating rules and management approach to water utilisation as well as examining such things as changes in catchment management, storage-yield relationships or extending existing data sets (Hughes,1991). By exploiting of hydrological models, effectiveness and efficiencies of water management strategies can be greatly enhanced (Wurbs and James, 2001). In the field of practical water resources planning there may be no time, funds and all data required to analyse and make appropriate decisions, therefore use of computer models may be cost effective.

Water engineering models are based on sets of algebraic or differential equations representing governing principles, such as conservation of mass, momentum and energy.
The models can be grouped into simulation and optimization models (Wurbs and James, 2001). According to Mhizha (2000), management systems employed in water resources management have to be flexible enough to respond to the dynamic nature of water resources problems. There are several types of models available, therefore choice of models to purchase should be based on accuracy and easy of application in different set ups.

2.2 Decision Support Tools in Management of Reservoirs Operation

2.2.1Simulation Models

Simulation models are a representation of a system and they are used to predict its behavior under a given set of conditions. Various executions of the simulation model are made to analyze sets of alternative plans, hence the performance of the system can be analysed and strategies can be drawn. Optimization strategies may be drawn after several runs of a simulation model (Wurbs and James, 2001). There are a number of hydrological simulation models which vary from simple, single function empirical models to complex multi-function models whose parameters can be estimated from measurable characteristics of the system which can be a whole catchment, an aquifer or reservoir being modeled. The degree of complexity is usually related to the number of time steps used in the simulation procedure as well as the extent to which spatial variability is accounted for in the development of the model (Hughes, 1991). Some understanding of the relationship between the functions and measurable characteristics of hydrological system simulated by a model, whether the model is complex or simple can be the most crucial starting point if useful strategies are to be drawn from the runs of the simulation model.

According to Savenije (1999), a simulation model mimics the functioning of the real system. The hydrological or economic performance of a reservoir system for given hydrological or economic performance of a reservoir system for given hydrological conditions under certain operation rules is reproduced. This is basically based on the water balance equation:

$$I - O = \Delta S \quad \text{……………………………………………Equation 2.1}$$

Where I is the inflow into the system which includes runoff and rainfall
O is the outflow from the system which includes evaporation, abstraction transmission losses and spillage
ΔS is the change in storage over the period under consideration and is given by:

$$\Delta S = St - S(t\text{-}1) \quad \text{………………………………………..Equation 2.2}$$

Where St is storage level at time t
S(t-1) is storage level at time t-1.

Savenije (1999), gave the following equation for the simulation of reservoirs for yield analysis directly on the reservoir for the duration

$$(S\, t_1\text{-}St_0))*(t_1\text{-}t_0) + (P\text{-}E)*\, t_1\text{-}t_0)*A(H_0) = Q(t_1\text{-}t_0) \quad \text{……….Equation 2.3}$$

Where;

St_1 is storage level at time t_1 [10^6 m^3/day]
St_0 is storage level at time t_0 [10^6 m^3/day]
T is the inflow into reservoir during the duration (t_1-t_0) [10^6 m^3/day]
Q is the outflow from the reservoir during the duration (t_1-t_0) 10^6 m^3/day]
P is the precipitation directly on the reservoir for the duration (t_1-t_0) [m/day]
E is the evaporation from the reservoir for the duration (t_1-t_0) [m/day]
t_1 is the end of the simulation time step [days]
t_0 is the beginning of the simulation time step [days]
A (H_0) is the surface area of the reservoir at a water level, H_0 [m]
H_0 is the water level at time to [m]

2.2.2 Optimization Models

Optimization models are usual mathematical formulations in which a formal algorithm is used to compute a set of decision variables that minimize or maximize an objective function subject to constrains, and they automatically search for an optimal decision policy (Wurbs and James, 2001). Optimization models provide a unique answer. The mathematical techniques used to solve reservoir operation problems in optimisation modeling are linear programming, dynamic programming and network flow programming Mhizha, (2000). For example, optimisation computer models for real-time management of complex surface water systems have been developed to provide management strategies that minimizes the total cost of system operation while satisfying specific constraints and maximizing benefits from the operation of individual reservoirs (Martin, 1991). In linear programming the mathematical function links the objective function to decision variables. The disadvantage of linear programming is that some parameters of reservoir operation are non-linear. Non-linear functions have to be converted to linear functions before linear programming models are applied on them (Wurbs and James, 2001). In dynamic programming a complex problem is broken down into a sequence of subproblems that are linked to each other. Each subproblem requires a decision and has a particular state variable associated with it (Wurbs and James, 2001). In network flow programming the system is represented by a network of nodes and arcs (Mhizha, 2000). These mathematical models have to be solved to provide information that is needed for decision making. The solution process is generally complex and time consuming, hence the need for use of computers that make the calculations easier. Use of computers requires software packages. Wurbs (1995) describes a wide range of computer models that are used in water management. Amongst these are graphics, spreadsheet and database software. Optimization models can be most useful where a problem in a system requires a unique solution and the mathematical formulations closely represent the system.

2.2.3 Use of Software Packages and Models

Exploited worldwide are generalized models designed for application to a range of problems dealing with systems of various configurations and locations, rather than being developed to address a particular problem at a specific site. In applying the software package, the model user develops input for the system of concern. Examples are the Hydrologic Modeling System (HEC-HMS and River Analysis System (HEC-RAS developed by the Hydraulic Engineering Center (HEC) which may be applied to essentially any watershed and river system (Wurbs, and James, 2001). Other examples of hydrological models that have been used extensively are the Pitman and RESSIM models, applied on water resources planning in South Africa. The RESSIM model has been modified and expanded to simulate several linked reservoirs. The Pitman and RESSIM models are also contained and operated in the generalized Hydrological Modeling Application System (HMAS) as stated in Hughes (1991). Models and their software success depend on their applicability and use by practitioners and these give an indication of the degree of their acceptability. Therefore modelers (producers of commercial models) have to understand and provide what the practitioners want.

Savenije (1995), defined ready to use or generalized computer models as commercial models. He commended that ready to use models are very important but practitioners should not become so dependant on them that they loose track of the processes that are simulated by the models. This is similar to a comment made by Wurbs and James (2001), that although computer models play important roles in all aspects of water resources engineering, models must be carefully and meticulously applied with professional judgement and good common sense. Therefore understanding both the process that is simulated and the model helps in drawing up useful benefits out of a model.

The alternative to the commercial models are the spreadsheet based models. Advantages of spreadsheet models as given by Savenije (1995) are;

1. All over the world all kinds of professionals have become acquainted with spreadsheets, much in the same way as professionals have started to use word processing.
2. Spreadsheets have a ready to use graphical interface such that it is easy to import data to other software.
3. Spreadsheets have simple data base management facilities and built-in statistical packages.
4. Spreadsheets can be programmed using macro language.

Disadvantages that Savenije (1995) gave include;

1. They require large memory and it takes longer to run them.
2. They are not foolproof. Errors can easily be introduced in the model.

Therefore it is easier for professionals to understand and use a model based on the spreadsheets, although it can only be operated by a professional who is conversant with spreadsheets. The professionals can even modify the model to suit their system and hence make better models and derive better solutions to problems possibly at a lesser cost compared to purchasing commercial models.

2.2.4 The Waflex Software Package

Savenije (1995) developed a water resource system simulation spreadsheet model called Waflex. The cells of the spreadsheet replicate the network of the water resource system using formula. The water resource system network can be made up of reservoirs, rivers and their tributaries, inflow and abstraction points.

❖ The Structures of a Model in the Waflex Package (Mul and Makurira, 2008)

The Computer model is composed of interlinked spreadsheets. In a supply sheet a schematisation of the river basin is made. The flow availability in the river basin is calculated by adding the inflows (demands are negative inflows) to the stream, from upstream to downstream. Therefore flow available can be represented by the expression; Flow available = inflow – demands. An example of the Waflex supply structure is shown in figure 2.1.

A	B	C	D	E	F	G	H	I	J	K	L
1	Tributary	2			River inflow	6					
2		2				6					
3		2				6	-1	-1	-1	(use1)	
4		2				5					
5		2				5					
6		2	2	2	2	7					
7						7					
8						10	3	3	3	Tributary2	
9						10					
10	Use2	-4	-4	-4	-4	6					
11						6					
12						6	River outflow				

Figure 2-1: Waflex Network Structure
(Source: Savenije, 1995)

A river or canal section is represented by a series of cells. The formula in each cell adds up the value encountered in the upstream adjacent cell. The formula at a confluence or abstraction point cell is the sum of the values of the cells directly north and east or west of it.

In a demand sheet a schematisation of the river basin is made similar to the schematisation in the supply sheet. The demand driven approach in this sheet is applied. From downstream to upstream the demands are subtracted. The water users in the area can allocate the water from upstream to downstream either on priority basis or as a percentage of water available. At first the priority of the water demand is the upstream users. A shortage of water resources in the reservoir is allocated to all users. Another option is to assign priorities in water supply to the users. The other parts of the structure are the reservoirs, the user interface and the output section which shows the abstractions**,** shortages, reservoir volumes etc. In the Waflex package a river basin simulation model simulates the response of the river basin on management strategies and can therefore be used for decision support. Successive and systematic runs of the model evaluate the responses to the variations in inputs or operating conditions. When used in conjunction with engineering and economic criteria, the results of these runs allow:

- The systematic comparison of alternative configurations of water resources projects in the basin; and
- The evaluation of the effect of the upstream development on the flows at the outfall and the consequent downstream development.

In order for the values in the Waflex to reflect a particular time step a macro is needed. The macro is the spreadsheet program language that uses range names to indicate cells in the spreadsheet as parameter names. The macros in Waflex are composed of the basic macro and macro subroutine. A typical macro procedure for water inflow, storage and release from a reservoir is shown in Appendix 9. The basic macro directs the program to macro subroutines if the time step counter is less or equal to the total number of time steps and quits the program if all the time steps have been achieved (Savenije, 1995). A working knowledge of spreadsheets is vital for developing a model that uses the Waflex package apart from the hydrological system that it simulates.

2.2.5 Testing and Calibration of Models

There are a number of tests that can be made on a computer model to check on its accuracy and stability. The mass conservation test is used to check the ability of a model to conserve mass or volume. Flow rate is varied or volume of water is abstracted and added sinusoidally in the input or upstream end of the model, while there is no output at the downstream end. The model should show no change in volume if it is accurate. Calibration of a model is required depending on the objective of using the model, especially if the model is used for the operation of an existing scheme. This is the process of adjusting the dimensions of simplified geometric elements and the values of empirical hydraulic coefficients so that flow events simulated on the model will reproduce as faithfully as possible the compared natural events (Contractor and Schuurmans, 1991). If accurately measured natural historical inputs are entered at the upstream end of the model, outputs of the model can be compared to the measured natural events outputs, and the difference in output can show the degree of accuracy of the model.

2.3 Water Management

2.3.1 Water Management for River Basins

Technologically advanced techniques, like automation which make use of electronic, electrical and mechanical devices that control and regulate canal and pumping systems are used as management tools in developed economies. These are combined with well executed water management principles as tools that can be used to enhance the rational use of water in farming communities. The rational use of water not only helps in higher production but also makes the benefits available to as many as possible thus meeting the ends of social use (Sharma and Sharma, 2004). According to (Sharma and Sharma 2004), the principal objective of water management are allocation according to entitlement at the right time for optimum yield of the crop with the allocated water, equitable distribution of supplies to irrigators especially at the tail end and realization of sense of justice and equity among the users by proper implementation of water management rules. Effective management of a river basin requires management rules that take care of all components of a river basin, reservoir, conveyance system, land, rainwater, farm water (which include land leveling and shaping, cropping techniques, irrigation efficiencies), conjunctive use of water, command area development (which include modernisation, operation and maintenance, planning and execution of programmes, enforcement of proper systems of distribution and allocation, and development of alternative sources of water). Modern technology combined with rational policies can be effectively used to monitor and control flow in rivers and canals in order to improve distribution of water for equitable allocation of water and management of entire river basins.

2.3.2 Irrigated Agriculture

Agricultural irrigation accounts for 65% of total withdrawals in the world and about 75% in developing countries (Wurbs and James, 2001). Irrigation increases crop yields and the amount of land that can be productively farmed, stabilizes productivity, facilitates a greater diversity of crops, increase income and employment, and helps alleviate poverty and on a larger scale can contribute to regional development (Wurbs and James, 2001). In developing countries the multiplier benefits of irrigation development include alleviation of pressure on scarce land resources (Manzungu, 1999). The importance of irrigation to drought prone areas can not be taken lightly. According to Michael (1978), the problem of drought has a socio-economic dimension because of glaring disparities in income and living standards between the dry and drought prone areas on the one hand, and the irrigated and high rainfall areas on the other. Providing irrigation to the maximum possible extent is the major step in relieving the drought affected areas from scarcity conditions. Shortages and scarcity always result in conflict whenever water access is denied to some sections. Farmers at the tail end are the usual victims. Water shortage is not only caused by lack of rainfall and increased users, but also because of poorly managed water distribution systems which at times lead to water losses when some people get more water than they want (Mvungi et al., 2005). Irrigation is critical to Zimbabwe but not to the same extend as countries like Egypt and the Sudan where 90% of crops are irrigated (Manzungu, 1999). Irrigation is the largest consumer of water in the world, and vital for food security and poverty alleviation in drought prone areas, therefore minimizing shortages by practicing good irrigation water management safe guards the social and economic benefits and prevent conflict.

❖ Lack of Measurement devices in Zimbabwean Irrigation Schemes

The lack of water flow measuring devices is a major drawback to the promotion of efficient water utilisation in irrigation schemes. This has resulted in farmers not having information on water use, with the result that they can not adequately monitor water use patterns on their own. In addition, water charges are not applied uniformly as some projects do not actually pay for water at all, making water a cost or a free input depending on who supplied the water. The practice of estimating water use data does not provide an incentive to farmers to save water. This puts farmers in a compromising situation, since they can not contest the water consumption figures on which charges are based. This scenario can lead to the lack of trust between the water supply institution and the farmers, a situation which is undesirable for improved water management (Ndamba, et al., 2005).

❖ Irrigation Water Management Objectives for Performance Measurement

According to Oad and Sampath (1991), the research premise is that performance evaluation is meaningful only in terms of certain management objectives, and these must be defined for a given social and economic context. Then, some key variables that describe these management objectives are formulated and used to develop a performance measure. Analysis of the existing system performance, using this performance measure, can identify required improvements. Oad and Sampath, (1991) proposed that an irrigation system consists of a water delivery and a water use subsystems, can be conceptualized to have two sets of objectives. One set relates to the output from its irrigated area, and the second set relates to the performance characteristics of its water delivery system. Inherently the two set of objectives are linked. If the water delivery performance objective is met then the output objectives should be achieved. This argument implies that one needs to only analyse the water delivery subsystem performance in order to understand performance of the whole irrigation system.

For irrigation systems, adequacy and dependability are the most common management objectives of water delivery systems. Adequacy in water delivery systems may be defined as the ability to deliver the amount of water to meet farmers' irrigation needs. Farmers' irrigation needs can be based on the knowledge of a crop consumptive use and/or social norms of equity. Dependability is defined as the delivery of a relatively uniform amount of water over time. Dependability reflects the combined effect of reliability and predictability and describes the arrival of a scheduled amount of water at a given place in a given time. The concept of equity deals with the distribution of irrigation water among users in a fair and just manner (Oad and Sampath, 1991). Thus, for a water supply utility, high efficiency of delivery of water up to the farmers' field edge can be considered as an indicator of good performance, but for overall water management, high infield application efficiency is crucial, because application efficiencies of irrigation methods vary from as low as 60% to over 90%. Efficient technologies and irrigation scheduling are employed to achieve high application efficiency. According to (Savva and Frenken, 2002), drip and automated sprinkler systems give over 90% application efficiencies. Scheduling methods include use of the open pan, plant or soil based monitoring methods and the cropwat computer programme

❖ Hydraulics of water flow in a Canal

According to Savva and Frenken (2002), a canal is an open water channel, therefore the hydraulics of open channel flow apply. The flow rate is determined by the equation

$Q = VA$……………………………………………………………………………Equation 2.4

Where

Q is the flow rate (m^3/s)
A is the cross-sectional area of canal
V is the velocity of water in the canal.

Using Manning's formula

$V = 1/n(R^{2/3} * S^{1/2})$ in m/s…………………………………………………..…Equation 2.5

Where

n is Manning's roughness coefficient
S is the slope of the canal
R= A/P and is called the hydraulic radius
P is the wetted perimeter of cross-section of canal

According to Savva and Frenken (2002), the average time taken by a particle of water to travel from one point to another in the canal depends on the average speed of the water. The formula used to calculate the average time is

$T = V/L$……………………………………………………………………Equation 2.6

Where

T is the average time
V is the average velocity of water in the canal
L is the distance between the two points.

2.3.3 Balancing Water Supply System and Demand in a Catchment

According to Mhizha (2000), water management is only possible if the quantity of water available in a system is known, the regulation, measurement and control infrastructure is operational. For easy regulation and supply water managers and regulating authority should always know the quantity of water available to users. The available water resources in a catchment can be measured by the mean annual runoff (MAR) and its variability over time, the coefficient of variation (CV).

Mhizha (2000), gave the following formula for MAR into a reservoir;

$MAR = Sp + E + Yd$……..Equation 2.7

Where:

MAR is Mean Annual Runoff
Sp is Average Spillage
E is Average Evaporation
Yd is the yield that can be obtained from the reservoir

The spillage will reduce if the storage is increased while on the other hand evaporation increases with increase in storage. As a result the yield decreases following the law of diminishing returns with the increases in storage. Mhizha (2000) indicates that as the storage in the catchment is increased the corresponding increase in yield that results from the increased storage decreases until it becomes uneconomic to increase the storage. This yield is the potential yield of the catchment and it varies with coefficient of variation (CV).

- Annual Runoff Data

Studies in Zimbabwe showed that a minimum of 10 years of flow data gives a reasonable estimation of most flow statistics (Mazvimavi, 2003). According to Wilson (1990), many small catchments in the world are not gauged and engineers often have to resort to empirical equations. In Zimbabwe major rivers and reservoirs have gauging stations which provide flow data. Some smaller rivers and most streams are ungauged or the runoff data is not available, hence flow data has to be estimated.

❖ Runoff Estimation in Ungauged Basins

This is a method for obtaining estimates of flood discharge for ungauged catchments through the use of catchment characteristics (Wilson, 1990). MAR and CV for ungauged sub-zones from catchment characteristics can be estimated using a number of formulae. Due to the different characteristics and the magnitude of their influences or contribution to runoff in different catchments, estimation formulas apply to particular catchments.

For Zimbabwean river basins Mazvimavi, (2003.) came up with the following formula for Save (excluding the Eastern Highlands), Sanyati, Mazowe and Manyame catchments;

$MAR = 0.393MAP - 197.4,\ r^2 = 0.75$ ....Equation 2.8

Where
MAP is the mean annual precipitation.

Other models by Mazvimavi (2003) incorporate catchment characteristics like lithology and slope.

According to Savenije (2007), the Equation 2.8 is a typical simplified lumped model. It treats a whole catchment as if it were homogeneous in character and subject to uniform rainfall. The remaining (‘hidden’) part of the simplified catchment model involves evaporation and groundwater recharge, which constitutes a major problem due to the non-linearity of the processes of evaporation and groundwater recharge.

Savenije (2007) stated that, to determine catchment runoff characteristics, a comparison should be made between rainfall and runoff. For that purpose, the monthly mean discharges are converted first to volumes per month and then to an equivalent depth per month Q over the catchment area. Rainfall P and runoff Q being in the same units (e.g. in mm/month) may then be compared.

A statistical model on the basis of the water balance equation can be used. For a specific period, one can write:

$Q = P - E - \mathrm{d}S/\mathrm{d}t$ ……..…………………………………………………Equation 2.9

The presence of the evaporation and the storage term makes it difficult to establish a straight forward relation between Q and P. The problem is further complicated in those regions of the world that have distinctive rainy and dry seasons. In those regions the different situation of storage and evaporation in the wet and dry season make it difficult to establish a direct relation.

For analysis of rainfall-runoff relationship typical monthly rainfall pattern for the catchment of the Cunapo River in Trinidad, Savenije (2007) concluded that, there appears to be a clear threshold rainfall below which no runoff takes place. The threshold would incorporate such effects as interception, surface detention, and bare soil evaporation. The same amount of rainfall gives considerably more runoff at the end of the rainy season than at the start of the rainy season. At the start of the rainy season the contribution of seepage to runoff is minimal, the groundwater storage is virtually empty and the amount to be replenished is considerable; the value of dS/dt in Equation 2.9 is thus positive, reducing the runoff R. At the end of the rainy season the reverse occurs.

The concept of threshold rainfall is quite in agreement with Equation 2.8 and has more physical meaning than the commonly used proportional evaporation "losses". Proportional evaporation losses are rather a result of averaging. They can be derived from the fact that a high amount of monthly rainfall is liable to have occurred during a large number of rainy days, so that threshold losses like interception and open water evaporation have occurred a corresponding number of times.

Therefore for small catchments, when accuracy is important, the use of lumped models may introduce huge errors. Equation 2.8 also takes into account the fact that there is a threshold rainfall (MAP = 502mm) below which runoff is zero. However the model may be inaccurate if MAP is characterized by precipitation that falls in few storms of high intensity. For small watersheds, the relation between effective precipitation P_e and surface runoff Q_s could often be considered as a linear system, i.e. twice the amount of P_e results in a doubling of the surface runoff values (e.g. the Unit Hydrograph concept). It appeared, furthermore, that the relationship is approximately constant in time (Savenije, 2007).

❖ Estimation of Frequency/Probability of Occurrence of Precipitation

Hydrological events like most natural events are usually random in nature and may have any or all the non-negative values. If precipitation at a place is measured daily for a period of time, a knowledge about what is a probable daily rainfall will be built up, but it will not, however long it goes on, lead to any limiting possible value of daily rainfall, other than intuitively (Wilson, 1990). Runoff is a product of effective precipitation therefore the fact that there are records on daily runoff does not lead to any limiting possible value of runoff. For a reservoir operator in arid/semiarid climatic conditions the determination of dry year precipitation and dry year MAR is crucial in determining the available water, hence optimum operation of the reservoir in years of drought.

According to Savenije (2007), in many cases the normal or lognormal distribution fits well to monthly rainfall. In such a case the computation of the mean and standard deviation per month (per column) can be used to compute the rainfall with a probability of non-exceedence of 20% (a dry year value) or 80% (a wet year value).

According to Mkhandi (2008), a distribution can be used to give probabilities of occurrences in the population. For a random variable X, the cumulative distribution function denoted as F(x), is the probability the random variable X is less than or equal to the value x, i.e.,

$F(x) = P(X = or < x)$ ……………………………………………………Equation 2.10

F(x) is referred to as non-exceedence probability, i.e., it is the probability of occurrence of events that are equal to or less than a specified event.

For a flood of magnitude Q(T) corresponding to a return period (T**)**, probabilities are estimated from records from gauging stations using statistical distributions. The common formulae are;

Weibull Formula: *F(Q) = i/(N+1)* ………………………….Equation 2.11

Gringorten Formula: *F(Q) = (i-0.44)/(N+0.12)* …....................Equation 2.12

Where F(Q) = Non-exceedence probability
i = Rank (1,2,3,…., N)
N = Total number of data points.

2.4 Reservoir Operation

2.4.1 Reservoir Yield Theory

According to Alexander (1995), the yield of a reservoir can only be defined where there is utilization of the water. In other terms, a reservoir that has fluctuating levels and overflows has a potential yield equal to the potential draw-off at a given risk. Therefore, the yield equal of a reservoir is the amount of water that can be drawn off to serve various purposes, at a stated risk of failure. There are several factors that affect yield of reservoirs namely; demand or requirements, runoff variation, reservoir characteristics (like capacity and surface area), evaporation, risk of failure, pattern of draw-off (unsteady or constant), compensation water for downstream users and reservation water for upstream users, operating rules.

Water supplies are not guaranteed because of the temporal variation in a river flow within the seasons, between the seasons and from year to year. Therefore reservoirs are built to even out fluctuations. Determining the reservoir yield helps to analyses and come up with a balance of supplies and demand requirements. In Zimbabwe, less than 10% of the seasonal rainfall appears as flows in the river systems, the rest being lost to evaporation, transpiration or replenishment of groundwater (Mazvimavi, 2003). Therefore, reservoirs have to be build to hold water for use during the dry seasons.

2.4.2 The Yield-Storage Capacity- Risk-Relationship

According to Alexander (1995), the yield-storage capacity-risk relationship provides neither help nor comfort to the operator of the system once the reservoir has been built. The carry-over period, (which is important) is a function of variability of flow and consequently duration of the drought as well as the degree of exploitation of the river. The length of this period is typically two to five years for many storage reservoirs. Faced with the necessity for ensuring that the reservoir does not empty during the next two to five years the obvious course of action is to restrict the supply of water as the storage level drops. The operator does not require an estimate of the probability that the reservoir will empty but a set of operating rules that will effectively prevent it from emptying whatever the future inflows may be.

2.4.3 Supply Development VS Demand Management

The basic issue to be resolved is not the determination of the economic optimum solution for the provision of a secure supply of water, but to determine both the minimum as well as the desirable supply levels; determine tolerable restriction for each group of consumers (domestic, irrigation and industrial); develop the system operating rules that will accommodate these criteria (Alexander, 1995).

2.4.4 Responses of Reservoirs to Utilisation and Management

Shahin (1995) defined a reservoir or reservoir as a storage facility used to store surplus water during high flow periods and release it for use when flow is low and does not meet demand. Reservoirs are usually designed to serve different purposes. Shahin (1995) stated the following groups: water supply (which included irrigation, domestic, industrial and mining use), flood control, generating hydropower, fishing and recreation. In Zimbabwe medium size to large reservoirs can combine water supply to irrigation schemes and towns, and recreation uses.

The water levels in a reservoir vary with the degree of abstraction that is made on it. The water level fluctuations also have an effect on spillage and hence the flows downstream. Goodman (1984) indicates that the outflow from a reservoir depends on the water level in the reservoir, hydraulic characteristics of the outlets and, the operating procedure. Since the rate of withdrawal can be decided upon and varied a dynamic (or variable) yield can be obtained from a reservoir. According to Mhizha (2000), although consumers prefer to have a long term assurance of supply they however agree to rationing when the supply sources dwindle so that they avoid having no supply at all. This rationing has to be carried out following specific operation rules. These rules should be such that the degree of rationing should be progressively increased as the stored volume reduces and progressively decreased as the stored volume gets some increases (Alexander, 1995). To come up with operation rules an analysis of reservoir conditions has to be carried out under certain inflow regimes. This has to be done following specific operating rules and policies.

According to Mhizha (2000), the operating policy is the guiding principle on what the authorities are trying to achieve through the operation of the reservoir. In Zimbabwe there has been very little if any document policy guidelines on operation of reservoirs. Most guidelines are in terms of statements made by influential people or negotiations made during development of projects. Even then these are mainly related to water allocation than to reservoir operation. A good example is Acardia reservoir in Mashonaland Central which was constructed illegally. When it was legalized a condition was made that 30% of the water was to be allocated to communal farmers. The same policy has now been applied to all the major reservoirs being constructed in the country although percentages allocated to communal areas differ for each reservoir.

The general policy guideline for water allocation and reservoir operation is to manage the water resources so that widely held public aspirations can be achieved (Mhizha, 2000). Some of these public aspirations include:

1. National economic efficiency which is high if shortages of water to various sectors of the economy is minimized.
2. Income distribution which is enhanced by distributing water resources to different and many economic groups.
3. Social impact and equity where the expectations of society on water management are that basic needs should always be catered for, for everyone.
4. Reservoir operation should always take care of environmental requirements, hence the release of mandatory minimum environmental flows for each reservoir.

2.5 Governance of Water

A study in Mwanga district in Tanzania by Mvungi et al., (2005), showed that rationing was the most famous strategy used in distributing water. Leaders made decisions on how water should be distributed, daily allocations per user and allocation according to application. Despite the existence of a water distribution mechanism, some individuals used various means to get water without following the laid down procedures especially during the dry season. This was because there was not enough water and people were not sure whether water will ever get to their fields. Due to the shortages some irrigators resort to stealing water at night and paying of bribes to water distributors. Mvungi et al. (2005), proposed solutions and one is that there is a requirement for strong leadership by water boards which ensures equitable water use, prevent non-member interference and strictly enforce by laws and deterrent fines which make stealing of water unprofitable. For the laws to be respected and hence effective it is important that they are just to all parties.

Mvungi et al. (2005), suggested that conflicts on water shortages could be mitigated by employing good governance and stakeholder participation in decision making on water issues. Good governance of water involve effecting of rationing to aid distribution of water, a transparent and systematic approach to water allocation, which also ensures that issuing of any water to one user does not deny others access. Stakeholder participation and representation at various levels of decision making are vital in policy making, hence coordination of implementation of policies. This ensures that people and their leaders emerge from the process not only understanding the policies but also their responsibilities and that of others in the implementation of the policies. If policies on water use are clear to people then transparency and accountability will reign and this will ensure efficiency in water use and distribution.

According to Swatuk (2005), the systematic approach in policy making and implementation requires considerable financial, technical and human resources capacity from policy makers, but this is not always available. Therefore, policy makers seem to content with conflict resolution structures evolved by those who need them most. On evolution of conflict resolution structures, Swatuk (2005) supports the idea that the imposition of new institutional mechanisms for water allocation at once creates new conflicts among users in rural areas and undermines historically effective methods of conflict resolution.

According to Kinnersley (1983), the agencies should always be respectful towards all laws and conventions about the right of others, not least because they will often have common interests with them, e.g. in checking scope for pollution, discourage vandalism, theft and cooperation in collection of revenue, but they have to operate in the community as virtually everyone's neighbor: this may be their best guide on how to deal with their own legal powers, rights and obligations.

2.5.1 Water Laws and Institutions in Zimbabwe

The year 1999 saw the replacement of 1976 Water Act with a new act, 1998 Water Act which had the main objectives of increasing protection of the environment, improving equity of access, and water resources management in Zimbabwe. The 1976 Water Act had a provision for a right to own private water and vested all other water in the President, so called public water. Private water was belonging to the owner of land on which it was found (Natsa, 1999).

The right to use water was dependant on the type of water in question. For primary use no right was required. However public water use was based on the prior appropriation doctrine. An appropriation right did not depend on the land ownership, but on the application of the appropriated public water to some beneficial use. The granting of the right to public use was the exclusive function of the administrative court sitting as the Water Court. The right would only be granted if public water was available and if it could be ascertained that the water would be put to beneficial use. The right granted was dependant on the date on which application for the right was made. This date determined the applicant's priority in use of the water applied for. Two types of water rights could be granted: flow rights and storage rights. A flow right gave the right to abstract from the 'normal' flow of a river. A storage right was a right to store the 'floodwater' only of a given river. The right when granted was a real right registered under the title of the property to which it related and was granted in perpetuity (Natsa, 1999).

Some of the highlights of the 1998 Water Act by Manzungu et al, (1999), are;

- The state owns all water and any use of water, except for primary purposes must be approved by the state,
- All people with an interest in the use of water should be part of the decision making and management of water,
- Water is to be managed at catchment level,
- The environment must not be jeopardized by activities linked to the use and development of water and
- Water must be taken as an economic good which ensures efficient and fair use of the water, conservation and protection of water resources.

Some of the major changes cited by Manzungu et al, (1999), are;

- The priority date system will no longer apply,
- No water will be privately owned; both surface and underground water will belong to the state,
- The distinction between normal flow, flood flow and storm water no longer apply,
- Water shortages will be better managed by shortening the process of declaring water shortage areas,
- Better management due to creation of catchment councils,
- More effective penalties will be imposed and
- Polluter pays principle will apply and the environment will be recognized as a legitimate user.

2.5.2 Competition for Water Resources in Zimbabwe

The major competing water users in Zimbabwe are the urban, industrial and mining sector and the agricultural sector, mainly the irrigation sector. Within the agricultural water sector the large scale commercial sub-sector and the small holder sub-sector are the major competitors (Ndamba et al., 2005).

The large scale commercial sub-sector has good access to water from government reservoirs apart from farm reservoirs. As a result, the commercial farmers enjoy the benefit of this long term investment and are able to minimise the effects of droughts and improve their returns through the cultivation of high value crops, such as tobacco and horticultural crops. Despite this seemingly obvious accessibility by the large scale farmers, conflict often arises with the local authorities (Ndamba et al., 2005).

2.5.3 Water Allocation

Van der Zaag (2000), defines water allocation as the function of assigning water from a given source to a certain number of users. Van der Zaag, (1999), argues that in order to use water from a catchment area, one has to have water at the right place and at the right time. In a system that is already in operation institutions need to be in place in order to manage the storage facilities, conveyance systems and delivery of water to farmers.

According to Manzungu et al., (1999), where a large number of competing users are sharing a resource conflicts are inevitable. What is important is how the conflicts are handled and resolved. It is important that stakeholders participate in the conflict resolution, but this is possible if conflict resolution is decentralised to the appropriate levels, and conflict resolution ensures sustainable development. Van der Zaag (1999) added that the institutional set-up should be in accord with what the people perceive as just and reasonable. The physical infrastructure should be conducive to implement any rule or regulation that would follow from the legal institutional arrangement.

❖ Alternatives in Water Allocation

According to Teerink (1993), water is a renewable resource, replenished by precipitation. Its occurrence in a particular region may be irregular and supplies used may be drawn at a rate exceeding the rate of replenishment. As the demand for water supply increases and shortages are created, the management of the resource is increasingly important. Effective management policies require a system for water allocation and water right administration that recognizes a private use of a public resource. Competition for a scarce resource needs to be regulated in order to achieve societal goals. The main aim of water allocation is to manage the resource so that the widely held public aspirations can be achieved. Due to societal changes and differences in emphasis and value put on water use, different countries have adopted various systems in water allocation. Some of the systems are described below.

Public (Administered) Water Allocation System

Teerink (1993) defined this as a situation where the state decides, allocates and distributes water among different users. Water is perceived as a public good. According to van der Zaag, (2000), the advantages of this system are on ensuring equity, environmental sustainability. However the weaknesses are the high likelihood of an uneconomic supply system and wastages.

Prior Appropriation System

The allocation is on a first come first served basis. Therefore during times of shortages the longest term appropriators receive their full share regardless of whether the rest have a share or not. If no water is left, then the junior appropriator receives no water at all (Huffaker et al., 2000). The major disadvantage is that there is no accommodation of new appropriators.

Tradable Water Right System

According to Binswanger and Mark (1994), this system consists of the right to consume, earn income from or sell the asset. The system involves enshrining legal ownership of the water. Water rights are treated as real ownership rights, conferring the rights of access, exclusion and alienation to the right holder. The disadvantages of this system are diminished role of government in water management and the high likelihood of rights holders hoarding water in times of scarcity in order to derive huge speculative profits.

Fractional Allocation System

It is defined as the system where a user has a proportional share or percentage of the water available and this is independent of the amount available (Natsa, (1999). The system can be practised with both flow and storage rights. In the case of flow rights the right can be divided proportionally in continuous flow or rotated in turn. Where the flow in the system is rotated each user has a fixed amount of time for abstraction from the watercourse. This flow need not be measured where the flow is constant. However where the flow is highly variable it becomes necessary to measure the flow and adjust the time of abstraction that ensure that the volume for different turns corresponds with equality.

Advantages of the proportional allocation

- The system is very robust and can work in a wide range of socio-economic contexts. It provides a basis for mobilizing local resources needed for system operation, (Natsa, 1999),
- It can ensure equity, is simplistic and predictable,
- In principle it can cater for ecology as a share is simply allocated to the environment, (van der Zaag, 1999) and
- Fractional allocation ensures efficient allocation among users during shortages in a system where all users are alike.

A disadvantage of the proportional allocation is that when users are not alike water sensitive users can incur excessive losses in times of shortages (Natsa, 1999).

It should also be noted that it is possible to create different degrees of reliability by acquiring more shares, and in a fractional allocation system rights are homogenous thus it is easier to establish water markets. These two factors may have disadvantages and advantages in the water allocation system.

Capacity Sharing

According to Natsa (1999), when the system of fractional allocation is practiced in a combination of flow and storage rights the resultant system can be referred to as capacity sharing. According to Dudley (1990), the essentials of capacity sharing are that each user gets a percentage share in reservoir capacity (not contents) and inflows into that reservoir. Thus each user can be said to own their own little stream and reservoir. It is important to clarify that each user is only entitled to the water in their share of the reservoir. The percentage share of reservoir capacity and inflow contents need not be the same as much as the shares among users (Dudley and Musgrave, 1988).

Central to the operation of a scheme of capacity sharing is the maintenance of proper up to date records of the water transactions of each user. Detailed daily records are required for each user's deposits and withdrawals as used in any banking system using commonly agreed procedures to ensure transparency and equity (Natsa, 1999).

❖ Some International Experiences with Fractional Allocation

There are some experiences with the system of fractional allocation which are found all over the world. Some examples are the Galeria system in Purisima3 and the Izucar East Gravity system in Mexico. The Galeria system was a privately owned 240 ha by 75 shareholders systems. Financial capital was provided by owners who manage the water supply systems. Each shareholder was entitled to an irrigation turn equal to his share in the system. The system of shares is also rigidly applied in collecting fees for maintenance and investments. The Galeria system has been a success. Izucar East Gravity system is communally owned irrigation scheme of some 550 ha and 500 users. When flow decreases all farmers get correspondingly less water during the same time length, irrigation turn and at the same intervals for the whole season. When flow decreases all farmers get correspondingly less water during the same length irrigation turn and at the same intervals for the whole season (Natsa, 1999). The success of the two systems was hinged on the ability to periodically determine the amount of water available and allocate it proportionally, and abiding by standing operational and distribution policies.

❖ Experiences with Fractional Allocation in Zimbabwe

The Lower Mazowe Canal in Zimbabwe, Natsa (1999)

The canal is located in Middle Mazowe. This was a government owned structure that stretched for about 13 km serving seven commercial farms and a government crop research station. The canal had its off-take from Mazowe River and flows through the respective users' properties. The Mazowe catchment river board provided water management services. Users submitted their daily water requirements to the canal water bailiff who adjusted the balancing weir accordingly at the Mazowe rive off-take. Siphons were used to abstract directly from the canal into small earth reservoirs close to the canal. Pumps were installed into the small earth reservoirs.

All users were metered at strategic points along the canal. Therefore all users had to submit verifiable records of abstraction and receive a monthly water account. In times of shortage the water available was shared fractionally among the users to ensure equity of access. Each user was allocated an amount corresponding to a fraction equaling their normal sub-right over total canal right of the available flow during the time of shortage.

A farmer was contracted to do the canal maintenance work and the cost of the work was deducted from the farmer's water fees. Conflicts on water abstraction were resolved by the water bailiff, failure of which the case was taken up to the Mazowe River Board which would institute litigation which the offender was obliged to pay for. The water charges were levied on the amount of water righted per year and not what was actually used.

Contracting a responsible user of the system, keeping of records made sure the system continue to operate. Levying of farmers on fixed amounts without considering consumption could cause over abstraction, cheating or increase some unwillingness to pay among users.

Mwenje reservoir (Natsa, 1999)

Mwenje reservoir was constructed by the government of Zimbabwe. The reservoir was used to supply water to urban, industrial, mining, and agricultural users through a system of agreement or ministerial water, a system used on all government owned reservoirs.

Agreements could be either permanent or provisional in terms of duration of the agreement.

Water management was centralised. Originally the reservoir was operated on 4% risk of failure for urban, industry and mining and 10% for agriculture. However agricultural consumers in 1988 requested that their allocations be operated at 20% from 10% risk of failure. This had the effect of increasing the water available for agricultural allocation though at increased chances of failure. Agriculture users were allocated the balance of water available for allocation in the reservoir for the particular year irrespective of their actual demands or agreements. The allocation to agriculture users was not necessarily decreasing all the time as temporary agreements lapse and were not renewed at times thus freeing up more water for allocation to the agriculture users. The success of the prior year rainy season was also crucial in determining the allocation to agriculture users. Water unused from the urban, industrial, mining allocation could also be allocated to the agriculture users.

Thus all agricultural users shared the remaining water available fractionally or proportionally at a uniform rate to accommodate all agricultural agreements. Evaporation losses were shared out in proportion to the users' agreement water in the reservoir to total reservoir contents every month. A user was charged that part of his/her agreement that is lost to evaporation.

It was a policy that as much as possible urban, industrial and mining consumers are not rationed based on political and economic reasons. The Mazowe Valley Catchment River Board on behalf of the government did the day to day management as long as all the water users concerned did not feel prejudiced. Thus as in any over committed sub-catchment, in the Mazowe Catchment comprehensive record keeping was done by the river board due to the intense competition for the resource. Approved measuring structures were in place at all strategic points. Detailed records existed for all reservoir reconciliations done on a monthly basis.

Up to date determination of water available and a flexible allocation system was important to the operation of the Mwenje reservoir. Communication to all users who were affected by shortages and the equitable reduction of water supply due to the shortages reduced chances of conflict, but close monitoring and accurate measurement of water abstracted records keeping were equally important.

CHAPTER 3

3.0 DESCRIPTION OF STUDY AREA

This chapter presents the location, physiographical description, water resources and management system and issues arising in the study area. It has maps and sketch of the study area showing the rivers, reservoirs farms and canals.

3.1 The Location of Study Area

The study area is the Safari-Igava irrigated farming area, located in the Macheke sub-catchment of the Save catchment. Access from Marondera Town is by the Ruzawi Road and Igava Road. Safari reservoir, the main reservoir of the irrigated farming area is located on Wenimbi River about 20 km south east of Marondera Town.

3.2 Physiography

The altitude of the catchment ranges from 1400 to 1600m above sea level. The vegetation cover is predominantly combination of savanna woodlands and grasslands. The soils are predominantly sandy loams derived from granite rock formations. The terrain varies from mountain ranges and undulating low lying areas. Rivers draining through the area are Wenimbi River, a tributary of Ruzawi River that drains into Macheke and then Save River. Therefore administration of water affairs falls under the Save Catchment. Zimbabwe is divided into seven hydrological catchments. The catchments are subdivided into sub catchments shown in figure 3.1. The study area falls under the Macheke sub catchment. Figure 3.2 shows the farm boundaries and canal map layers overlaid on a google earth photograph from which maps of Ruzawi and Wenimbi Rivers were digitized.

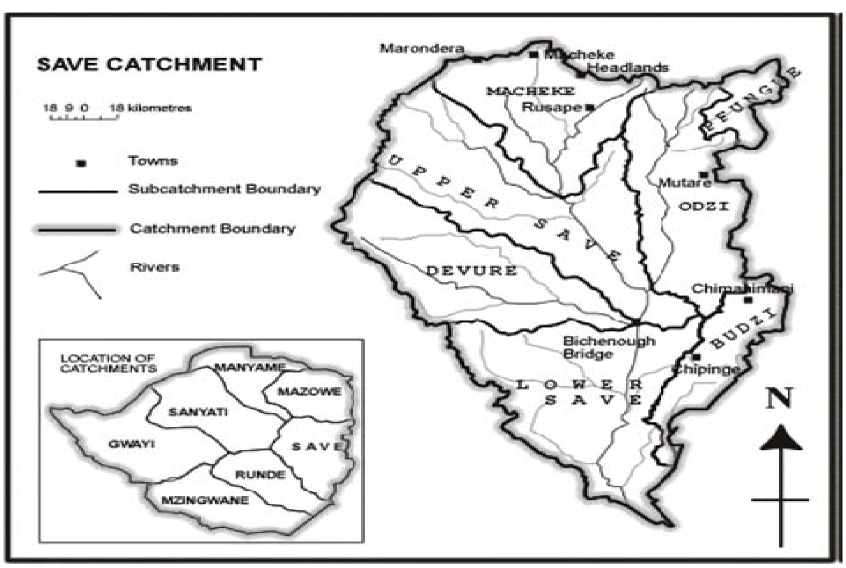

Figure 3-1: Map of Catchments of Zimbabwe and Sub-Catchments of Save

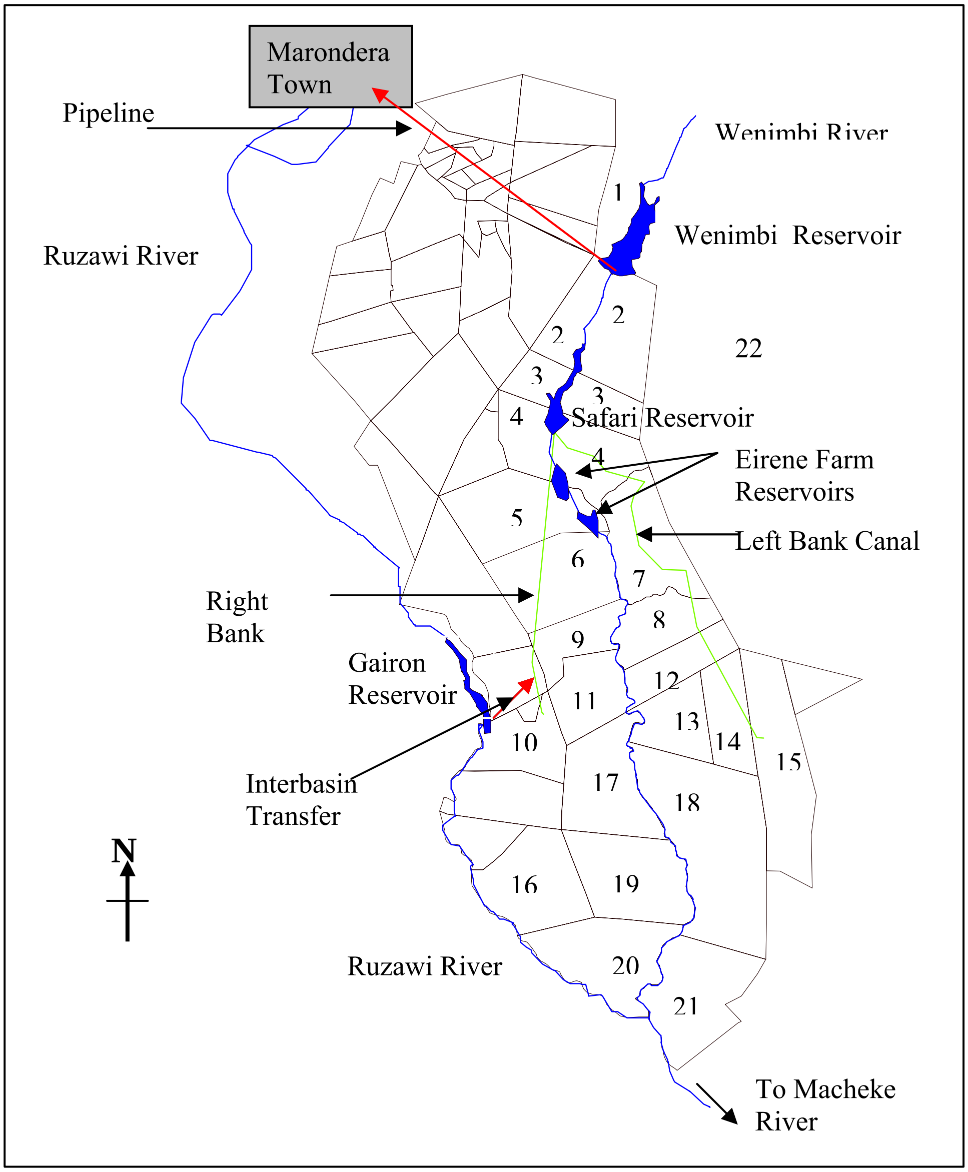

Figure 3-2: Map of Safari-Igava Area

Appendix 1 has the details of the farms number 1 to 20 which abstract water from Wenimbi River. Farm number 21 gets water from Ruzawi River.

3.3 Water Resources of the Study Area

3.3.1 Hydrology

The area receives a mean of rainfall of 880mm with a coefficient of variation of 0.9. Average evaporation is 1650 mm per year (Meteorology Department, 2009). Table 3.1 below shows the catchment area, Mean Annual Runoff (MAR) and coefficient of variation. Most of the Safari-Igava farming area can be classified as semi-arid and the rainfall erratic. Like most rivers in Zimbabwe, flow is mainly during the rainy season, (Mazvimavi, 2003).

3.3.2 The Water Demand Situation

For the past 3 years, farmers in the Safari-Igava area were irrigating a total of 500 hectares which requires $6*10^6$ m^3 per annum as per ZINWA allocations of $12*10^3$ m^3 per hectare per year. Most of the irrigation is by means of the Safari canal system. Four pumping units for sprinkler irrigation systems are located on the Wenimbi River. Currently farmers using the LBC are not abstracting water from Gairon reservoir, although underground pipelines connecting the Gairon reservoir to the canal are in place on Igava farm. Permit number 14384 for Igava farm gave the water allocation of 0.3 x 10^6 m^3 per year from Gairon reservoir. Since Gairon reservoir was gazetted as government dams in the year 2006, the permit system has been substituted by an agreement system.

Currently Marondera Town is drawing water from the Mazowe catchment; Nyambuya and Kushinga-Pikelela reservoirs at $3.5*10^6$ m^3 per annum. Wenimbi water supply ($4.2*10^6$ m^3/year at 4% risk) currently under construction will augment the existing supply system (ZINWA, 1996).

3.3.3 Water Development

- Surface Water

To improve water supply in the Safari-Igava area, 5 reservoirs were constructed. On Wenimbi River, Wenimbi reservoir is upstream of Safari reservoir, and Eirene farm reservoirs 1&2 are downstream. Gairon reservoir is located on Ruzawi River. Figure 3.2 shows the details of the surface water resources in the Safari-Igava area.

Safari reservoir, the main reservoir that supplies the irrigated farming community has two concrete lined canal systems located on either sides of the riparian land of Wenimbi River. Interbasin transfer of water from Gairon reservoir, on Ruzawi River, into the right bank canal was done through pumping. Wenimbi reservoir, built upstream of Safari reservoir, was completed in 2004, for urban water supply, specifically to Marondera Town, riparian and downstream farmers. Wenimbi reservoir is not more than 5 km upstream of the throw back of Safari reservoir. Reservoirs upstream of Wenimbi reservoir owned by government have a total storage of 5.4 x 10^6 m^3 (Government Gazzete, 2006). Table 3.1 summaries the available water resources in the Safari-Igava area.

Table 3.1: Hydrological Properties of the Study Area

Reservoir Name	Wenimbi reservoir	Safari reservoir	Eirene farm reservoir 1	Eirene farm reservoir 2	Gairon reservoir

River	Wenimbi	Wenimbi	Wenimbi	Wenimbi	Ruzawi
Storage right priority (1976 Water Act)	6/4/93	2/4/91	24/4/90	3/1/90	
Storage(1000 m^3)	21 268	10 400	2 300	500	6 200
Net Storage (1000 m^3)	17 468	9 360	2 170	450	5 680
Catchment Area ($10^6 m^2$)	131.45	203.43	216.31	227	7 500
Intermediate Catchment Area ($10^6 m^2$)	131.45	71.95	12.88	10.69	7 500
MAR (1000 m^3)	140	140	140	140	140
CV	0.9	0.9	0.9	0.9	0.9

(Source: Luxemburg, 1996).

❖ Ground Water

The lithology of the area is predominantly of granite rock formations and the yield of aquifers is expected to be low, (Mazvimavi, 2003). There are no known significantly high yielding aquifers that can supply extensive irrigation projects in the Safari-Igava area, (DDF, 2009).

3.3.4 Water Management System

❖ The Legal System and Institutional Arrangements

The Zimbabwe Water Act of 1998 sets the rules for governance and management of water affairs in the Wenimbi River basin. As per government gazette of 26 January 2006, all the reservoirs under consideration in this study are owned by ZINWA. The state owns all water and any use of water, except for primary purposes must be approved by the state, therefore there is no private ownership of water and access to water other than for primary purposes is after obtaining a permit or an agreement with ZINWA. Before the government gazette of the year 2006, only water in Wenimbi reservoir was allocated by ZINWA as agreement water, but the other reservoirs' allocation used the permit system. The permits were allocated by the Save Catchment Council after an application has been made and submitted to the MSCC. The Water Act states that the transfer of land ownership also transfers the water permits to the new owner. Before the land reform water permits were allocated to a farm/ property; therefore allocations per farm were not changed after the land reform, until the government gazette of 2006.

The Water Act of 1998 also stipulates that;

- All people with an interest in the use of water should be part of the decision making and management of water and
- Water is to be managed at catchment level. Water must be taken as an economic good which ensures efficient and fair use of the water, conservation and protection of water resources.

It was expected that water shortages will be better managed by shortening the process of declaring water shortage areas and creation of catchment councils would bring better management of water resources, (Manzungu, 1999).

❖ The Reservoir Operational Management

- Wenimbi reservoir

Wenimbi reservoir was constructed by the government of Zimbabwe, mainly to supply water to Marondera Town. According to the Zimbabwe Water Act of 1998, the water belongs to the state but under the custodian of ZINWA which is responsible for management, operation and maintenance of the reservoir. Users of water enter into an agreement with ZINWA; hence users get agreement water after an application and signing an agreement with ZINWA.

- Safari, Eirene farm reservoirs 1&2 and Gairon reservoir

The government gazette of January 2006 states that ZINWA owns these reservoirs. Management of operation of the four reservoirs is under the sub-catchment council on behalf of ZINWA. The management involves repair and maintenance work, and regulation of release of water. Currently the Safari reservoir, Eirene 1 reservoirs and Eirene 2 reservoirs are operated and maintained by the Macheke sub-catchment council and the farmers. ZINWA is responsible for management of water in the four reservoirs but on the ground the MSCC is operating the other four reservoirs on behalf of ZINWA and allocations used in the permit system before the year 2006 have not been changed.

According to Luxemburg (1996), at the design stage, it was agreed that Wenimbi reservoir had an obligation to pass water to make up for the shortages in downstream reservoirs, notably Safari, Eirene 1 and Eirene 2 reservoir. There was enough water in the system to satisfy demand if everyone complies with their requirement to pass normal flow.

Currently, water release from Safari, Gairon, Eirene farm reservoir 1 and Eirene farm reservoir 2 is controlled by the Macheke Sub Catchment Council (MSCC). The MSCC charges a sub-catchment levy which is proportional to the quantity of water allocated and the levy is used for operation and maintenance of infrastructure. Also, ZINWA charges a water levy to all permit holders. From Wenimbi reservoir farmers pay for the water which is sold as agreement water. In the event that reservoirs downstream of Weninbi reservoir run out of water the MSCC and farmers' committee negotiate with ZINWA for the amount of agreement water required before payments are made to ZINWA's Save Catchment.

The MSCC monitor abstraction and use on the canals and the river. Farmers are allowed to pump from the canals at designated points (sumps). Before the land reform sluice gates were used as control structures. Flumes and 'v' notches were used for measuring flow at each abstraction point. Currently these measurement structures are not in use and some are in a state of disrepair.

Flood irrigation by blocking the canal is an offence. Breaking into the canal to build a diversion is an offence unless an application is made to the MSCC and permission is granted. Only users with paid up permits are allowed to access water for productive use.

There are no fixed rules for rationing water on the 5 reservoirs. Rationing policies are applied when the shortages arise and to suit the prevailing situation. Flood water is captured in reservoirs upstream and released as spillage. Downstream reservoirs receive flow if upstream reservoirs spill and/or the utility (MSCC and/or ZINWA) releases normal flow; 10% of mean annual runoff (MAR) or when users downstream pay and order for water.

- ❖ Water Allocation

Farmers have to get agreement water from Wenimbi reservoir, except for an irrigation scheme for communal farmers in the Masikana communal land of Chief Svosve area who are entitled to water for irrigating 150 ha per year ($1.8*10^6$ m^3/year) at 10% risk. The irrigation scheme is yet to be constructed and allocation of plots has not been done. Marondera Town water supply has been allocated $4.2*10^6$ m^3 per year at 4% risk. Water from Safari, Gairon and Eirene farm reservoirs was allocated as shown in Appendix 15.

- ❖ Operating Rules for Irrigators

Every farm has a fraction of water allocated to it from the normal flow and the storage reservoirs. The basis for allocation of water is the water rights the farms had before the Water Act of 1998 which was based on contribution to construction of reservoirs (for storage rights only) and the priority date system. Resettled individual farmers applied and were allocated individual permits which they pay for annually. The total amount of water allocated should not be above the permitted amount of the farm. Irrigation requirements were factored at 12 000 m^3 per hectare per year. The quantity of water allocated by a permit on each farm was subdivided among the new farmers so that the total amount of water allocated per farm remained constant.

Farmers with access to both the river and canal could abstract from the two sources at the same time. In case of a shortage of water in the Safari and Eirene farm reservoirs the sub-catchment council and the farmers committee applied and paid for release of agreement water from Wenimbi reservoir. To date, they were getting up to $6*10^6$ m^3 per year from Wenimbi reservoir since 2007.

- ❖ Problems in Safari-Igava Irrigated Area

In the year 2000, the land ownership changed, and this increased the number of farmers from 20 large scale farmers to over 600 plot holders. Farmers on the canal system have been requesting for water releases from Wenimbi dam every year since 2005 after depletion of storage in Safari Dam.

Access is reliable for upstream farmers on both canals, right bank canal (RBC) and left bank canal (LBC). Tail end farmers face shortages during periods of high demand, like prolonged dry spells during the summer season and the dry winter season. Some tail end irrigators are failing to plant especially during the dry season. Farmers pumping directly from the river do not experience shortage problems (AREX, 2005).

3.4 Issues Arising

The land reform of the year 2000 has resulted in the increase of 600 farmers on an irrigation system that was designed for 20 large scale farms. The new farmers have different plot sizes, ranging from 6 ha for A1 to over 20 ha for A2 farmers. Appendix 1 has the details of the farms. The new farmers have new crops and irrigation scheduling practices, which means new water demand characteristics. These changes have brought more competition and shortages. Shortages have resulted in conflicts among farmers (upstream and downstream), and between ZINWA and the farmers (AREX, 2005). The problem might escalate when Marondera starts abstracting water from Wenimbi reservoir; therefore careful operation of the reservoirs becomes crucial for equitable distribution and management of water resources.

This research sought to establish the capacity of available water resources, productive water use levels, allocations and underlying causes of shortages and conflict. This information is vital for developing a simulation model as a water management tool that can be used to analyse reservoir operation strategies. The analysis by the simulation model was vital for establishing efficiency and equity on water allocation and timely reservoir water release for minimizing shortages and conflicts. This also enhances water supply security, good planning by both farmers and ZINWA and hence optimisation of productive water use.

CHAPTER 4

4.0 METHODS

This chapter presents various research methods which were used to collect data, the type of data collected, how it was processed or treated. It also explains the development and components of the Computer model, the scenarios that are used to test the model and analyse reservoirs operation under the different water demand scenarios. The chapter starts by giving the data collected.

4.1 Data Collection

Data was collected from the water utility, government departments, farmers and allied institutions. Recorded data and information was collected from various organizations and the field. The data was processed through desk and field studies and analytical techniques.

4.1.1 Desk Study

The data was collected, processed and analysed as part of the desk study. The tables 4.1 and 4.2 show quantitative and qualitative data collected respectively.

Table 4.1: Quantitative Data Collected

Data Type	Organisation	Information collected	Record length	Reference
Historical	ZINWA, MSCC, Farmers	Water permits and/or water rights	40 years	Appendix 15
Design	ZINWA,MSCC	reservoirs capacities	15 years	Table 3.1
Time series	ZINWA	Reservoir releases, inflow	3 years	Appendix 10
Historical	MSCC	Water permits and water rights	40 years	Appendix 14
Time series	Meteorology Department	Climate data and information	40 years	Appendix 5 &7
Historical	Ministry of Lands, AREX	Resettlement data,	9 years	Appendix 11
Developmental and Agricultural	Department of Irrigation	Irrigation infrastructure and coverage.	9 years	Appendix 11

Table 4.2: Qualitative Data Collected

Data Type	Organisation	Information collected	Record length	Reference
Historical	AREX, farmers' committee	Irrigated crops and summer crops data	3 years	Appendix 11
Geographical and historical	Ministry of Lands, DDF	Resettlement plans and maps	9 years	Figure 3.2
Agricultural and Historical	Farmers and farmers' committee	Crops, irrigation and farming practices, plans, history of farming operations and opinions.	9 years	Table 5.3
Policy	ZINWA, MSCC, Farmers	management practices and schedules, rules and regulations	9 years	Table 5.3
Geographic	U.Z. Geography Department	Data from Digital elevation model of study area	1 year	Appendix 8

4.1.2 Water Inflow

Water inflow into Wenimbi reservoir was recorded by a gauging station E188, located upstream of the reservoir and out flow was recorded by gauging station E187, located downstream of the reservoir. The water out flow from the Wenimbi River before the confluence with Ruzawi River is recorded by gauge station E47 located at Idapi farm. Daily and monthly water flow data was converted to weekly data for use in the computer model and are shown in Appendix 10.

4.1.3 Rainfall Data

The monthly total rainfall of 40 years obtained from the meteorology department was arranged into hydrological years and total annual rainfall was calculated for each year. The total annual rainfall was ranked in increasing order and the probability of non-exceedence was calculated using the Weibull formula;

$F(Q) = i/(N+1$

Where

$F(Q)$ = Non-exceedence probability
i = Rank (1,2,3,…., N)
N = Total number of data points.

4.1.4 Questionnaire

An unstructured questionnaire was used to obtain general information on cropping practices of the farmer. The other information sought was for establishing the perception of farmers about the service of the utility supplying them with water. A questionnaire was also used on ZINWA and MSCC to get information on the day to day operations, challenges they are facing and management practices in the Wenimbi River basin in particular, Macheke sub catchment and the Save catchment.

❖ General Information

An unstructured questionnaire survey and data collection from farmers and ZINWA and MSCC employees was done in order to get the following information;

- types of crops,
- the crop yield,
- area they irrigate,
- scheduling methods,
- water allocation,
- expansion plans,
- future crops,
- alterative sources of water they wish to invest in,
- farmers' willingness and ability to pay for water.

❖ Efficiency and Effectiveness of the System to Allocate Water to Irrigators in the Igava Area

Also, unstructured questionnaire survey and data collection from farmers and ZINWA and MSCC employees was done in order to get to find out if the water allocation system is efficient and effective. The following information was asked for;

1. If the system was able to provide mechanisms by which farmers can be able to estimate the amount of water they are entitled to in a given year, i.e. whether they can judge beforehand how much water they can count on, and therefore adapt their farming and irrigation strategy to different seasonal situation. The water permit should be clear enough and the permit holders fully understand the contents of their permits, their rights within the system and the powers of the water apportioning authority that administer the permit,

2. If the apportioning authorities are able to monitor adequately with efficiency and transparency the water availability, water abstraction and use. This is important for farmers to trust data and decisions taken by the authority (Ndamba, et al., 2005),

3. If farmers were comfortable and willing to pay for water charges and how quick ZINWA was in responding to requests for release of agreement water after payments and requests have been done and

4. The level of participation of irrigators in decision-making in terms of water resources management.

4.1.5 Field Study

Data collected from the field was by means of a topographic surveys, canal dimensions measurements on water flow rate and depth in the canal.

❖ Topographic Survey and Measurements

A topographic survey of the two canals was done using GPS equipment. Ilwis and Arcview GIS computer programmes were used in the processing of survey data into maps. Google earth was used to take a photograph of the area, which was georeferenced and transformation of coordinates from geographic to Universal Transverse Mercator (UTM) coordinates was done. Rivers and reservoirs were digitized from the photograph after transformation. Figure 3.2 shows overlaid map layers of farm boundaries, canals, rivers and canals.

A map of the canal was produced using the GIS and was overlaid on a digital elevation model (DEM) map. The DEM map was then used in determining the difference in elevation and distance between canal inlet, points along the canal and outlet ends. An average canal slope was calculated using the formula;

Slope (S) = elevation difference between canal inlet and outlet / distance between inlet and outlet.

The sumps and reservoirs fed by the canal along the canal are fed by means of diversion structures, fitted with sluice gates for flow measurement and control of diverted flows. Their impact on average velocity was assumed to be negligible.

Using the canal dimensions (cross-sectional area) and the slope the maximum possible flow rate was determined using the formula;

$Q = AV$……………………………………………………………………………Equation 4.1

Where

Q is the flow rate (m^3/s)

$A = ½ (W_t + W_b) * D$…………………………………………………………Equation 4.2

Where

A = Area of trapezoidal canal cross-section (m^2)

W_t is average top width (m) of the canal

W_b is average bottom width (m) of the canal

D is the depth of the canal (m) less $(D \text{ in cm})^{0.5}$ for freeboard (Savva and Frenken, 2000)

V is the velocity (in m/s) obtained using Manning's formula

Where

$V = 1/n * (R^{2/3} * S^{1/2}$…………………......................................………………..Equation 4.3

Where

S is the slope (No Units)

N is the Manning's roughness coefficient for concrete lined canals.

R is the hydraulic radius (m) and

R= A/ P

Where

P is wetted perimeter (m)

Time (s) it takes for tail end farmers to get water after release at inlet

T = V/ L……………………………………………………………….…….Equation 4.4

Where

T is the time (s) and

L is the length of the canal (m).

Appendix 8 has the processed data of the flow rate and time. The average capacity of the canals were determined in order to find out the optimum area the canal could irrigate per unit time and check if this could cope with the farmers irrigated area in each season. The calculated average time of travel of water from the dam outlet to the canal tail end was used to check if it caused any significant time lag between water release and access for tail end farmers.

The topographic survey data could not be used to calculate elevation differences because the GPS equipment was inaccurate in determining elevation, an inherent disadvantage of the GPS equipment, but it is very accurate in determining coordinates. Therefore the surveyed map was overlaid on the digital elevation model in order to get elevation on points of interest the canals.

❖ Transmission Losses in the Canal

Canal transmission losses were determined by taking water depth at flume and separation distance along the canal and these were used to calculate water losses. Measurements on canal dimensions using a tape measure and flow rates using readings on inbuilt flumes, sluice gates were recorded. Water depths were taken at each flume and sluice gates and rating tables was used to convert levels to flow rates. The conveyance efficiency was determined using three successive flumes spaced over 4 km apart. Calculation of loss per unit length of canal was obtained using the formula;

Loss of water (Depth) = {Water depth at Flume (n) – Water depth at Flume (n+1) level}/ (canal length between flumes n and n+1)……………………………………………..Equation 4.5

It was only possible to determine the transmission loss of the right bank canal (RBC) because it was the only canal with flowing water, hence the losses obtained were assumed to be the same as that of the left bank canal (LBC). The naming of the canal was done facing the flow direction of the river therefore the canal to the right was named as the right bank canal (RBC). The canal was less than half of depth full; therefore the value of transmission loss obtained may change when the canal is full. Also, the value was determined during the rain season therefore it may change in the dry season. Transmission losses on the river were not determined because a 10% of MAR is released as normal flow.

4.2 Analytical Techniques

Analytical techniques used were for determining water demand, estimation of flow in ungauged streams, the development and use of the Computer model in analysis of operation of the reservoirs.

4.2.1 Water Demand

The main water demands in the Wenimbi basin are urban water supply, productive water use and environmental water demand. The environmental demand was estimated to 10% of MAR.

❖ Urban Raw Water Demand

Raw water demand by Marondera Town was obtained from records and design data for Wenimbi reservoir and pipeline provided by ZINWA Mazowe catchment. The data provided is shown in Appendix 2 and Appendix 1 respectively. The data from 1992 to 2002 was plotted on a graph with quantity of raw water (abstracted per year) against time (years). The most fitting trendline was obtained and a forecast was done by means of a trendline extension to the year 2020.

❖ Productive Water Demand

The area and crops under irrigation were used to determine the irrigation water requirements. The data on type of irrigation system, area and crops were obtained from DOI and AREX. The data on irrigated area was plotted against time and the most fitting trendline was extended in order to forecast the future water demand. Irrigation water requirements per week for the main crops (maize and wheat) were converted to weekly water demanded by the productive water users.

Calculation of Irrigation Water Requirements

Crop water requirements were determined using the cropwat model and these were used to calculate irrigation water requirements. Since there were no records on individual irrigator’s abstractions the cropwat model was used to determine water use by farmers.

Input data into the model obtained from the meteorology department were wind speed, relative humidity, sunshine hours as in Appendix 13. The cropwat model calculates the reference evapotranspiration ETo (mm) using the modified Penman-Monteith method. Comparison of measured class A pan evaporation ETo (Meteorology Department, 2009) and the modified Penman-Monteith derived ETo was done as a data quality analysis. Crop evapotranspiration, also called crop water requirements was calculated as follows;

ETc = Kc * ETo ……………………………….……………………..…………..Equation 4.6

Where

ETc is the crop water requirements (CWR) (mm)

Kc is the crop factor which was determined by the cropwat model for each crop growth stage (no units).

Net irrigation water requirements (Net IWR) are calculated as follows;

Net IWR = ETc – Pe ....Equation 4.7

Where

Pe is effective rainfall (mm)

Where

Pe = 0.5 * Total P -5, (P < 50 mm)

Pe = 0.7* Total P – 15 (P > 50 mm)

Where

P is precipitation measured at the weather station (mm).

Weekly irrigation requirements were determined for the maize and wheat crops as shown in Appendix 16. An irrigation efficiency of 75% (was assumed for sprinkler systems). Data on area under irrigation was obtained from DOI and AREX and is shown in Appendix 11.The formula used to obtain irrigation water demand was:

Gross IWR = Net IWR * A / 0.75 / (1-Transmission Loss)……………….……Equation 4.8

Where

Gross IWR is gross irrigation water requirements (m)

Net IWR is the net crop water requirements per hectare (m)

A is the area under the given crop (m^2)

Transmission loss is a ratio of water lost in conduit to water released at source (no units).

4.2.2 Estimation of Flow in Ungauged Streams

For ungauged streams that flow into Safari and Eirene farm reservoirs, the similar catchments method was used, on the basis of inflow at gauging station E188 on Wenimbi

River, upstream of Wenimbi reservoir. The runoff per unit catchment area was multiplied by the catchment area of the streams as in the formula;

$Q_u = Q / A * A_u$………………………………………………………...Equation 4.9

Where

Q_u is the runoff in ungauged catchment (m^3/year)
Q is the runoff measured at a gauging station (m^3/year)
A is the catchment area of gauged catchment (m^2)
A_u is the catchment area of ungauged catchment (m^2)

This method was used because the catchments have similar land uses, soils and topography, and there are storage reservoirs in use by farmers upstream of the reservoirs. The formula by Mazvimavi, (2003), does not take into account the effect of upstream reservoir storage changes over time, hence it was considered unsuitable.

4.3 The Computer Model in the Waflex Package

The computer model in the Waflex package was developed on the basis of the water mass balance equation. For each weekly time step;

$R = Sp + E + Yd$ ………......................................…………………………………Equation 4.10

Where

R is comprised of runoff flowing into the system, precipitation and ground water contribution into the system (m^3/week),
Yd is the total of abstractions per week (m^3/week),
E is the evaporation (m^3/week) and
Sp is the spillage and ground water contribution out off the system (m^3/week).

The flow diagram for the Wenimbi basin reservoirs (Wenimbi, Safari reservoirs, Eirene farm reservoir 1&2) structure as in the spreadsheet is in Figure 4.1.

Figure 4-1: Wenimbi River and Multi Reservoir Supply System

❖ Wenimbi Reservoir Storage Calculation for Each Time Step

The time step was a period of one week, therefore water volumes are in m^3/week, therefore for a reservoir like Wenimbi Reservoir the water balance equation for each week is;

$Stor\_Wen_1 = Inflow1_1+P_1–E_1–Rel\_Wen_1+(GW\_in_1–GW\_out_1)+InflowTR_1$…….. Time Step 1

$Stor\_Wen_2 = Inflow1_2+P_2–E_2–Rel\_Wen_2+(GW\_in_2–GW\_out_2)+InflowTR_2$…….. Time Step 2

.
.
.

$Stor\_Wen_n = Inflow1_n+P_n– E_n–Rel\_Wen_n+(GW\_in_n–GW\_out_n)+InflowTR_n$……..Time Step n

Where;

$Stor\_Wen_n$ = the storage of Wenimbi reservoir after time step n.

$Inflow1_n$ = the runoff into the reservoir for each time step measured by gauging station E188 for each time step n.

Rel_Wen_n = outflow as spillage (when full) + outlet releases and abstractions by users on reservoirs riparian land for time step n.

E_n = evaporation from the reservoir storage for time step n.

P_n = precipitation over the reservoir surface for time step n.

GW_in_n = ground water contribution into the reservoir from the riparian land for time step n.

GW_out_n = seepage ground water out of the reservoir from the riparian land for time step n.

$InflowTR_n$ = runoff from the riparian land and tributaries into the reservoir for time step n.

Evaporation and precipitation was input into the equation as a depth.
Therefore volume of water gained = $(P_n– E_n)* A\_Wen_{n-1}$ for time step n.
Where;

A_Wen_{n-1} is area of surface area of Safari reservoir at previous time step (n-1)

The ground water net contribution to the reservoir storage was assumed to zero, that is $GW\_in_n = GW\_out_n$

❖ Safari Reservoir Storage Calculation for Each Time Step

The time step was a period of one week, therefore water volumes are in m^3/week, therefore water balance equation for each week is;

$Stor\_Saf_1 = Inflow1_1+P_1-E_1-Rel\_Saf_1+(GW\_in_1-GW\_out_1)+InflowTR_1$….. Time Step 1
$Stor\_Saf_2 = Inflow1_2+P_2-E_2-Rel\_Saf_2+(GW\_in_2-GW\_out_2)+InflowTR_2$….. Time Step 2

. .
. .
. .

$Stor\_Saf_n = Inflow1_n+P_n- E_n-Rel\_Saf_n+ (GW\_in_n-GW\_out_n)+InflowTR_n$….. Time Step n

Where;

$Stor\_Saf_n$ = the storage of Safari reservoir after time step n

$Inflow1_n$ = the runoff into the reservoir for each time step measured by gauging station E187 just down stream of Wenimbi dam less abstractions along the river between Wenimbi reservoir outlet and Wenimbi River inlet into Safari reservoir for time step n.

Rel_Saf_n = outflow as spillage (when full) + outlet releases and abstractions by users on reservoirs riparian land for time step n

E_n = evaporation from the reservoir storage for time step n.

P_n = precipitation over the reservoir surface for time step n.

GW_in_n = ground water contribution into the reservoir from the riparian land for time step n.

GW_out_n = seepage ground water out of the reservoir from the riparian land for time step n.

$InflowTR_n$ = runoff from the Masikana communal tributary and left bank riparian land of the reservoir for time step n.

Inflow2 = runoff from the Alexandra farm tributary and left bank riparian land of the reservoir for time step n.

Evaporation and precipitation was input into the equation as a depth.
Therefore volume of water gained = $(P_n- E_n)* A\_Saf_{n-1}$ for time step (n)
Where;

A_Saf_{n-1} is area of surface area of Safari reservoir at previous time step (n-1)

The ground water net contribution to the reservoir storage was assumed to zero, that is $GW\_in_n = GW\_out_n$

❖ Eirene Farm Reservoir Storage Calculation for Each Time Step

The methods for the Eirene farm reservoirs were similar to the method used for Safari reservoir.

❖ Water Supply

Water inflow into the system from tributaries and Wenimbi River is added to the storage and water supply to users is subtracted from the releases from reservoirs. Interbasin transfer from Gairon reservoir (from Ruzawi River) was added into the RBC system as inflow4. Flow diagram in Figure 4.1 has the details. The time step was a period of one week, therefore water volumes are in m^3/week. Therefore the RBC water demand when there is interbasin transfer is calculated as;

$Use4_1 = Use4a_1 – Inflow4_1$ ……. Time Step 1
$Use4_2 = Use4a_2 – Inflow4_2$ ……. Time Step 2
. .
. .
. .
$Use4_n = Use4a_n – Inflow4_n$ ……. Time Step n

Where
$Use4_n$ is the RBC demand for time step n.
$Use4a_n$ is the gross irrigation water requirements for time step n.
$Inflow4_n$ is the water transferred from Ruzawi River for time step n.

At an abstraction point e.g. for Marondera Town (MarTwn), Use1, the water mass balance equation used is;

$Outflow_1 = Inflow_1 - Use1_1$ ……… Time Step 1
$Outflow_2 = Inflow_2 - Use2_2$ ……… Time Step 2
. .
. .
. .
$Outflow_n = Inflow_n – Use1_n$ ……… Time Step n

Where;
$Outflow_n = Rel\_Wen_n$ for time step n.
$Rel\_ Wen_n$ is the quantity of water released from Wenimbi dam for time step n.

The time step was a period of one week, therefore water volumes are in m^3/week.

❖ Water Demand

Farms were grouped according to location of their water abstraction points along the Wenimbi River and the canals. For example, farms abstracting from the left bank canal (LBC) were called LBC and their total water demand is called use3. The inflow into the LBC canal is subtracted from the release of the immediate upstream reservoir, Safari reservoir. The flow diagram in Figure 4.1 has the details.

All farms downstream of Safari reservoir have access to both Wenimbi River and either LBC or RBC, therefore their demands were allocated and named according to the point of abstraction. The area under irrigation command from each point of abstraction was used in the cropwat model to calculate the irrigation water requirements (IWR) for seven day time steps, which were converted into weekly water demands. Appendix 11 has the irrigation water requirements data for maize and wheat.
For example water demand for LBC, Use3

$Use3_1 = IWR_1 * A\_LBC_1$ …………. Time Step 1
$Use3_2 = IWR_2 * A\_LBC_2$ …………. Time Step 2
. .
. .
. .
$Use3_n = IWR_n * A\_LBC_n$ …………. Time Step n

Where
$Use3_n$ = Water demand by LBC for time step n.
IWR_n = Irrigation water requirements per unit area for time step n.
A_LBC_n = under irrigation by LBC for time step n.

The time step was a period of one week, therefore water volumes are in m^3/week.

A shortage in demand is the ratio of water supplied to the water demanded. In the Computer model; for example, for Use1 percentage demand shortage is calculated as follows;

% Demand Shortage = 100 * Sum (input Use1) / Sum (Output Use1)

Shortage time is the total time when demand is not met. Percentage Shortage is calculated as follows;

Shortage time % = (No of time steps when water supplied < demand) / (Total number of time steps)

❖ Rationing

To control the amount of water that is released from reservoirs, a rationing method was used at predetermined levels/stages of reservoirs capacities, called utility rule curves (URC). The time step was a period of one week, therefore water volumes are in m^3/week
The formula used for rationing for Wenimbi reservoir is

$Rel\_Wen_1 = Use_1 - Rat/100 * Use_1$…………Time Step 1
$Rel\_Wen_2 = Use_2 - Rat/200 * Use_2$…………Time Step 2
.   .
.   .
.   .
$Rel\_Wen_n = Use_n - Rat/n00 * Use_n$…………Time Step n

Where;

Rel_Wen_n is the release by Wenimbi dam time step n.
Use_n is the water demand from Wenimbi dam time step n.
Rat is the rationing as a percentage

4.4 Data Processing Using the Computer Model

A check on shortages or ability to satisfy demand while avoiding over abstraction was made under each scenario. Farmers and Marondera's water supply is at 10% and 4% risk respectively.

4.4.2 Scenarios

Scenarios were drawn after an analysis of the present and the trend of water demand for productive and urban water supply. The scenarios considered for analysis using the computer model were as follows;

ZERO: (a) Present set up where farmers are the only users from 2006 to 2008 with an average of 500 ha of winter wheat and 500 ha of maize in summer as the main irrigated crops. At the beginning of the 2005/6 rain season Wenimbi reservoir was at dead storage capacity, but there are no records on level of Safari reservoir, hence it was assumed to be at full storage capacity. Records at Wenimbi reservoir show that in the year 2005 water was released from Wenimbi reservoir. Farmers did not request for water in 2006, but they did every year there after. The main users were irrigators downstream of Safari reservoir. The model was run under two different water demand levels; 50 % and 75% irrigation efficiencies since the current irrigation efficiency is unknown.

Water demand is for;

Irrigated Area = 500ha,

Initial conditions of reservoirs

Stor_Wen = DSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

(b) The model was also run under another set of reservoir initial storage levels, where all are full except Safari reservoir which is at dead storage capacity. This condition is the most common since farmers exhaust water in Safari reservoir by the end of each hydrological year especially years 2006/7 and 2007/8 and food water in Wenimbi river is captured by Wenimbi reservoir and only releases when it overspills.

Stor_Wen = FSC
Stor_Saf = DSC
Stor_FD1 = FSC
Stor_FD2 = FSC

ONE: The advent of Marondera Town water supply project and 500 ha of winter wheat and 500ha of maize in summer as main crops. Water demand regime is the same as the scenario zero. The reservoirs are full at the beginning except Safari which is at dead storage capacity. The rain season is a mixture of high and low rainfall like the hydrological years 2005/06 with 78%, 2006/7 with 15% and 2007/08 with 45% probabilities of non-exceedence as shown in Appendix 7. The model was run under two different water demand levels; 50 % and 75% irrigation efficiencies since the current irrigation efficiency is unknown.

MAP has year 1 =78%, year 2 = 15%, year 3 = 45% probabilities of non-exceedence.

Water demand is for;

Irrigated Area = 500ha per year and
Marondera town water supply = 61 740 m^3 per week

Initial conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = DSC
Stor_FD1 = FSC
Stor_FD2 = FSC

TWO: Marondera Town is connected to the Wenimbi water supply at pipeline design; demand of 61 740 m^3/week when pumping is for 14 hours per day (ZINWA, 2009). The irrigation water demand remains unchanged as in 2008, irrigating 540 ha per year for maize and the same area for wheat. The reservoirs are full at the beginning except Safari which is at dead storage capacity. There are three dry consecutive years like the hydrological year 2006/07 which had MAP with non-exceedence probability of 15%. A dry spell of three years was chosen because there is a need to evaluate if there is water security in the river system under severe dry conditions. For the past 40 years the longest dry spell was two years (1990/91 and 1991/92 hydrological years). The drought of three years was chosen because if a river system can provide enough water for a three-year drought spell then it can adequately supply a two-year drought spell. Also, According to Alexander (1995), the recommended reservoir storage carryover is at least two years in climates that receive seasonal rainfall like in Southern Africa. The inflow and weather data of the hydrological year 2006/07 was replicated twice and used for the dry year data.

MAP has 15% probability of non-exceedence.

Water demand is for;

Irrigated Area = 540 ha per year and
Marondera town water supply = 61 740 m^3 per week

Initial conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

THREE: Demand for water is at maximum level for both Safari-Igava farmers and Marondera Town. Marondera Town is connected to the Wenimbi water supply at maximum demand of 80 800 m^3/week equal to 4.2 x 10^6 m^3/year. Irrigation water demand is at ZINWA's total allocation, of 17.14 x 10^6 m^3/year for irrigating 4 760 ha of maize in summer and 4 760 ha of wheat) as per cropwat scheduling, with 75% sprinkler irrigation efficiency and determined conveyance efficiency. The reservoirs are full at the beginning and there are three dry consecutive years with non exceedence probability 15% like the hydrological year 2006/07, as in scenario one. MAP is 15% probability of non-exceedence.

Water demand is for;

Irrigated Area = 4 760ha per year requiring 17.14 x 10^6 m^3 per year and
Marondera town water supply = 80 800 m^3 per week.

Initial conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

FOUR: The demand is at maximum as in scenario three. Igava farmers utilizing the canal pump water from Gairon reservoir as per ZINWA allocation of 0.3 x 10^6 m^3 per year. The reservoirs are full at the beginning and there are three dry consecutive years with non exceedence probability 15% like hydrological year 2006/07 season, as in scenario one. The MAP is 15% probability of non-exceedence

Water demand is for;

Irrigated Area = 4 760ha per year requiring 16. 84 x 10^6 m^3 per year
Marondera town water supply = 80 800 m^3 per week.

Initial conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

FIVE: Marondera Town release wastewater into Ruzawi and Safari-Igava farmers transfer the water through pumping from Gairon reservoir into the canal. The demand is at maximum as in scenario three; Maximum possible farmers demand (at potential irrigable area = 4 760 ha) and Marondera supply is at maximum (allocation of 1.68 x 10^6 m^3/yr). Half of Marondera's waste water finds it way into Ruzawi River (Save catchment) while the other half flows into the Mazowe catchment (ZINWA, 2009). Volumes of wastewater are shown in Appendix 3. The reservoirs are full at the beginning and there are dry consecutive years with non exceedence probability of 15% like 2006/07 hydrological year, as in scenario one.

MAP is 15% probability of non-exceedence.

Water demand is for;

Irrigated Area = 4 760ha per year requiring 15.16 x 10^6 m^3 per year
Marondera town water supply = 80 800 m^3 per week

Initial Conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

SIX: The demand is at maximum as in scenario three. Igava farmers utilizing the canal pump water from Gairon reservoir as per ZINWA allocation of 0.3 x 10^6 m^3 per year. All reservoirs are full at the beginning. The rain season is a mixture of high and low rainfall like the hydrological years 2005/06 with 78%, 2006/7 with 15% and 2007/08 with 45% probabilities of non-exceedence as shown in Appendix 7.

MAP has year 1 =78%, year 2 = 15%, year 3 = 45% probabilities of non-exceedence.

Water demand is for;

Irrigated Area = 4 760ha per year requiring 17.14 x 10^6 m^3 per year
Marondera town water supply = 80 800 m^3 per week

Initial Conditions of reservoirs

Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

SEVEN: The demand is at maximum but farmers are utilizing water at the rate 12 000 m^3 per ha per year, which means they irrigate 1 430 ha maize in summer and 1 430 ha wheat in winter every year. Igava farmers utilizing the canal pump water from Gairon reservoir as per ZINWA allocation of 0.3 m^3 per year. All reservoirs are full at the beginning. The rain season is a mixture of high and low rainfall like the hydrological years 2005/06 with

78%, 2006/7 with 15% and 2007/08 with 45% probabilities of non-exceedence as shown in Appendix 7.

MAP is year 1=78%, year 2= 15%, year 3= 45% probabilities of non-exceedence

Water demand is for;
Irrigated Area = 1 430 ha per year requiring 19.068 x 10^6 m^3 per year
Marondera town water supply = 80 600 m^3 per week

Initial Conditions of reservoirs
Stor_Wen = FSC
Stor_Saf = FSC
Stor_FD1 = FSC
Stor_FD2 = FSC

4..4.3 Checking for Sensitivity of the Computer Model

The sensitivity of the model was tested by running it after changing input data and checking on the results on shortages. The different scenarios provided the required variations in input data. In the different scenarios the computer model was subjected to the following conditions;

- ❖ when demand is low, for example, when some users are not abstracting water, e.g. scenario zero and one,
- ❖ when there was restricted inflow of inflow e.g. as in scenarios with drought conditions like scenarios one to five,
- ❖ when there was addition of inflow e.g. interbasin transfer, that is, when water is added to the RBC from Ruzawi River, e.g. scenario four and six,
- ❖ when there is no rationing, that is when there is no restriction to water released from each reservoir and
- ❖ over abstraction under peak demand scenarios, when storage is below dead storage capacity like in scenario five.

4.5 Assumptions Made

1. Gauging stations upstream and down stream of Wenimbi reservoir have records starting hydrological year 2005/6, inflow and out flow recorded was considered to be representative of the long term conditions in some scenarios.

2. For ungauged tributaries (streams) flowing into Safari and the two Eirene farm reservoirs the method of similar catchments based on the Gauges Station E188 upstream of Wenimbi reservoir was used to estimate their inflow. Rate of change

in storage of upstream farm reservoirs have a steady impact on inflows recorded by gauging station E188 in the same manner as in years 2005 to 2008.

3. Climatic data recorded at Marondera town weather station 15 km away from Wenimbi River and Safari-Igava area was used in the computer model and Cropwat. It was considered to be representative enough on the advice of the Meteorology department that weather data at stations in Zimbabwe is considered to be representative of an area within a radius of 100km from the weather station.

4. Farmers grow a number of irrigated crops, for example vegetables, green maize and tobacco. According to Arex (2009), the water used and area under these crops are small (less than 7% of irrigated area) compared to wheat and commercial maize therefore the water demand for the other crops apart from wheat and maize was considered too small to influence results, hence negligible.

5. There may be a possibility that Safari-Igava farmers can access more water from Ruzawi River by applying for a fraction of waste water released into the Ruzawi River after transfer from the Wenimbi River as raw water supply to Marondera Town.

6. The impact of climate change was negligible and the climatic data for the past 40 year averages were used.

7. Soils and hydrographical conditions are relatively homogenous in the Wenimbi basin.

8. The canal conveyance efficiency determine when the canal was less than half full, in the rainy season is the average value.

9. Irrigation application efficiency was fixed for sprinklers at 75% for all farmers since it is the predominant method of irrigation in the area. The study was done during the rain season. No irrigation was done during the study period, which could have been used to assess the efficiency of irrigation. Also, there are no historical records on water abstraction by individual farmers which could also be used to determine and published literature on irrigation efficiency resettled farms (on the year 2000) was not available.

10. In the absence of design data and/or reservoir capacity measurements, dead storage capacity of Safari and Eirene farm reservoirs was estimated at 10% of full capacity. Effect of siltation on storage capacity of all reservoirs was considered to be negligible.

11. River normal flow was fixed at 10% of MAR and was considered adequate for environmental and primary purposes for downstream users of the Safari-Igava area.

12. Net seepage from all reservoirs was not considered as a loss from the system because there and evaporation from Eirene farm reservoirs were considered negligible because they have relatively small capacities.

13. The supply from reservoirs with a combined storage 5.4 x 10^6 m^3 located upstream of Wenimbi reservoir was considered too small to help in alleviating shortages in the Safari-Igava Area because there are upstream irrigators using the water resources. The water use and operation of the reservoirs by these irrigators are steady under all scenarios.

CHAPTER 5

5.0 RESULTS AND DISCUSSION

This chapter presents results and discussion of the results obtained after application of the various research methods described in the chapter 4. The chapter has the information on productive water demand, urban water demand, water allocation, questionnaire survey and analysis by a computer model.

5.1 Productive Water Demand in the Wenimbi River Basin

The main water demands in the Wenimbi basin are urban water supply, productive water use and environmental water demand. The environmental demand was fixed at 10% of MAR.

5.1.1 Comparison of Pan and Evaporation as a Data Analysis

Comparison of measured class-A pan evaporation and the modified Penman-Monteith derived reference evaporation was done as a data quality analysis. The coefficient of the evaporation pan Kp =1. The figure 5.1 below shows that both methods can be used to predict the reference evapotranspiration (ETo).

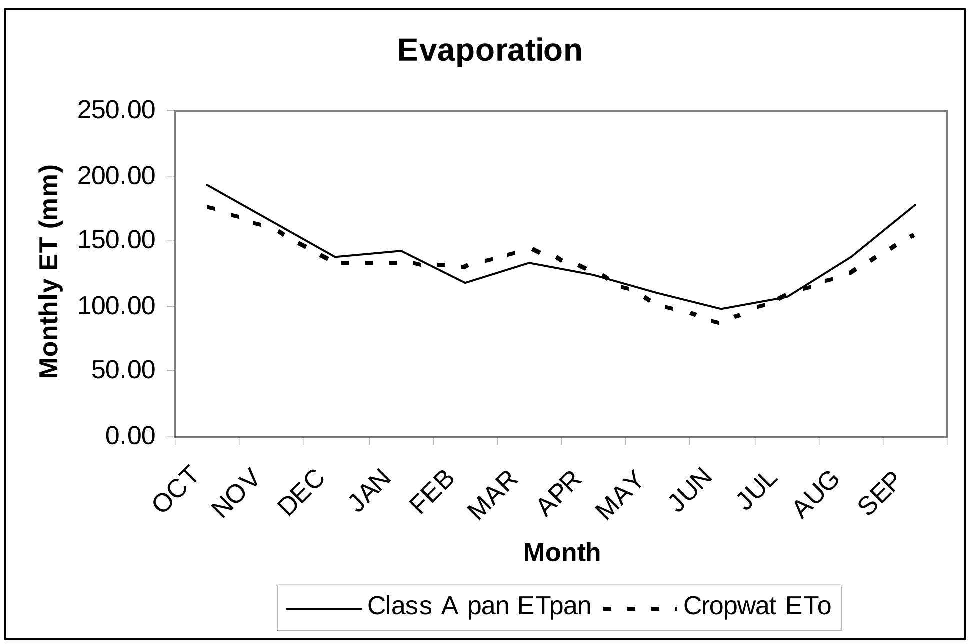

Figure 5-1: Evaporation

5.1.2 Productive Water Demand

There are no records on irrigators' water abstractions; therefore the size of land under wheat was used as the optimum area that is under irrigation (MSCC, 2006). Wheat is the main crop in the dry season and its production is mainly under irrigation. The increase in area under irrigation means there is an increase in demand for water. If the rate of increase in Figure 5.2 continues the agricultural water demand is expected to reach the maximum water allocation by the year 2016 as shown by the extended trend line in Appendix 11. If scheduling using cropwat is employed the period can be doubled provided all other conditions like application efficiency and the crop types remain the same.

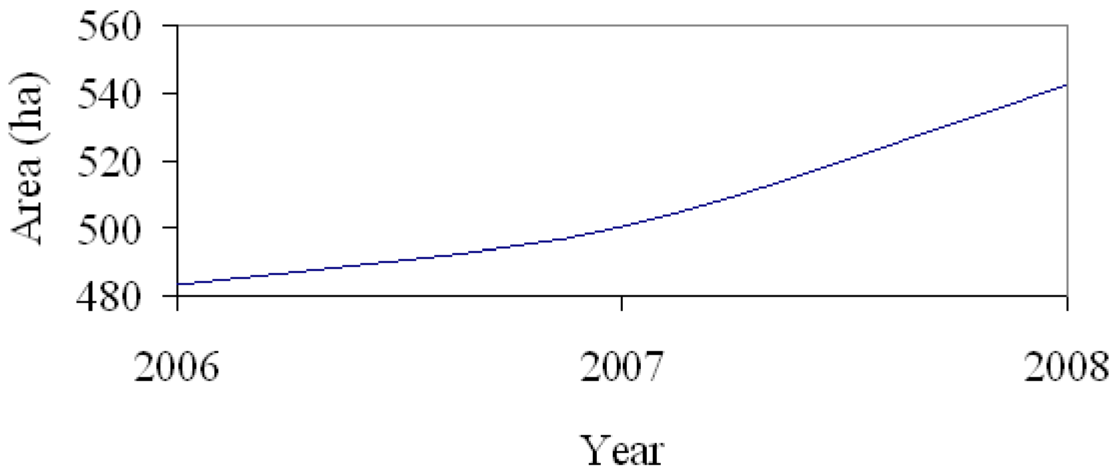

Figure 5-2: Area under Irrigation of Wheat

❖ Wenimbi Reservoir Water Releases

Water released for Safari-Igava farmers from Wenimbi dam from 2005 to 2008 are shown in Table 5.1. The information was processed from records on Wenimbi reservoir and MSCC water allocations and demands for the Safari-Igava irrigated area.

Table 5.1: Water Demand from Wenimbi Reservoir in Years 2005-08

Date	Opening Stage Reading	Closing Stage Reading	Target Water Volume Released (10^3 m^3)	Useful Volume at stage (10^3 m^3)	Water Released (10^3 m^3)	Remark
2005						Storage was heavily depleted after farmers complained that Safari dam was not able to supply up to their irrigation requirements and government had to persuade ZINWA to release water
2006						No Demand for water from Wenimbi dam by

Date	Opening Stage Reading	Closing Stage Reading	Target Water Volume Released (10^3 m^3)	Useful Volume at stage (10^3 m^3)	Water Released (10^3 m^3)	Remark
						farmers because Safari dam was full
18/05/2007	99.85			9314		
18/06/2007		99.21	5000	8082	1232	
11/10/2007	98.07					
		*				There was no closing stage reading. Farmers are not acknowledging that there was a shortfall hence its assumed that farmers were fully supplied as per payment made to ZINWA
11/11/2008	99.22			8101		
11/12/2008		98.44	3000	6733	1368	Farmers paid for 6 x 10^6 m^3 therefore they are entitled to a balance of 4.768 x 10^6 m^3 which is still in Wenimbi Dam storage

Source: ZINWA, 2009 and MSCC, 2009

Farmers are expected to get their water from Safari and Eirene farm reservoirs, and only after they have exhausted these reservoirs they apply and pay for agreement water from Wenimbi reservoir (MSCC, 2006). As shown by Table 5.1 farmers purchased agreement water from Wenimbi reservoir in 2007 and 2008. There are no time series records on levels and abstractions from Safari and Eirene farm reservoirs except allocations by MSCC gazetted in 2006. The shortages may be a result of the following;

- inefficient operation of Safari and Eirene farm reservoirs,
- insufficient natural inflow and Wenimbi spillage and releases into downstream reservoirs,
- insufficient storage in Safari dam reduced by siltation
- irrigation inefficiencies and/or
- excessive canal leakage during the dry season

The mentioned possible causes of shortages have to be investigated by further studies in order to establish the main cause of current water shortages. If conditions remain the

same then farmers are expected to continue to demand for water releases from Wenimbi reservoir.
In 2008, farmers paid for more water than they required, hence they have water in storage in Wenimbi reservoir. The water was paid in Zimbabwean dollars, a currency that is no longer in use, but foreign currency. Therefore in 2009, ZINWA has to release water which has a foreign currency value. This may be some form of loss in revenue collection on the part of ZINWA.

5.2 Urban Raw Water Demand

In 1992 Marondera Town was rationing water because of shortages induced by two years of successive droughts, (ZINWA, 2009). The histogram in Appendix 5 shows the rainfall received during the 1990/91 and 1991/92 rain seasons were below average of 800mm.The Appendix shows that the probabilities of non-exceedence are 3% and 8% for 1990/91 and 1991/92 respectively. The likelihood of rainfall exceeding any these two dry years is 92%. Since 1992 the Marondera Town's raw water demand has been increasing as shown by a trendline in Figure 5.3 below.

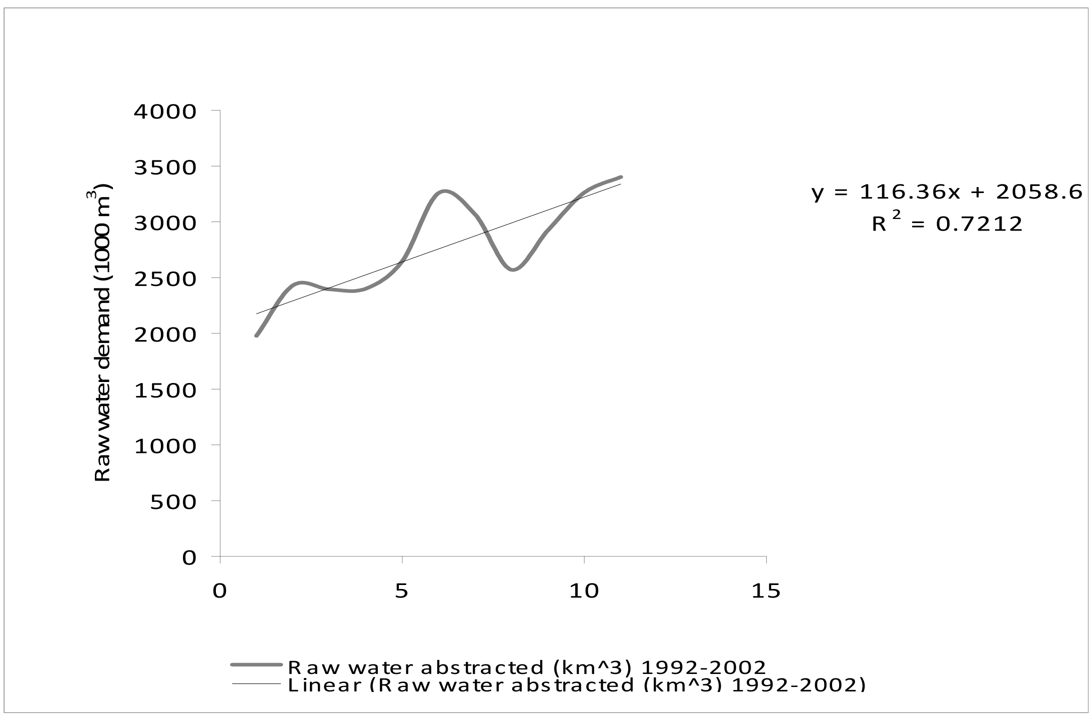

Figure 5-3: Marondera Raw Water Demand 1992 to 2002 (ZINWA, 2009)

5.2.1 Marondera Town Raw Water Demand; Forecast

The period from 1992 to 2002 the water utility supplying Marondera Town was able to cope with demand. Due to the macroeconomic problems that were characterized by high inflation and general shortage of foreign currency to import chemicals to treat water; the utility had to resort to rationing treated water (ZINWA, 2009). Rationing began in the

2002/03 hydrological year, therefore demand after 2002 was not considered because it did not reflect the natural demand but an induced demand. Currently, in 2009, water rationing is still in place because of the same reasons. Figure 5.3 was used to produce the graph in figure 5.4 by extending the trendline. As shown on the Figure 5.4, in 2009 the demand for water will exceed the yearly allocation of 4.2 x 10^6 m^3/yr. Therefore the existing reservoirs will have to continue to supply water to meet demand. This strengthens the likelihood of the scenario that abstraction from Wenimbi reservoir may be at maximum allocated reservoir yield in the near future.

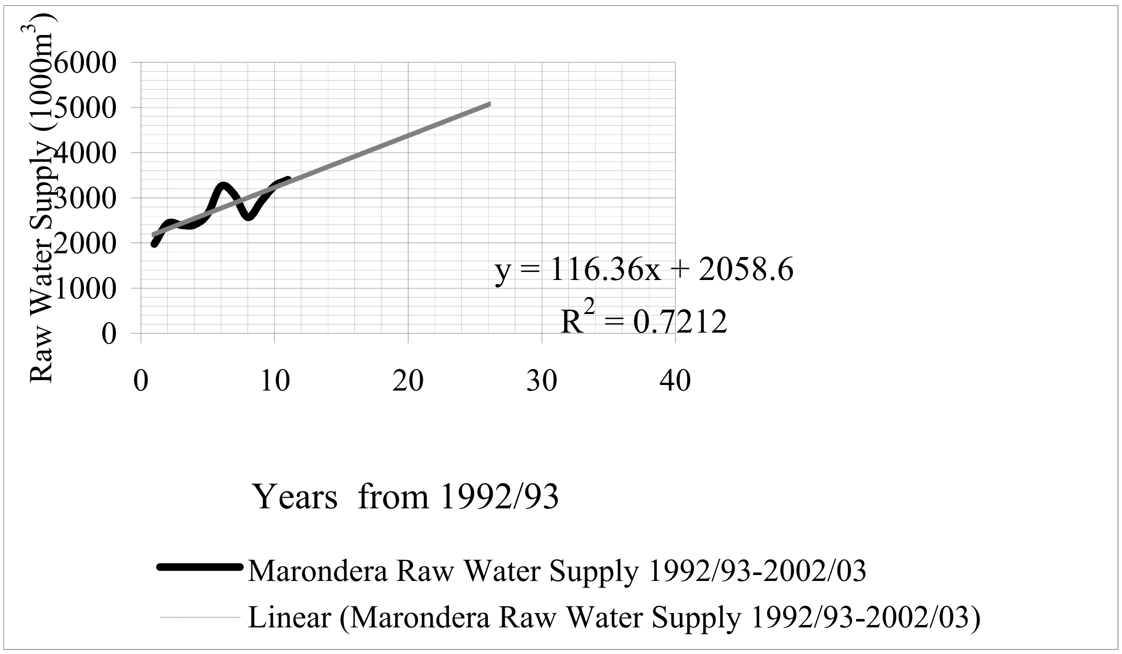

Figure 5-4: Yearly Forecast: Marondera Raw Water Demand

5.3 Available Water and Allocation in Safari-Igava Area

Available water is comprised of runoff flowing into Wenimbi Reservoir and storage in the reservoirs. Water allocated is the amount of water each user is allowed to use per annum.

5.3.1 Wenimbi Inflow

The river inflow data was measured from 2005/6 to 2007/8 hydrological years, as shown in Appendix 10. The gauging station E188, located just upstream of Wenimbi reservoir, was commissioned in the year 2005 and therefore it was used to measure flow starting in the year 2005. The least total annual rainfall recorded was 583 mm, in the 2007/8 hydrological year which has a probability of non-exceedence of 15%. According to Savenije, (2007), a dry year has a non-exceedence probability value of 20%. Probability of exceedence is 85% which means that inflows are more likely to be better than in 2005/6 85% of the time.

The total annual runoff in the hydrological year 2007/8 recorded by the gauging station E188 is 1.158 x 10^6 m^3. The annual runoff obtained from the product of catchment area of

Wenimbi reservoir and MAP using Equation 2.2 gives 4.195 x 10^6 m^3. This is an overestimation by more than 3.6 times the recorded value. For this reason Equation 2.2 was not used to estimate inflows in ungauged tributaries of Wenimbi River. Instead the method of similar catchments was used where size (area) is proportional to runoff. The presence of farm reservoirs upstream of Wenimbi reservoir contributes to some difference in the two results, as alluded to by Savenije, (2007), that change in storage and interception are non-linear functions that may cause linear and lumped models to inaccurately predict runoff.

Table 5.2: Water Storage & Allocation from Wenimbi and Ruzawi Rivers for the Safari-Igava Area

MAR (1000 m^3)	140
Primary Use and Environmental Water Requirements at 10% MAR (1000 m^3)	14
Storage Upstream of Wenimbi reservoir (1000 m^3)	5400
Total Allocations Wenimbi River system (1000 m^3)	14687
Total Storage Wenimbi reservoir & D/stream (1000 m^3)	34500
Carryover after exhausting allocations (1000 m^3)	19813
Carryover period in Wenimbi river (years)	1.35
Total storage available from Ruzawi &Wenimbi Reservoirs (1000 m^3)	34800
Carryover period in Ruzawi & Wenimbi Reservoirs (years)	1.37

Source: ZINWA, 2009 and Government Gazette, 2006

There is little security of water supply in the Safari-Igava area because the carryover period is 1.35 years as shown in Table 5.2. According to Alexander (1995), the safe reservoir storage carryover for Southern Africa, where river flow is seasonal is 2 to 5 years. In the event that there are three consecutive dry years and there is no releases or spillage of upstream reservoirs, all water demand (storage and flow permits) are met from reservoir releases, then Wenimbi river system may not be able to meet demand. Then strict rationing has to be applied in order to avert total failure.

Water allocation (0.3 x 10^6 m^3) from the Ruzawi River is too small to have an impact on overall water security since it only increases carryover period from 1.35 to 1.37 years. There are smaller farm reservoirs upstream of Wenimbi reservoir serving upstream farmers. Their impact on water availability and security to the study area was considered insignificant since their combined storage of 5.4 x 10^6 m^3 is relatively small compared to 34.5 x 10^6 m^3. Further investigation on impact of their operation may be required because they have active irrigators.

Water allocated by the MSCC is more than available water. For example, Safari farm was allocated 12.5 x 10^6 m3 per year from the storage of Safari reservoir. Safari reservoir storage is only 10.4 x 10^6 m^3 and other farms have fractional allocation of the reservoir storage. Total allocation for all farms is 40.959 x 10^6 m^3 against total storage of 34.5 x 10^6 m^3 and MAR of 0.14 x 10^6 m^3. Appendix 14 has details of the allocations by MSCC.

5.4 Results of Questionnaire Survey

Results from the questionnaire are shown in Table 5.3

Table 5.3: Results and Analysis of the Farmers Practices

Information Requested for	Response from Farmers
Types of crops	Wheat and commercial maize were the main irrigated crops. Other crops planted on smaller areas were sweat potato, peas, beans, tobacco, sunflower, rapoko, ground nut, tomato, green vegetables, irish potato. A1 farmers tend to intercrop except for wheat whereas A2 farmers do not intercrop.
Crop yield,	A2 farmers were not willing to give the yield on maize and wheat. But AREX gave average yield of 3t/ha for maize and 3.5 for wheat
Area they irrigate	An average of 500 ha for the past three years (2006, 2007 and 2008).
Scheduling methods in use	All farmers said that they use crop indicators like signs of wilting to determine when to irrigate, and sprinkler set time to control amounts they apply. They do not calculate amounts they apply before each irrigation cycle.
Water allocation	No-one came to check if there were sticking to their allocations so they did not care a lot about allocations.
Expansion plans	All irrigators hoped to expand their irrigation systems because there were areas with hydrants that were not under irrigation. The limiting factor was portable pipes and the water source especially for farmers who relied on the canal.
Future crops	They wish to expand area under irrigation for the crops they are producing at the moment
Alterative sources of water they wish to invest in	Borehole water but mainly for drinking purposes and small gardens. 100% of farmers, especially at the tail end of the canal were planning to invest in river pumping systems because the canal supply was unreliable.
Farmers' willingness and ability to pay for water.	All farmers were willing to pay for the water. They said that water cost was never considered as an input cost when budgeting because it was easily affordable. The economic situation characterized by high inflation made it easier for them to pay. Some canal tail end farmers were worried that they pay for the water but it rarely reaches their fields and therefore they pay every time they are requested to do so only to keep their right to access, moreover it was not costly.

5.5.1 Discussion of Questionnaire Results

- Competition for water is going to increase since most of the farmers wish to expand their area under irrigation; therefore reallocation of water permits to ensure efficient productive use and equity may be necessary in the long run.

- Checking and measurement of abstraction is not strict enough which makes water allocation and management in the system to be ineffective and inefficient. Over abstractions by upstream farmers and shortages for canal tail end farmers is possible under such situations and conflicts are inevitable.

- Accurate measurement and recording at each abstraction point can help to find out points where there are wastages. It is clear that the records at individual farm level could have revealed more on water use characteristics. This could give a clear picture on the efficiency of water use by the farmers.

- There was no evidence that farmers are employing well calculated irrigation scheduling methods as a water management tool. Scheduling irrigation can be one of the solutions to water shortages in the canal system.

- It is difficult to use pricing of water as a water demand management tool in this system because billing is not based on measured quantities of water used.

5.6 Results, Analysis and Discussion Using the Computer Model

The results for each scenario are in the respective tables under each scenario subheading.

5.7.1 Water Rationing

The rationing regime that gave some optimum water releases with little wastage of water (reduced spillage of the last reservoir) and minimum shortages to users for most of the scenarios is shown in Table 5.4 below. All scenarios were run under the same rationing regime in Table 5.4.

Table 5.4: Rationing as a Percentage of Demand

	Wenimbi reservoir	Safari reservoir	Farm reservoir1	Farm reservoir2	Gairon Reservoir
URC1	50	40	30	20	0
URC2	60	50	0	60	0

The rationing values in Table 5.4 were used to run the computer model. In practice rationing can be used to prolong supply in cases of droughts and high demand. This rationing is neither a ZINWA or MSCC policy or setting. Policies that govern rationing are always given in situations when rationing is required (ZINWA, 2009).

5.7.2 Scenarios

- Scenario Zero: Present demand levels (2006-08) and inflow into Wenimbi reservoir as in 2005/6, 2006/7 and 2007/2008 hydrological years.

The results of the computer simulation model for zero (a) and zero (b) scenarios at irrigation efficiency of 60% as shown in Table 5.5.

Table 5.5: Results of Scenario Zero at 60% Irrigation Efficiency

User	User Name	Average Demand (1000 m^3/week)	Demand Shortage %)		(%) Time Shortage	
			a	b	a	b
User 1	Mar Town	0	0	0	0	0
User 2	WenMas	0	0	0	0	0
User 3	LBC	8.6	0	0	0	0
User 4	RBC	17.9	49	0	67	0
User 5	CF1	0.0	0	0	0	0
User 6	CF2	0.0	0	0	0	0
User 7	CF3	0.9	0	0	0	0
User 8	CF4	7.0	0	0	0	0
User 9	D/Stream	0.3	0	0	0	0

The computer model shows that in (a) if there is no supply from Wenimbi reservoir but all other dams are full initially shortages are expected on the farms relying on canals, whereas in (b) if Safari reservoir is the only one at dead storage capacity there are no water shortages. The model shows high shortages on RBC whereas there are no shortages on LBC despite the fact that they draw water at the same dam outlet. The difference is there because the model allocates water to LBC first and then the remainder to RBC, therefore in reality the shortages should be shared fractionally to both canals. Therefore (b) shows that construction of Wenimbi reservoir improved water security in the Safari-Igava area. Wenimbi reservoir was commissioned in 2004, which means that it effectively started to capture flood waters in the 2003/04 hydrologic year thereby denying Safari reservoir substantial amounts of inflow, and there were no releases from Wenimbi reservoir to farmers until government intervention in 2005. The failure by farmers to access water from Wenimbi reservoir could be one of the reasons why farmers were experiencing shortages.

Despite the releases from Wenimbi reservoir some tail end farmers on RBC and RBC1 groups have been experiencing shortages every year. Safari reservoir is depleted to dead storage capacity during the dry season every year, according to interviewed farmers. As a result farmers are requesting for more water from Wenimbi reservoir every year as shown by reservoir releases in Table 5.1. These shortages may be as result of the following reasons which require further investigations;

- inefficient operation of Safari and Eirene farm reservoirs,
- insufficient natural inflow and Wenimbi spillage and releases into downstream reservoirs,
- insufficient storage in Safari dam reduced by siltation
- irrigation inefficiencies and/or
- excessive canal leakage during the dry season

❖ Scenario One: Demand of 2006-2008 in a Drought of Three Years

Results of scenario one with an irrigation efficiency of 60% and 75% are shown in Table 5.6.

Table 5.6: Results of Scenario One

User	**User Name**	**Average Demand (1000 m^3/week)**	**Demand Shortage (%) After 3 years**	**(%) Time Shortage After 3 years**
User 1	Mar Town	61.74	0	0
User 2	WenMas	0	0	0
User 3	LBC	8.6	0	0
User 4	RBC	17.9	0	0
User 5	CF1	0.0	0	0
User 6	CF2	0.0	0	0
User 7	CF3	0.9	0	0
User 8	CF4	7.0	0	0
User 9	D/Stream	0.3	0	0

The computer model shows that there should be no shortages at current demand levels and Marondera Town water supply connected. Wenimbi reservoir and Safari reservoir ends full and both of Eirene farm reservoirs end full after 3 years even with irrigation efficiency at 60% shown in Appendix 17. This shows that the current water demand regime can be satisfied because the probability that 3 consecutive dry years may follow each other is 0.34%. Therefore there is a need for analysis of the impact of the Marondera Town water supply project on the current set up.

❖ Scenario Two: Marondera Water Supply at Pipeline Design (61 740 m^3 per week) and Farmers' demand at 2008 level and a case of a drought spell of three years.

Results of scenario two with an irrigation efficiency of 75% are shown in Table 5.7.

Table 5.7: Results of Scenario Two

User	User Name	Average Demand (1000 m^3/week)	Demand Shortage (%) After 3 years	(%) Time Shortage After 3 years
User 1	Mar Town	61.74	27	0
User 2	WenMas	0	0	0
User 3	LBC	8.6	0	0
User 4	RBC	17.9	41	0
User 5	CF1	0.0	0	0
User 6	CF2	0.0	0	0
User 7	CF3	0.9	0	0
User 8	CF4	7.0	0	0
User 9	D/Stream	0.3	0	0

The water resources are capable of meeting demand without causing serious shortages for all time. The results of the Computer simulation model show shortages of 27% (700 m^3) for Marondera Town and an average of 21% of demand for both RBC and LBC. RBC and LBC abstract at the same point therefore the average of shortage is taken. LBC has a lower value of shortage because the in the supply procedure water demand from LBC is subtracted first. When rationing at Wenimbi and Safari reservoir is 30% for URC1 and 60% for URC2. Shortages start after the first year. Reservoirs end at half full after the three years of drought. Farm reservoir 2 spills all the time indicating wastage as shown by the respective graph in Appendix 18. Therefore adjustments of releases from Wenimbi and Safari reservoir can make the system supply enough water in the three year drought. Therefore the system can cope with a three year drought but some rationing to farmers will be required in the third year.

❖ Scenario Three: Maximum Demand in a Drought of Three Years

Results of scenario three with an irrigation efficiency of 75% are shown in Table 5.8

Table 5.8: Results of Scenario Three

User	User Name	Demand Ave (km^3)	Demand Shortage %)	(%)Time Shortage
User 1	Mar Town	81	39	25
User 2	WenMas	35	20	24
User 3	LBC	92	26	23
User 4	RBC	111	57	56
User 5	CF1	47	59	44

User 6	CF2	0	0	0
User 7	CF3	16	55	42
User 8	CF4	30	70	42
User 9	D/Stream (Environment & Primary Uses)	0.3	72	60

Graphs on reservoir storage in Appendix 19 show that the reservoirs drop to dead storage capacity as follows:
Wenimbi reservoir after 120 weeks, Safari reservoir after 100 weeks, Eirene Farm reservoir after 40 weeks and Eirene Farm reservoir 40 weeks.
This means that in case of a three year drought the Wenimbi Basin will not be able to cope with peak demand. Therefore to check if there is more water security the impact of existing extra allocation through inter-basin transfer from Ruzawi River has to be analysed.

❖ Scenario Four: Inter-basin Transfer from Ruzawi River for RBC Farmers

Results of scenario four with an irrigation efficiency of 75% are shown in Table 5.9.

Table 5.9: Results of Scenario Four

User	**User Name**	**Average Demand (1000 m^3/week)**	**Demand Shortage (%) After 3 years**	**(%) Time Shortage After 3 years**
User 1	Mar Town	81	33	51
User 2	WenMas	35	28	29
User 3	LBC	92	29	22
User 4	RBC	111	62	58
User 5	CF1	47	61	43
User 6	CF2	0	0	0
User 7	CF3	16	56	43
User 8	CF4	30	71	42
User 9	D/Stream	0.3	47	60

There is no significant change in water shortages when Igava farm, on RBC, is pumping water from Ruzawi River system. Total shortages have been reduced by 13% but for RBC alone the shortages have increased by 5% from 57% in scenario three to 62 % in scenario four. This means that inter-basin transfer can benefit the whole system since the total shortages have been reduced although RBC is the only recipient of more water. As shown in Appendix 20 the reservoirs end at dead storage capacity, it means the system can not cope with peak demand even with the allocated inter-basin transfer, in the event that there is a three year drought spell. Therefore there is no enough water security in the Safari-Igava area.

❖ Scenario Five: Reuse of Waste Water Through Inter-basin Transfer from Ruzawi River during a drought spell of 3 years.

Results of scenario five with an irrigation efficiency of 75% are shown in Table 5.10.

Table 5.10: Results of Scenario Five

User	User Name	Average Demand (1000 m^3/week)	Demand Shortage (%) After 3 years	(%) Time Shortage After 3 years
User 1	Mar Town	81	25	39
User 2	WenMas	35	20	24
User 3	LBC	92	26	23
User 4	RBC	111	57	56
User 5	CF1	47	59	44
User 6	CF2	0	0	0
User 7	CF3	16	55	42
User 8	CF4	30	70	42
User 9	D/Stream	0.3	47	60

The model shows that demand shortages for RBC in scenario 4 in Table 5.9 are reduced by 5% in scenario five as shown in Table 5.10. As shown in Appendix 21, all reservoirs end up at dead storage capacity. Which means the reuse of waste water might have relatively little impact on water shortages in the RBC. Other measures may be required for shortages reduction in case of a three year drought.

❖ Scenario Six:
Maximum Demand and 0.3 x 10^6 m^3 Interbasin Transfer from Ruzawi River in condition where there are 3 years with a mixture of high rainfall and low rainfall years, similar to 2005/06, 2006/07 and 2007/08 season.

Results of scenario six with an irrigation efficiency of 75% are shown in Table 5.11

Table 5.11: Results of Scenario Six

User	User Name	Average Demand (1000 m^3/week)	Demand Shortage (%) After 3 years	(%) Time Shortage After 3 years
User 1	Mar Town	81	9	29
User 2	WenMas	35	9	28
User 3	LBC	92	25	64
User 4	RBC	111	52	47
User 5	CF1	47	14	0
User 6	CF2	0	0	15
User 7	CF3	16	33	29
User 8	CF4	30	59	35
User 9	D/Stream	0.3	38	57

Water resources fail to meet demand especially in the third year. Shortages are over 20 % of demand and over 22% of the time. Wenimbi and Safari reservoirs reach dead storage after 100 weeks and Eirene farm reservoirs are at dead storage capacity after only 40 weeks as shown in Appendix 22. This means that the Wenimbi basin will fail to satisfy maximum water demand in average hydrological years at peak demand at allocated water resources.

- Scenario Seven:

Maximum area irrigated is 15890 ha at 12000 m^3 per hectare per year and total water allocation is 190.68 x 10^6 m^3 per year. Marondera town raw water demand is at maximum of 81 000 m^3 per week. There is 0.3 x 10^6 m^3 Inter-basin Transfer from Ruzawi River with 3 years with a mixture of high rainfall and low rainfall years, shown in Appendix 23 similar to 2005/06, 2006/07 and 2007/08 season.

Results of scenario seven with an irrigation efficiency of 75% are shown in Table 5.12.

Table 5.12 Scenario Seven Results

User	**User Name**	**Average Demand (1000 m^3/week)**	**Demand Shortage (%) After 3 years**	**(%) Time Shortage After 3 years**
User 1	Mar Town	81	23	54
User 2	WenMas	10	31	39
User 3	LBC	28	0	0
User 4	RBC	33	40	51
User 5	CF1	14	0	0
User 6	CF2	0	0	0
User 7	CF3	5	0	0
User 8	CF4	9	0	0
User 9	D/Stream	0.3	0	0

The Water allocations can just meet demand except for shortage in water demanded to Marondera Town (Mar Town) at 23%, Wenimbi and Masikana (WenMas) at 31% and LBC at 40%. The average of shortages of water demanded for LBC and RBC is 20%, for 51% of the time. All reservoirs end up below a quarter full as shown by graphs in Appendix 23. This shows that the demand for water is higher than the water available under the demand condition, which means the total area permitted by allocations should be reduced or strict rationing should be expected when the area under irrigation has reached the peak.

5.7.3 Discussion of Results of Scenario Zero to Seven: Summary

Currently and in the short term there is enough water for all users in the Safari-Igava system. Demand is expected to rise to reach peak for both urban and productive uses after six years (in 2015). This is when Marondera town is connected and the irrigation water demand has reached peak, that is, water demand is equal to allocations in records at

ZINWA. Shortages are then expected, which may require that allocations to be reviewed or strict fractional allocation to be enforced when the scenario arises.

Three consecutive dry years at the current demand (where urban water supply is not yet operational) have no impact on water availability and demand can be met all the time, although release of water from Wenimbi reservoir should be well calculate and regulated soon after spilling has stopped in order to minimize wastages.

In a scenario of a drought spell that last three years (even with rationing), there will be acute shortages in the third year, which indicates that the security of supply is low. This is in agreement with the results in Table 5.2 which gave a carryover of 1.35 and 1.37 years without and with interbasin transfer respectively, and the carryover was considered low because the recommended carryover by Alexander (1995) is at least two years.

Current water demand can be met but the water available in the Safari Igava area can not meet peak demand or total allocations in case of a three year drought spell and even in average rainy years. Therefore allocations have to be revised downwards or a rationing policy should be put in place to regulate the release and abstractions for a sustainable water supply system in the Igava area.

5.7.4 Sensitivity Analysis of the Computer Model

When the model is run when there is no rationing (that is percentage rationing is zero), Wenimbi reservoir is run dry and then Safari reservoir is depleted to dead storage, while the Eirene reservoirs are spilling. The algorithm gives the instruction that the water release should be equal to demand when there is no rationing as long as storage is above dead storage. The model starts to regulate water release when rationing is above zero, that is, release of water from the reservoirs is limited. Also, the difference in shortages for LBC and RBC is a result of the model allocating water to LBC first ahead of RBC, but they should be fractionally allocated depending on respective water demand. This means that the users of the model should understand the procedure for them to derive meaningful benefit.

For Wenimbi and Safari reservoir, when storage is below dead storage capacity it gives a negative release equivalent to the net evaporation. The model gives a reasonable responds since the procedure does not allow release of water when storage is above dead storage, and in this case evaporation is a net loss (negative loss) from the system.

6.0 CONCLUSION

- The quantity of water available for the Safari-Igava area is just enough for present water demands, but the demand is increasing, although it has not reached total allocation. In case of a three year drought, the water available cannot satisfy total allocations by the national water authority especially in the third year, which means there is little water security. Permits or allocations by the Save Catchment Council, gazetted and used for billing by the Macheke sub-catchment council are above available water resources.

- The Computer model can simulate the multiple reservoir system in the Safari-Igava area; therefore it can be used as an analysis tool that helps in making decisions on regulation of water distribution and allocations, and analysis of reservoir operational strategies. The model can be used to analyse the impact of weekly inflows and abstractions on reservoir storage.

- There are conflicts between upstream and canal tail end farmers on the canal system that are caused by are water distribution problems, which threatening productivity for the farmers at canal’s tail end. The distribution problems and conflicts can be reduced by changing operation of reservoirs, applying fractional allocation of water during periods of peak demand. For management strategies that have an impact on quantities of water distribution, the simulation model can be used to assess the impact of the strategies for shortages and conflict reduction.

7.0 RECOMMENDATIONS

- There is a need for strict monitoring of water consumption and adherence to allocations. Therefore the national water authority in collaboration with the sub-catchment council should as a matter of priority make sure farmers install flow meters at all pump stations and make sure water measurement devices on the canals are functioning. Water bills should be based on the amount of water used. Where there are no meters, area under irrigation and method of irrigation should be used to determine the quantity of water consumed.

  Water should be fractionally allocated, and maximum allocations should be revised in times of shortages to ensure equity at peak demand. Conveyance efficiencies (transmission losses) of the canals have to be investigated during the dry season, the period when the canal is operating at full capacity most of the time and losses are expected to be at their peak rate. Farmers' water use efficiencies and operations of Safari reservoir need to be investigated to help in formulation of effective strategies for water release.

- Use of the simulation model as a decision support tool is recommended when evaluating the impact of rationing policies and water management strategies in the Wenimbi River system. Also, the model can be used in impact assessment before new developments of additional area for irrigation.

- Generally the running of the model under various scenarios lead to the suggestion that in order to minimize loss of water from the system, rationing at Wenimbi reservoir, for farmers downstream of Safari reservoir should begin soon after spillage has ceased.. Farmers pumping directly from the river downstream of Eirene farm reservoir 1 and 2 should be supplied from these two reservoirs until they are depleted to dead storage capacity before getting water from Safari and Wenimbi reservoir. These farmers should help in water supply management and the upkeep of the Eirene farm reservoirs.

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APPENDICES

Appendix 1: Wenimbi Reservoir Design Data

Reservoir Full supply capacity is 21.26 x 10^6 m^3
Yield is 4.2 x 10^6 m^3/yr at 4% risk (for Marondera Town)
Maximum depth is 27.2 m
Discharge capacity is 369 m^3/s
Catchment Area is 137sq.km
Reservoir Area is 315 ha

(Source ZINWA, Wenimbi file)

Table 1: Farms With Right of Access to Water From Wenimbi River and Dams

Farm No	Name of Farm	Status Before Year 2000	Current Status
1	De Wenimbi	Large Scale commercial	Ressettled (A1)
2	Albanie / Shandisai Pfungwa	Ressettlement Area and State Land	Ressettlement Area and State Land
3	Welterverden	Large Scale commercial	Ressettled (A1)
4	Safari	Large Scale commercial	Ressettled (A2)
5	Eirene A	Large Scale commercial	Ressettled (A2)
6	Mushangwe	Large Scale commercial	Ressettled (A2)
7	Kesera	Large Scale commercial	Ressettled (A1)
8	Tressmenan	Large Scale commercial	Ressettled (A1)
9	Dindingwe	Large Scale commercial	Ressettled (A2)
10	Gorejena	Large Scale commercial	Ressettled (A2)
11	Eirene C	Large Scale commercial	Ressettled (A2)
12	Tawomba	Large Scale commercial	Ressettled (A1)
13	Gresham	Large Scale commercial	Ressettled (A1)
14	Rushinga	Large Scale commercial	Ressettled (A1)
15	Chipesa	Large Scale commercial	Ressettled (A1)
16	Mutemwa	Large Scale commercial	Ressettled (A2)
17	Igava	Large Scale commercial	Ressettled (A1)
18	Monte Cristo	Large Scale commercial	Ressettled (A2)
19	Mari	Large Scale commercial	Ressettled (A1)
20	Idapi	Large Scale commercial	Ressettled (A1& A2)
21	Sheba	Large Scale commercial	Large Scale commercial
22	Masikana	Communal land	Communal land

Appendix 2: Marondera Raw Water Demand

(Volume is in 1000 m^3)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1989/90				202.68	189.25	237.4	219.95	237.77	216.33	235.77	334.8	283.85
1990/91	322.855	270.25	210.98	173.68	206.94	230.792	271.803	261.13	277.17	273.17	276.02	323.17
1991/92	327.28	276.84	259.7	240.79	206.94	222.17	197.36	148.09	140.41	127.96	122.62	155.04
1992/93	133.89	139.18	143.37	139.84	148.92	171.7	155.42	151.24	168.72	193.5275	203.245	227.565
1993/94	235.3	210.195	199.7725	151.37	187.895	189.16	195.94	197.6	205.83	203.39	225.49	227.15
1994/95	213.86	229.52	198.01	177.95	211.54	195.88	209.42	198.11	196.57	169.59	188.85	204.9
1995/96	266.17	195.24	198.01	174.41	188.09	180.66	203.6	154.68	209.25	195.57	203.57	230.74
1996/97	266.17	252.47	198.64	181.98	180.25	179.5	197.2	197.98	227.39	246.408	248.219	270.24
1997/98	266.793	287.09	282.42	229.74	230.635	231.53	273.69	286.011	270.28	289.82	299.997	309.36
1998/99	290.634	280.12	224.35	228.71	223.03	217.35	268.322	264.256	278.214	271.73	258.309	259.46
1999/2000	254.266	189.72	216.66	201.385	224.041	233.648	192.147	211.42	157.6	164.935	229.714	294.036
2000/01	311.688	258.274	192.147	221.402	199.221	224.542	234.029	256.301	230.93	242.627	258.996	294.306
2001/02	327.198	262.64	210.209	240.128	243.734	252.927	259.623	263.47	267.481	303.269	302.585	327.736
2002/03	334.832	337.606	340.09	308.169	227.533	219.487	255.581	258.744	269.377	271.403	275.259	303.237
2003/04	344.285	246.243	225.28	236.244	228.724	225.03	224.56	244.759	260.45	228.388	275.43	310.29
2004/05	276.107	277.033	218.88	234.106	256.71	272.47	260.318	300.82	312.828	321.233	318.73	348.352
2005/06	333.6	248.585	210.754	235.175	245.492	250	275.155	235.269	271.294	276.825	307.736	329.135
2006/07	318.631	294.057	214.817									

(Source: ZINWA, 2009, Wenimbi File)

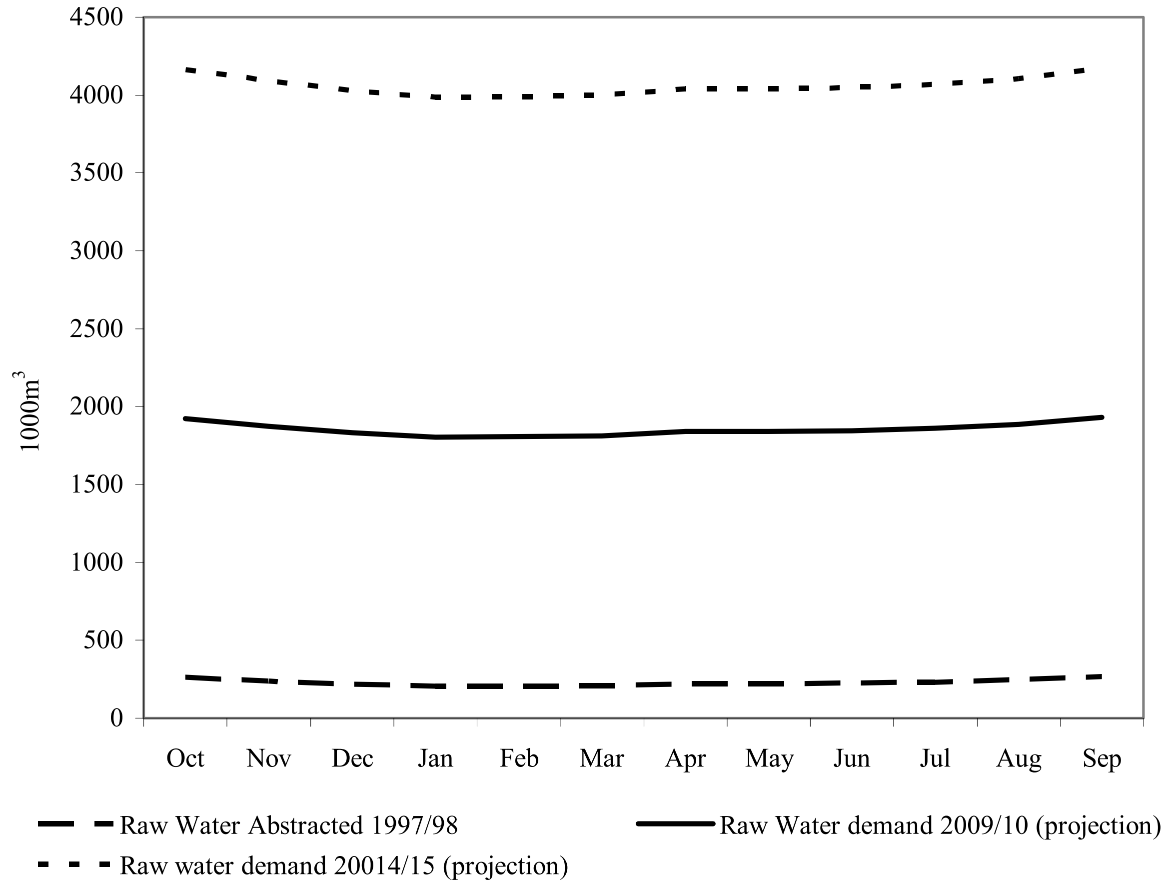
Appendix 3: Waste Water Released into Ruzawi River

(Volume is in 1000 m^3)

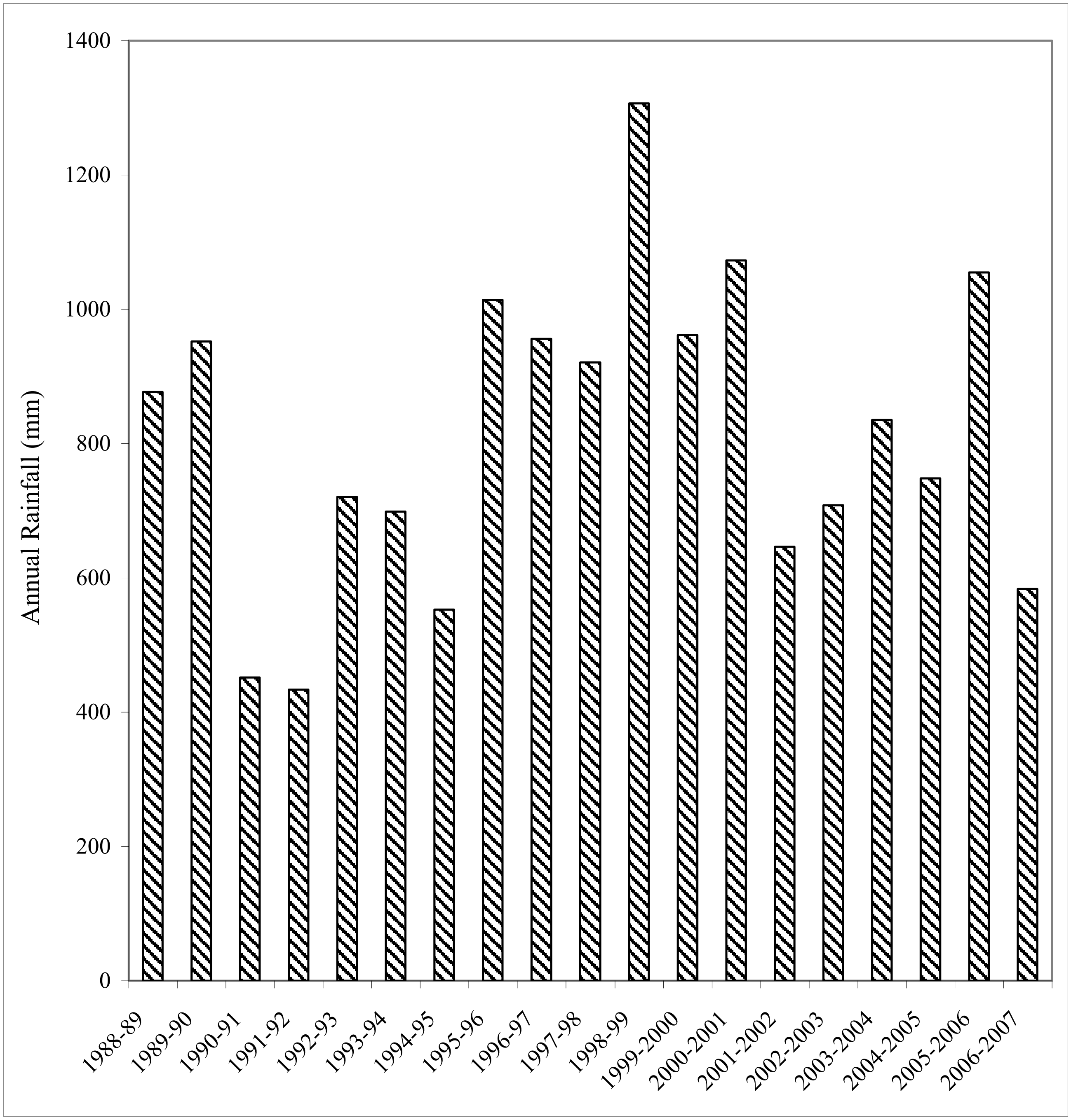
Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1989/90				81.072	75.7	94.96	87.98	95.108	86.532	94.308	133.92	113.54
1990/91	129.142	108.1	84.392	69.472	82.776	92.3168	108.7212	104.452	110.868	109.268	110.408	129.268
1991/92	130.912	110.736	103.88	96.316	82.776	88.868	78.944	59.236	56.164	51.184	49.048	62.016
1992/93	53.556	55.672	57.348	55.936	59.568	68.68	62.168	60.496	67.488	77.411	81.298	91.026
1993/94	94.12	84.078	79.909	60.548	75.158	75.664	78.376	79.04	82.332	81.356	90.196	90.86
1994/95	85.544	91.808	79.204	71.18	84.616	78.352	83.768	79.244	78.628	67.836	75.54	81.96
1995/96	106.468	78.096	79.204	69.764	75.236	72.264	81.44	61.872	83.7	78.228	81.428	92.296
1996/97	106.468	100.988	79.456	72.792	72.1	71.8	78.88	79.192	90.956	98.5632	99.2876	108.096
1997/98	106.7172	114.836	112.968	91.896	92.254	92.612	109.476	114.4044	108.112	115.928	119.9988	123.744
1998/99	116.2536	112.048	89.74	91.484	89.212	86.94	107.3288	105.7024	111.2856	108.692	103.3236	103.784
1999/2000	101.7064	75.888	86.664	80.554	89.6164	93.4592	76.8588	84.568	63.04	65.974	91.8856	117.6144
2000/01	124.6752	103.3096	76.8588	88.5608	79.6884	89.8168	93.6116	102.5204	92.372	97.0508	103.5984	117.7224
2001/02	130.8792	105.056	84.0836	96.0512	97.4936	101.1708	103.8492	105.388	106.9924	121.3076	121.034	131.0944
2002/03	133.9328	135.0424	136.036	123.2676	91.0132	87.7948	102.2324	103.4976	107.7508	108.5612	110.1036	121.2948
2003/04	137.714	98.4972	90.112	94.4976	91.4896	90.012	89.824	97.9036	104.18	91.3552	110.172	124.116
2004/05	110.4428	110.8132	87.552	93.6424	102.684	108.988	104.1272	120.328	125.1312	128.4932	127.492	139.3408
2005/06	133.44	99.434	84.3016	94.07	98.1968	100	110.062	94.1076	108.5176	110.73	123.0944	131.654
2006/07	127.4524	117.6228	85.9268									

(Source: ZINWA, 2009, Wenimbi File)

Appendix 4: Raw Water Projection for Marondera



Appendix 5: Annual Rainfall 19988/99 – 2006/7



Appendix 6: Marondera Mean Monthly Evaporation

(Evaporation in mm)

SEASON	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	Annual Total
1967-68	3.0	3.7	5.2	6.3	6.0	5.4	6.2	4.4	5.4	4.2	3.7	3.2	1730.3
1968-69	3.8	4.8	6.4	7.8	4.6	4.5	3.8	4.9	3.3	3.6	3.4	3.1	1641.6
1969-70	3.5	4.0	6.0	5.0	5.1	3.1	5.4	5.3	5.1	4.2	4.2	3.3	1645.7
1970-71	3.6	5.1	6.8	6.9	4.6	5.1	4.5		5.4	4.7	3.7	3.1	1639.3
1971-72	3.7	4.9	6.1	6.5	4.6	4.5	3.5	4.0	3.9	3.5	3.1	3.2	1571.1
1972-73	3.4	4.7	6.0	6.0	6.0	6.2	5.5	4.4	4.9	4.3	3.9	3.0	1774.8
1973-74	3.8	4.4	7.4	5.9	4.6	3.4	3.8	3.0	3.6	3.3	2.7	3.5	1503.6
1974-75	2.7	4.3	5.7	6.8	4.9	4.2	4.0	3.8	4.3	3.5	3.7	3.0	1549.4
1975-76	3.6	4.4	6.2	6.4	6.8	4.1	4.2	3.8	3.3	3.5	3.1	3.0	1597.3
1976-77	3.4	4.4	5.7	5.8	5.9	4.0	5.1	3.1	3.6	4.2	3.9	3.5	1602.0
1977-78	3.1	4.0	5.2	7.1	5.6	3.9	3.4	3.8	3.4	3.3	3.2	2.9	1487.5
1978-79	3.4	4.9	6.0	5.3	5.4	3.5	5.2	5.3	4.2	4.6	3.5	3.3	1657.4
1979-80	3.3	4.6	6.3	6.1	4.8	4.2	5.4	4.3	4.1	3.9	3.9	3.4	1656.3
1980-81	3.5	4.7	5.3	5.9	5.3	4.1	4.0	3.3	3.9	3.7	3.2	3.3	1528.7
1981-82	3.6	4.7	5.9	5.7	5.6	5.0	4.5	4.7	5.3	3.8	3.6	3.5	1700.0
1982-83	3.4	4.6	5.9	5.3	5.6	5.8	5.6	5.3	4.8	4.8	4.1	3.4	1781.0
1983-84	3.3	4.4	6.4	5.9	6.2	4.3	6.0	4.8	3.8	4.2	3.2	2.9	1688.1
1984-85	3.0	4.4	6.2	5.9	5.1	4.1	4.2	4.8	4.2	4.1	3.5	3.6	1612.7
1985-86	3.5	4.4	5.1	5.9	5.1	3.7	3.5	4.4	4.4	3.4	3.5	3.3	1526.1
1986-87	3.4	4.6	5.5	5.2	5.8	4.6	5.4	5.5	5.0	5.3	4.2	3.8	1770.4
1987-88	4.0	4.2	6.0	6.5	6.8	4.6	4.8	3.7	4.1	3.8	3.2	3.1	1671.7
1988-89	3.5	4.8	6.3	6.2	6.3	4.4	4.6	3.0	4.1	4.3	3.8	3.0	1654.4
1989-90	3.7	3.9	6.0	6.1	6.2	5.3	3.9	4.4	5.0	3.7	3.7	3.2	1675.8
1990-91	3.8	4.3	5.2	6.7	6.3	4.8	4.4	4.0	4.6	5.0	3.9	3.5	1718.0

SEASON	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	Annual Total
1991-92	3.7	4.8	6.5	6.4	5.8	5.3	5.7	6.8	4.4	4.7	3.7	3.3	1859.9
1992-93	3.8	4.8	6.5	6.3	6.2	4.3	4.5	3.8	4.0	4.6	3.6	3.3	1696.6
1993-94	3.1	3.9	5.7	6.1	4.4	5.1	5.5	4.6	5.0	5.2	4.1	3.6	1709.3
1994-95	3.6	4.2	6.1	7.0	5.5	4.7	5.7	5.5	5.8	5.3	3.7	3.6	1845.4
1995-96	3.9	4.7	6.9	7.9	6.8	3.8	4.1	4.0	4.2	4.0	2.6	3.1	1710.2
1996-97	3.1	4.8	6.7	7.2	5.9	4.2	3.2	3.9	3.8	3.6	3.7	3.3	1620.2
1997-98	3.2	4.8	4.8	5.0	5.7	5.4	3.7	5.6	4.5	4.2	4.4	3.9	1673.4
1998-99	4.0	5.0	6.3	6.7	5.7	3.4	3.2	3.0	4.2	4.0	3.8	3.4	1598.9
1999-2000	3.0	4.0	5.4	6.1	5.1	4.9	4.1	3.0	3.7	3.5	2.8	2.5	1463.6
2000-2001	3.2	3.8	5.6	6.5	5.0	4.0	5.1	3.7	3.4	4.2	3.5	3.3	1562.4
2001-2002	3.5	4.9	5.4	6.9	4.9	3.9	5.4	6.1	4.7	3.9	3.7	3.1	1714.4
2002-2003	3.4	3.8	5.5	6.1	4.9								
Total	124.4	160.8	214.2	225.2	198.9	155.9	161.1	148.0	151.4	144.2	125.4	114.5	57837.5
Ave Evap	3.5	4.5	5.9	6.3	5.5	4.5	4.6	4.2	4.3	4.1	3.6	3.3	1652.5

(Source: Meteorology Department, 2009)

Mean Weekly Evaporation

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Ave Evap	193.95	165.78	138.05	142.67	118.38	134.07	123.57	111.06	98.15	103.68	138.44	178.46
week1	27.71	23.68	19.72	20.38	16.91	19.15	17.65	15.87	14.02	14.81	19.78	25.49
week2	27.71	23.68	19.72	20.38	16.91	19.15	17.65	15.87	14.02	14.81	19.78	25.49
week3	27.71	23.68	19.72	20.38	16.91	19.15	17.65	15.87	14.02	14.81	19.78	25.49
week4	27.71	23.68	19.72	20.38	16.91	19.15	17.65	15.87	14.02	14.81	19.78	25.49

Appendix 7: Mean Annual Precipitation (Non) Exceedence Probability

SEASON	MAP (mm)	MAR (mm)	Rank	Ranked MAR (mm)	Ranked MAP (mm)	Non-exceedence (q)	Exceedence (p)
1968-69	890.3	152.4879	1	0	424.6	0.03	0.98
1969-70	767.1	104.0703	2	0	426.5	0.05	0.95
1970-71	770	105.21	3	0	448.6	0.08	0.93
1971-72	1058.8	218.7084	4	0	463	0.10	0.90
1972-73	426.5	0	5	19.9683	544.1	0.13	0.88
1973-74	1405.2	354.8436	6	31.9155	583.5	0.15	0.85
1974-75	1022.2	204.3246	7	36.7887	591.1	0.18	0.83
1975-76	835	130.755	8	56.6352	641.8	0.20	0.80
1976-77	915.1	162.2343	9	62.1372	660.4	0.23	0.78
1977-78	1038.1	210.5733	10	67.7178	673.6	0.25	0.75
1978-79	674.3	67.5999	11	77.1891	674.3	0.28	0.73
1979-80	890.7	152.6451	12	80.9619	708.3	0.30	0.70
1980-81	1655.3	453.1329	13	85.7565	720.5	0.33	0.68
1981-82	764.9	103.2057	14	96.7212	744.9	0.35	0.65
1982-83	591.1	34.9023	15	105.0528	764.9	0.38	0.63
1983-84	463	0	16	105.6423	767.1	0.40	0.60
1984-85	957.3	178.8189	17	108.354	770	0.43	0.58
1985-86	1120.9	243.1137	18	130.8336	831.9	0.45	0.55
1986-87	660.4	62.1372	19	131.148	835	0.48	0.53
1987-88	999.1	195.2463	20	147.1431	835.2	0.50	0.50
1988-89	866.8	143.2524	21	153.9813	843.9	0.53	0.48
1989-90	940.9	172.3737	22	161.5269	866.8	0.55	0.45
1990-91	448.6	0	23	163.6098	890.3	0.58	0.43
1991-92	424.6	0	24	164.3172	890.7	0.60	0.40
1992-93	720.5	85.7565	25	176.8932	915.1	0.63	0.38
1993-94	673.6	67.3248	26	178.1901	939.8	0.65	0.35
1994-95	544.1	16.4313	27	180.4695	940.9	0.68	0.33
1995-96	1001.7	196.2681	28	194.4996	952.2	0.70	0.30
1996-97	952.2	176.8146	29	195.5214	957.3	0.73	0.28
1997-98	843.9	134.2527	30	201.102	999.1	0.75	0.25
1998-99	1306.7	316.1331	31	217.1757	1001.7	0.78	0.23
1999-2000	939.8	171.9414	32	218.9049	1022.2	0.80	0.20
2000-2001	1071.1	223.5423	33	221.7345	1038.1	0.83	0.18
2001-2002	641.8	54.8274	34	222.1275	1041.6	0.85	0.15
2002-2003	708.3	80.9619	35	224.2497	1058.8	0.88	0.13
2003-2004	835.2	130.8336	36	247.6332	1071.1	0.90	0.10
2004-2005	744.9	95.3457	37	316.1331	1120.9	0.93	0.08
2005-2006	1041.6	211.9488	38	356.5335	1306.7	0.95	0.05
2006-2007	583.5	31.9155	39	470.5428	1405.2	0.98	0.03
2007-2008	831.9				1655.3		

Appendix 8: Canal Flow Conveyance Efficiency

	Flume 1	**Flume 2**	**Flume 3**	**12 km Mean Conveyance Efficiency (%)**
Flow Rate (l/min)	102	101	97	
Distance from flume1 (m)	0	2 400	11 900	
Loss per metre	0	$4.2*10^{-4}$	$4.2*10^{-4}$	$4.2*10^{-4}$
Conveyance Efficiency (%)		99.0	95.1	95

Appendix 9: Model Procedure/Algorithm for Wenimbi Dam

```
Sub Res_Wen()
'This procedure manages the releases form Wenimbi Reservoir (Dam_Wen).
Take Stor1_old_Wen as Variant
' The line above declares the dimensions of variables or constants in the procedure.

Range("Infl1_Wen").Value = Range("Infl_Wen").Value
Range("Req1_Wen").Value = -Range("Req_Wen").Value
Stor1_old_Wen = Range("Stor1_Wen").Value
Range("Stor1_Wen").Value = (Range("Stor1_Wen").Value + Range("infl_Wen").Value -
Range("req1_Wen").Value)
Range("Rel1_Wen").Value = Range("Req1_Wen").Value

If Range("Stor1_Wen").Value > Range("FRC_Wen").Value Then
    Range("Rel1_Wen").Value = Range("Rel1_Wen").Value +
Range("Stor1_Wen").Value - Range("frc_Wen").Value
    Range("Stor1_Wen").Value = Range("FRC_Wen").Value
End If

If Range("Stor1_Wen").Value < Range("URC_Wen").Value Then
    Range("Stor1_Wen").Value = (Range("Stor1_Wen").Value +
Range("Rat_Wen").Value * 1 / 100 * Range("Req1_Wen").Value)
    Range("Rel1_Wen").Value = (1 - Range("Rat_Wen").Value / 100) *
Range("Req1_Wen").Value
End If

If Range("Stor1_Wen").Value < Range("DSC_Wen").Value Then
    Range("Stor1_Wen").Value = Range("DSC_Wen").Value
    Range("Rel1_Wen").Value = Stor1_old_Wen + Range("Infl1_Wen").Value -
Range("DSC_Wen").Value
End If

Range("Stor_Wen").Value = Range("Stor1_Wen").Value
Range("rel_Wen").Value = Range("Rel1_Wen").Value
End Sub
```

Appendix 10: Inflow starting from Oct 2005 to Sept 2008

Gauging Station E188 Flow (1000 m^3/week)			
Week	**2005/06**	**2006/07**	**2007/08**
1	0	0	30.5424
2	0	0	0
3	0	0	12.21696
4	0	0	18.32544
5	0	0	18.32544
6	0	0	54.97632
7	0	48.8678	0
8	0	18.3254	0
9	0	24.4339	12.82781
10	0	18.3254	361.1098
11	53.1801	24.4339	94.72216
12	238.855	129.5	24.43392
13	44.5441	19.5471	350.5294
14	53.1801	24.4339	277.9358
15	202.511	108.935	651.4898
16	53.1801	24.4339	532.0486
17	102.837	52.5329	1426.636
18	161.418	85.6816	1197.635
19	43.4646	18.9363	140.495
20	42.3851	18.3254	122.1696
21	42.3851	18.3254	334.6429
22	53.1801	24.4339	596.717
23	42.3851	18.3254	307.2565
24	85.5652	42.7594	321.8587
25	184.736	98.8759	54.97632
26	183.26	98.0411	79.41024
27	68.2932	32.9858	61.0848
28	60.7367	0	24.4339
29	53.1801	24.4339	12.82781
30	42.3851	18.3254	0
31	24.4339	0	0
32	18.3254	0	0
33	0	0	0
34	0	0	0
35	0	0	0
36	42.3851	18.3254	0
37	53.1801	24.4339	12.82781
38	42.3851	18.3254	0

Gauging Station E187 Flow (1 x 0.1 x 10^6 m^3/week)		
2005/06	**2006/07**	**2007/2008**
0.12	0	0.28
0	0	0.28
0	0	0.32
0	0	1.14
0	0	2.23
0	0	3.43
0	0	4.55
0	0	4.39
0	0.06	0.06
0	0	0.07
0	0	0.07
0	0	0.17
0	0	0.29
0	0	0.07
0.06	0	0.07
0.07	0	0.07
0.07	0	1.08
0.07	0.6	7.1
0.1	0.7	4.76
0.1	0	2.61
0.07	0	1.81
0.28	0.05	1.14
0.33	0.07	0.93
0.07	0.07	1.54
0.07	0	0.38
0.07	0.03	0.02
0.07	0	0
0	0.06	
0	0.07	
0	0	
0	0	
0	0	
0	3.48	
0	4.2	
0	4.2	
0	1.6	
0	0	
0	0.54	

Gauging Station E188 Flow (1000 m^3/week)			
Week	**2005/06**	**2006/07**	**2007/08**
39	42.3851	18.3254	0
40	53.1801	24.4339	0
41	24.4339	0	0
42	18.3254	0	12.82781
43	0	0	0
44	0	0	0
45	0	0	0
46	53.1801	24.4339	0
47	42.3851	18.3254	0
48	24.4339	0	0
49	18.3254	0	12.82781
50	0	0	0
51	0	0	0
52	0	18.3254	0
Total Runoff	**2269.021**	**1158.147**	**7158.111**

Gauging Station E187 Flow (1 x 0.1 x 10^6 m^3/week)		
2005/06	**2006/07**	**2007/2008**
0	1.92	
0	2.82	
0	3.88	
0	4.94	
0	3.83	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
0	0.28	
1.55	**35.64**	**38.86**

Source: ZINWA, 2009

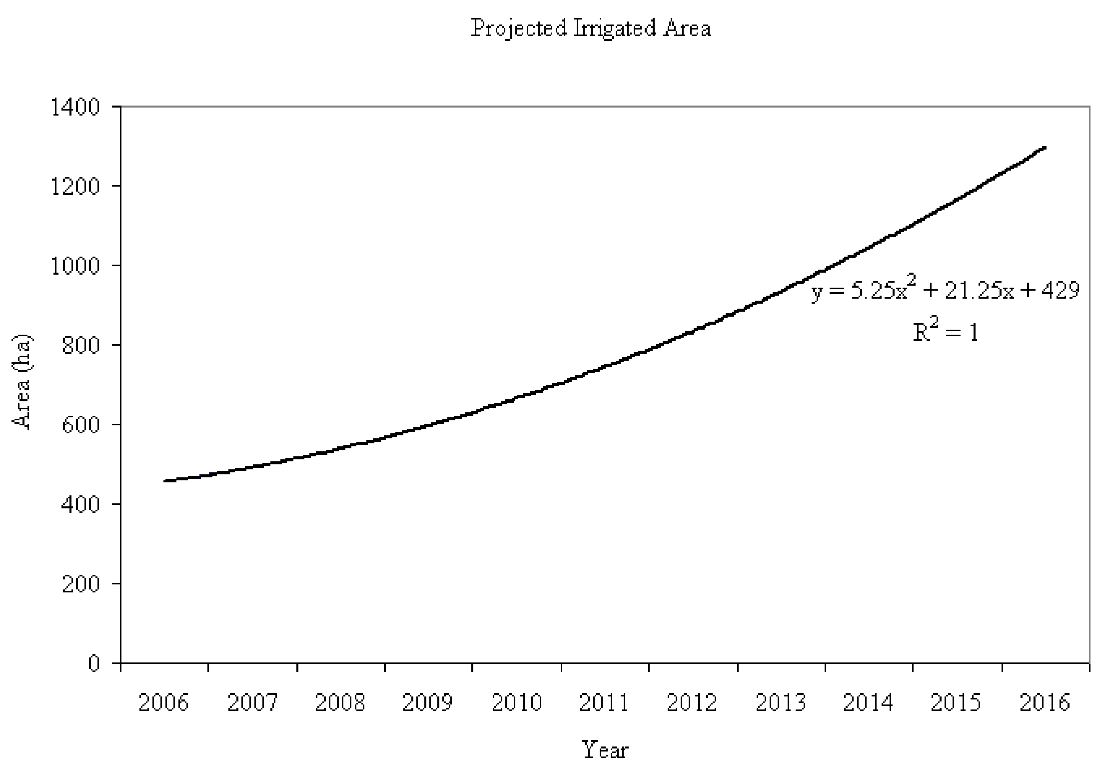
Values of zero mean no flow or too small to be measured by the gauging station hence insignificant.

The hydrological year in Zimbabwe starts in the month of October, therefore records were taken starting in October 2005 although both of the gauging stations were commissioned earlier than the month of October but in the year 2005.

Appendix 11: Irrigated Area

Farm Group	User No	Area (ha)		
		2006	2007	2008
WenMas	2	0	0	0
LBC	3	110	99	164
RBC	4	197	281	295
CF1	5	0	0	0
CF2	6	0	0	0
CF3	7	15	10	12.5
CF4	8	133.5	102.5	68.5
Total		**455.5**	**492.5**	**540**

(Source: AREX, 2009)



Appendix 12: Canal Flow

Canal	RBC	LBC
Length (m)	14830	18420
Canal ends Elevation Difference (m)	43.00	16.00
Slope	0.00290	0.00087
Bottom Width (m)	0.50	0.50
Top width (m)	2.00	2.00
Depth (m)	1.00	1.00
Trapezoidal Cross-sectional Area (m^3)	1.25	1.25
Side length	1.25	1.25
Wetted Perimeter (m)	3.00	3.00
Wetted Radius (m)	0.42	0.42
Speed m/s	2.00	1.10
Flow rate 1000 m^3/week	1513.98	828.65
Time of travel from inlet to canal end in dry canal (Hours)	2	5

Appendix 13: CROPWAT Input Data

Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Temp max (^oC)	28	27	26	26	26	25	25	23	21	21	24	27
Temp min (^oC)	13	15	14	14	14	14	12	9	6	6	7	11
Relative Humidity (%)	18	40	65	80	58	32	19	5	2	2	2	5
Wind Speed (km/hr)	151.2	142.3	120.1	127.2	148.6	122.8	126.3	105.9	112.1	145.3	134.9	14.6
Daily Sunshine Hours	9	8	6	7	7	8	8	9	9	9	10	10

(Source: Meteorological Department, 2009)

Appendix 14: MSCC Water Permits

	WENIMBI RIVER PUMPING			CANAL WATER SUPPLY				RUZAWI RIVER'S GAIRON DAM		
FARM NAME	WENIMBI RIVER PERMIT NO	RIVER PERMIT VOLUME (1000 m^3)	AREA AT 12000 m^3/ha	CANAL PERMIT NO	CANAL PERMIT VOLUME (1000 m^3)	AREA AT 12000 m^3/ha	PERMIT AREA PER RESSETTLED FARMER	GAIRON PERMIT INTO CANAL No	GAIRON PERMIT VOLUME (1000 m^3)	AREA BEFORE 2000 at 12000 m^3/ha
ABOVE SAFARI DAM										
Pinewood	7090	265	22						0	0
Shandisai Pfungwa	15581	536	45						0	0
Total		**801**	**67**							
LEFT BANK CANAL										
Safari LBC				14912	6200	516.5	114		0	0
Kesera	12775	264	22	13737	288	24	2		0	0
Pressmennan	6644	395	33	15582	175	20	2		0	0
Tawomba	13734	621	52	15396B	320	26	2		0	0
Grasham	9008	494	41	15396A	320	26	2		0	0
Rushinga	10854	328	27	9495	70	18	1		0	0
Chipesa	15560	1024	85	13736	621	52	3		0	0
Monte Cristo	15398	1016	85	11855	270	22	2		0	0
Total		**4142**	**345**		**8264**	**705**	**128**		**0**	**0**

	WENIMBI RIVER PUMPING			**CANAL WATER SUPPLY**				**RUZAWI RIVER'S GAIRON DAM**		
FARM NAME	**WENIMBI RIVER PERMIT NO**	**RIVER PERMIT VOLUME (1000 m^3)**	**AREA AT 12000 m^3/ha**	**CANAL PERMIT NO**	**CANAL PERMIT VOLUME (1000 m^3)**	**AREA AT 12000 m^3/ha**	**PERMIT AREA PER RESSETTLED FARMER**	**GAIRON PERMIT INTO CANAL No**	**GAIRON PERMIT VOLUME (1000 m^3)**	**AREA BEFORE 2000 at 12000 m^3/ha**
RIGHT BANK CANAL										
Safari RBC				14912	6200	516.5	114		0	0
Rem of Eirene (A)	13005	2300	192	12775	2300	191	191		0	0
Mushangwe	11188	190	16	13294	312	26	26		1000	83
Dindingwe			0	15397	12400	1033	34		496	41
S/DC Eirene	15785	1590	133	15579	1612	134	10			0
Igava	14385	32	3	14384	320	26		6% of 5738	300	25
Mutemwa			0	15559	496	41			0	0
Total		**4112**	**343**		**23640**	**1968**	**375**		**1796**	**150**

(Source: ZINWA, MSCC)

The left bank canal (LBC) is to the left hand side when facing the direction of flow and the RBC is to the right hand side.

The area per resettled farmer is calculated based on number of plots with access to irrigation infrastructure presently.

The total number of resettled farmers is 614 (AREX, 2005).

The total area of 3472 hectares could be irrigated per year according to AREX specifications of 12000 m^3/ha

Before the year 2000, farmers had developed areas far above the limit due to water availability because of crop rotation requirements in tobacco production.

The MSCC use an allocation with a permit number 14912, of volume 12.8 x 10^6 m^3, the number is for Safari dam (according to ZINWA records). The volume allocated to safari farm is higher than storage of Safari dam.

Summary of Table in Appendix 14

	USE1	USE2	USE3	USE4	USE5	USE6	USE7	USE8
	Mar Town	WenMas	LBC	RBC	CF1	CF2	CF3	CF4
Irrigated Area (ha)		67	705	1968	0	192	345	151
Volume (m^3)		801	8264	23640	0	2300	4142	1812

Appendix 15: Zinwa Annual Water Allocation in Safari-Igava Farming Area

Permit No	Water Resource	Flow (ML/yr)	Storage (ML)	Name of User	Allocation Type	Name in model	User No in model
5280	Wenimbi River	144		DeWenimbi farm	Permit	Wen Mas	2
6426	Wenimbi River	99		Dindingwe farm	Permit	CF3	7
10854	Wenimbi River	328		Rushinga farm	Permit	CF4	8
6644	Wenimbi River	395		Tressmennan	Permit	CF4	8
9008	Wenimbi River	494		Gresham	Permit	CF4	8
11188	Wenimbi River	380		Mushangwe	Permit	CF3	7
11855	Wenimbi River	270		Monte Cristo farm	Permit	CF4	8
12124	Wenimbi River	264		Eirene A farm	Permit	CF1	5
12464	**Verde FD**		**1300**	**Verde farm dam**	**Dam Storage**		
	Other dams		**4300**		**Dam storage**		
12775	**Eirene Farm Dam1**		**2300**		**Dam Storage**	**FD1**	
	Eirene Farm Dam2		**500**		**Dam Storage**	**FD2**	
27% of 12775	FD1		621	Eirene A farm	Permit	CF1	3
13294	Wenimbi River	315		Mushangwe	Permit	CF3	7
13005	Wenimbi River	67		Tressmenan	Permit	CF4	8
13734	Safari dam		621	Tawomba	Permit (LBC)	LBC	3
13736	Safari dam		218.5	Tawomba, Gresham, Chipesa farms	Permit (LBC)	LBC	3
13737	Safari dam		288	Kesera	Permit (LBC)	LBC	3
14384	*Gairon dam*		*300*	*Igava farm*	*Permit (RBC)*	*RBC*	*Inflow4*
14835	Wenimbi River		32	Igava farm	Permit	CF3	7

Permit No	Water Resource	Flow (ML/yr)	Storage (ML)	Name of User	Allocation Type	Name in model	User No in model
14912	**Safari dam**		**10400**		**Dam Storage**	**Saf**	
15398	Safari dam		1352	Monte Cristo farm	Permit (LBC)	LBC	3
15420	Safari dam		884	Mushangwe farm	Permit (RBC)	RBC	4
15547	Safari dam		416	Mutemwa farm	Permit (RBC)	RBC	4
15559	Safari dam	417		Rushinga, Chipesa farm	Permit (LBC)	LBC	4
15560	Safari dam		312	Rushinga, Chipesa farm	Permit (LBC)	LBC	3
15578	Safari dam		1248	Eirene A farm	Permit (RBC)	RBC	4
15579	Safari dam		884	Dindingwe	Permit (RBC)	RBC	4
15582	Safari dam		624	Tressmenan	Permit (LBC)	LBC	3
15580	Safari dam		884	Eirene A farm	Permit (RBC)	RBC	4
15396	Safari dam		1352	Tawomba, Grasham	Permit (LBC)	LBC	3
15374	**Wenimbi River dam**		**230**	**Farm 8 of Wenimbi Estate**	**Dam Storage**		
15397	Safari dam		936	Eirene C farm	Permit (RBC)	RBC	4
5% of 14912	Safari dam		520	Safari Farm	Permit (RBC)	RBC	4
	Wenimbi Dam		1800	Masikana Communal area	Aggreement water	CF1	2
	Wenimbi Dam		4200	Marondera town	Aggreement water	MarTwn	1
15785	Wenimbi river	1680		Mutemwa farm	Permit	CF3	7
16312	**Wenimbi Dam**		**21300**	**Wenimbi Dam**	**Dam Storage**	**Wen**	

The volume of water in permits mentioned above were volumes in water rights under the Water Act of 1976, converted to permits in Water Act of 1998. After the government gazette of 2006, no new allocations have been gazetted. The allocations should be agreement water and ZINWA has to do the allocations because the government gazette means the reservoirs now belong to government and ZINWA should be responsible for their management.

(b) Total Annual Allocations and Storages (1000 m^3)

Total Allocations Wenimbi River system	14 687
Total Storage Wenimbi Dam & D/stream	34 500
Total allocations Ruzawi &Wenimbi Rivers	14 987
Carryover after exhausting allocations	19 513
Storage Upstream of Wenimbi Dam	5 400

(c) Maximum Volumes and Irrigated Area Allocation per Year

	USE1	USE2	USE3	USE4	USE5	USE6	USE7	USE8
	Mar Town	WenMas	LBC	RBC	CF1	CF2	CF3	CF4
AREA (12000 m^3/ha)		150	397	481	202	0	69	130
VOLUME	4200	1800	4768	5772	2421	0	826	1554
AREA (3600 m^3/ha) as per Cropwat scheduling at 75% SE & 95 % CE		500	1324	1603	673	0	229	432

SE = Sprinkler Efficiency
CE = Conveyance Efficiency

Appendix 16: Crop Water Requirements for Maize and Wheat

(a) Maize

Planting Date 15 October

Calculation Time Step = 7 days

Irrigation Efficiency = 75%

Date	ETo (mm/period)	Planted Area (%)	Crop Kc	CWR (ETm)	Total Rain (mm/period)	Effect. Rain (mm)	Irr. Req. (mm)	FWS (l/s/ha)
15-Oct	36.92	50	0.15	5.54	4	0	5.54	0.12
22-Oct	37.34	50	0.15	5.6	5.13	0.6	5	0.11
29-Oct	37.6	50	0.15	5.64	6.68	2.37	3.27	0.07
5-Nov	37.69	50	0.15	5.65	8.63	4.03	1.63	0.04
12-Nov	37.6	50	0.18	6.78	10.84	5.84	0.94	0.02
19-Nov	37.33	50	0.28	10.36	13.17	7.63	2.72	0.06
26-Nov	36.86	50	0.38	13.88	15.42	9.26	4.62	0.1
3-Dec	36.22	50	0.48	17.23	17.45	10.63	6.6	0.15
10-Dec	35.4	50	0.56	19.92	19.13	11.71	8.21	0.18
17-Dec	34.44	50	0.57	19.8	20.37	12.49	7.31	0.16
24-Dec	33.34	50	0.57	19.17	21.15	12.99	6.18	0.14
31-Dec	32.2	50	0.57	18.52	21.35	12.63	5.88	0.13
7-Jan	32.45	50	0.57	18.66	22.21	12.96	5.7	0.13
14-Jan	32.69	50	0.57	18.8	22.89	13.47	5.33	0.12
21-Jan	32.8	50	0.54	17.86	23.18	13.93	3.94	0.09
28-Jan	32.78	50	0.45	14.67	22.97	14.22	0.45	0.01
4-Feb	32.63	50	0.35	11.37	22.22	14.19	0	0
11-Feb	32.35	50	0.25	8.06	20.93	13.7	0	0
18-Feb	18.32	50	0.17	3.14	11.19	7.4	0	0

ETo data is distributed using polynomial curve fitting

Rainfall data is distributed using polynomial curve fitting

(b) Wheat

Planting Date

Calculation Time step = 7 Days

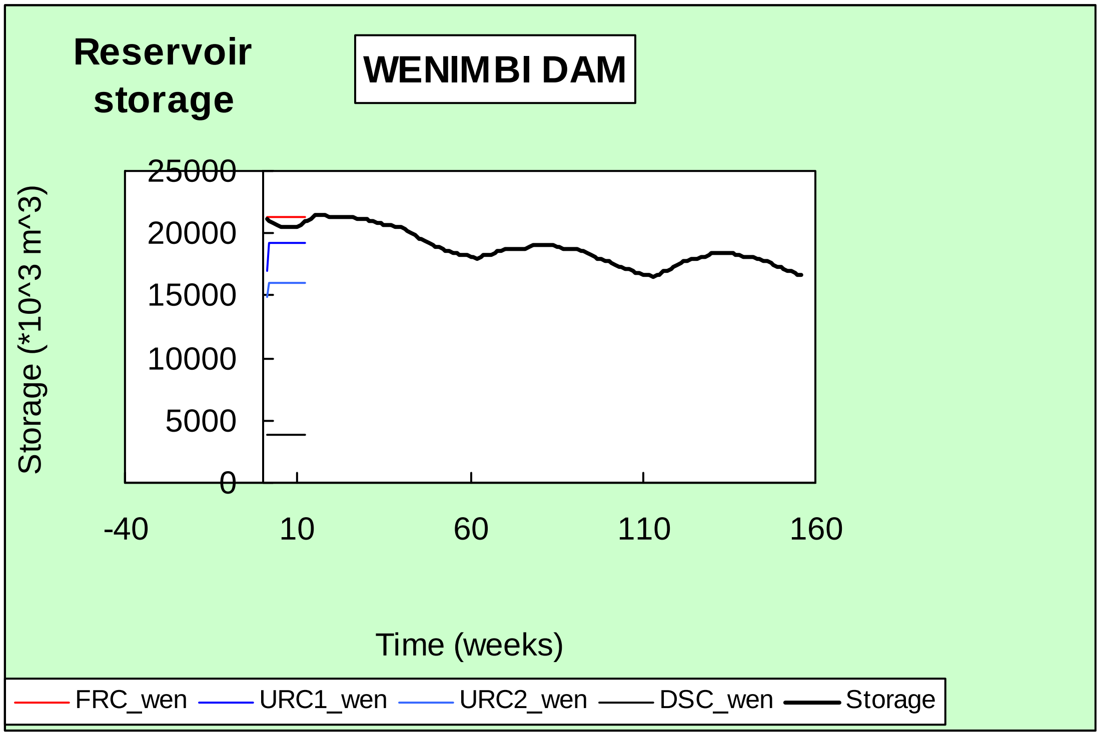
Irrigation Efficiency = 75%

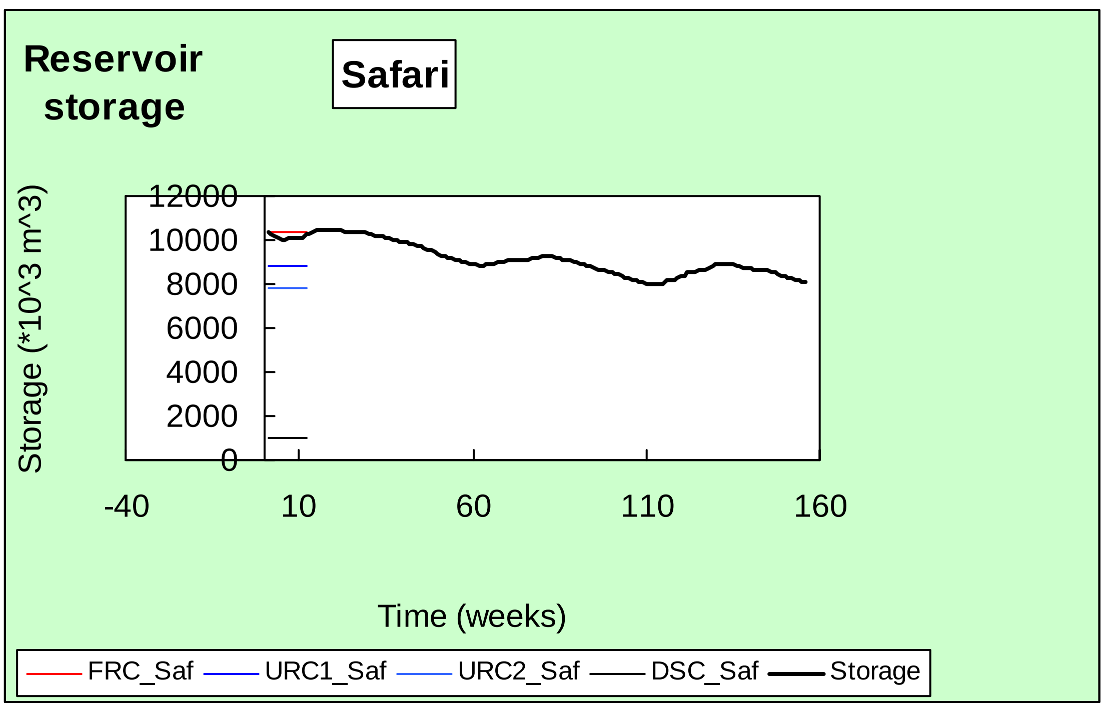
Date	ETo (mm/period)	Planted Area (%)	Crop Kc	CWR (ETm)	Total Rain (mm/period)	Effect. Rain (mm)	Irr. Req. (mm)	FWS (l/s/ha)
1-May	25.23	50	0.15	3.78	1.06	0	3.78	0.08
8-May	24.72	50	0.15	3.71	0	0	3.71	0.08
15-May	24.31	50	0.15	3.65	0	0	3.65	0.08
22-May	24	50	0.15	3.6	0	0	3.6	0.08
29-May	23.8	50	0.18	4.29	0	0	4.29	0.09
5-Jun	23.71	50	0.28	6.58	0	0	6.58	0.15
12-Jun	23.76	50	0.38	8.95	0	0	8.95	0.2
19-Jun	23.92	50	0.48	11.38	0	0	11.38	0.25
26-Jun	24.21	50	0.56	13.63	0	0	13.63	0.3
3-Jul	24.63	50	0.57	14.16	0	0	14.16	0.31
10-Jul	25.16	50	0.57	14.46	0	0	14.46	0.32
17-Jul	25.79	50	0.57	14.83	0	0	14.83	0.33
24-Jul	26.53	50	0.57	15.26	0	0	15.26	0.34
31-Jul	27.35	50	0.57	15.73	0	0	15.73	0.35
7-Aug	28.25	50	0.54	15.38	0	0	15.38	0.34
14-Aug	29.2	50	0.45	13.06	0	0	13.06	0.29
21-Aug	30.19	50	0.35	10.51	0	0	10.51	0.23
28-Aug	31.19	50	0.25	7.76	0	0	7.76	0.17
4-Sep	18.28	50	0.17	3.13	0	0	3.13	0.12

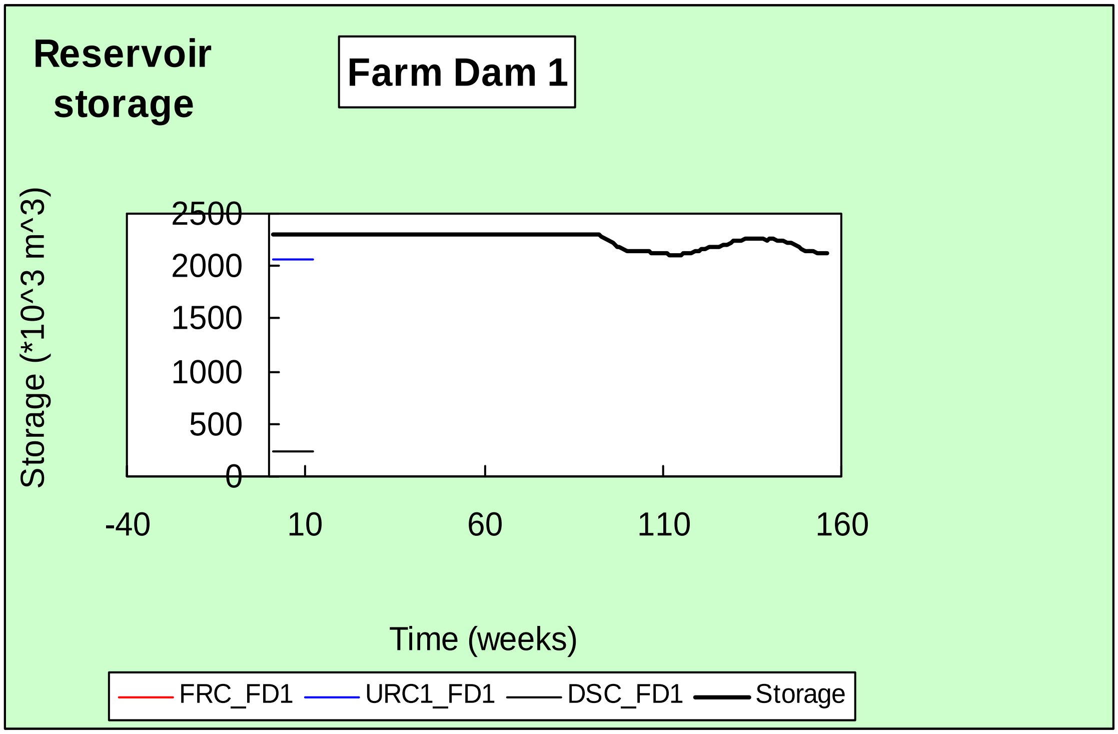
ETo data is distributed using polynomial curve fitting

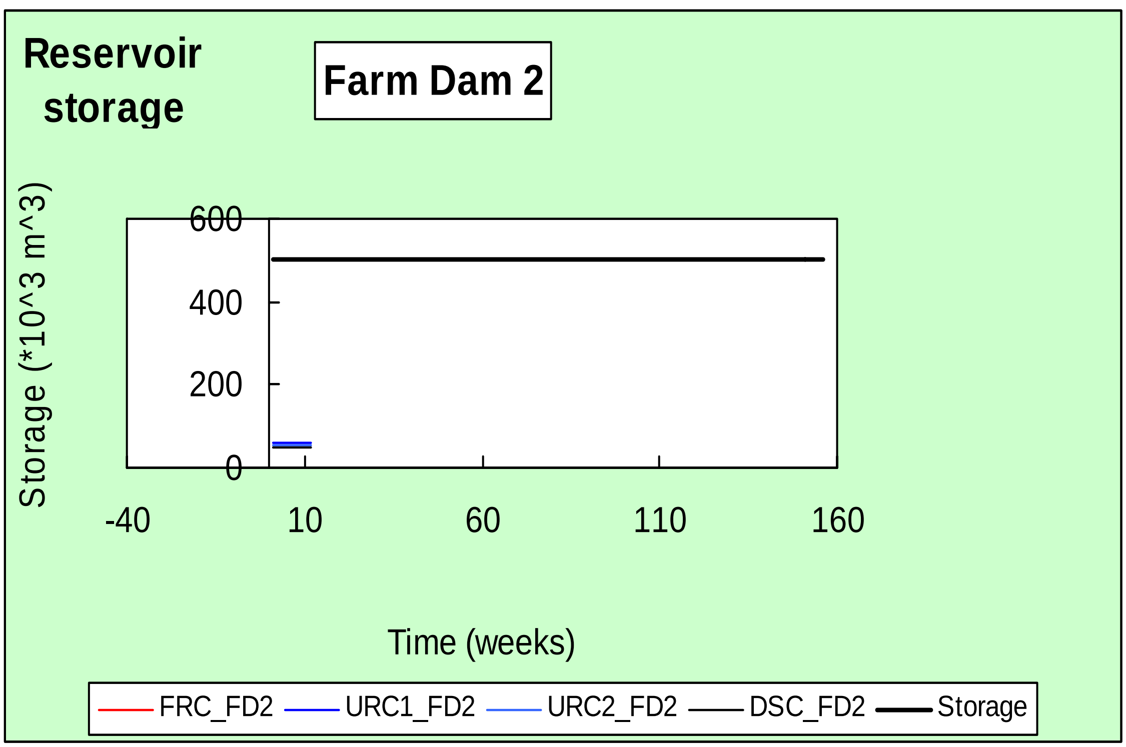
Rainfall data is distributed using polynomial curve fitting

Appendix 17: Model Results for Scenario 1

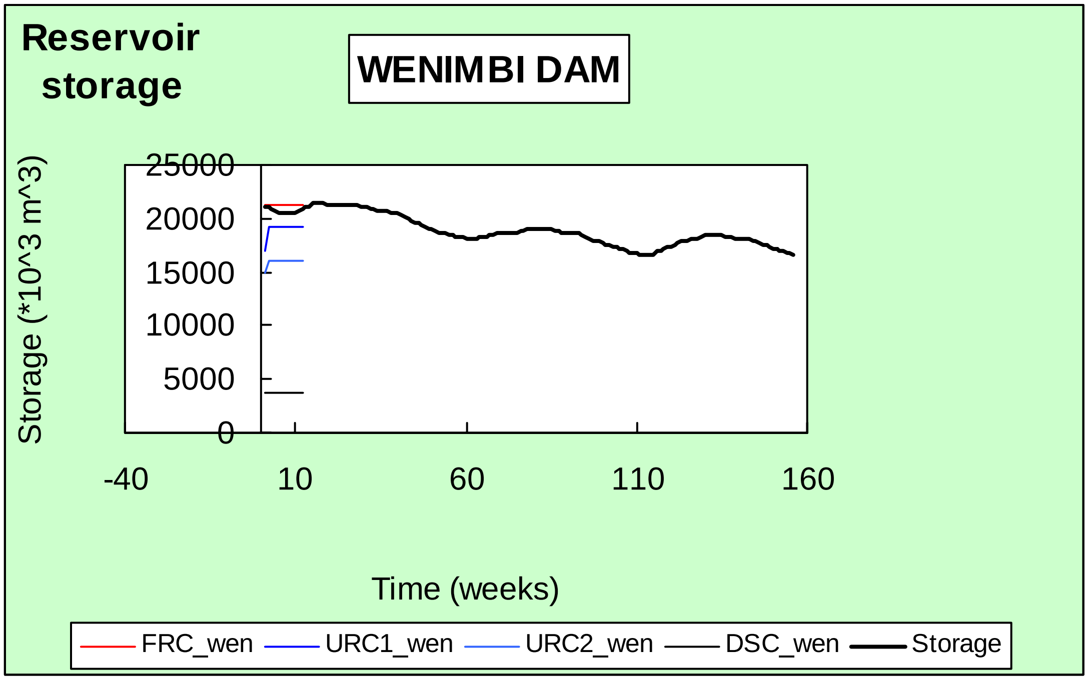


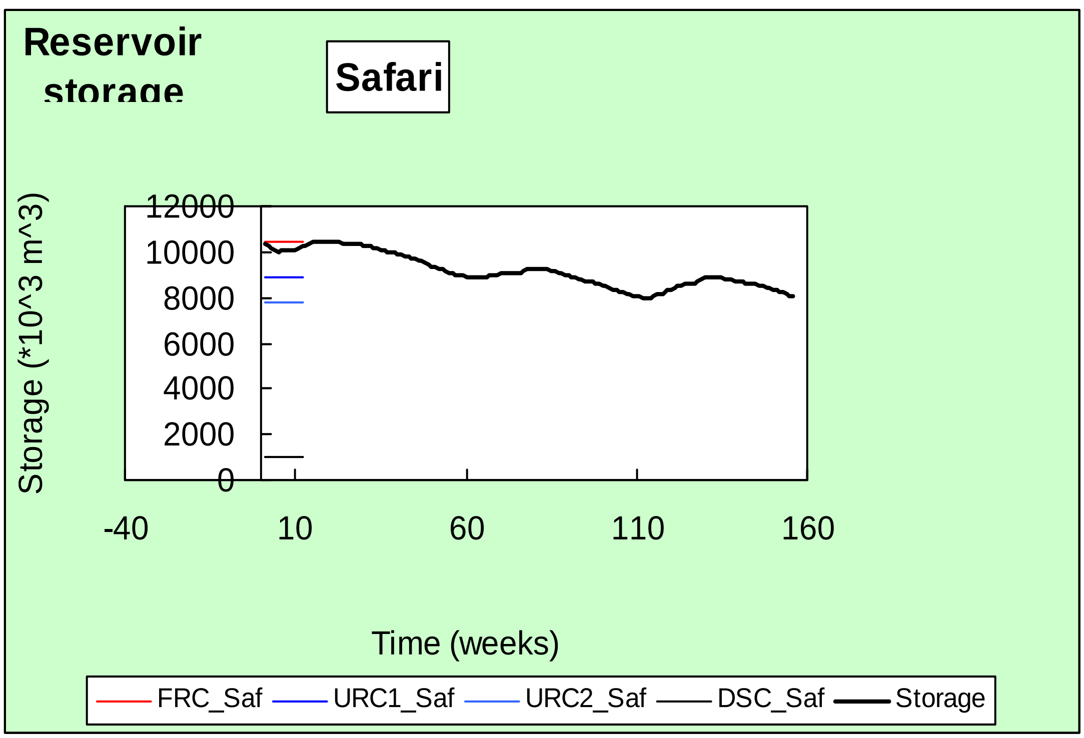


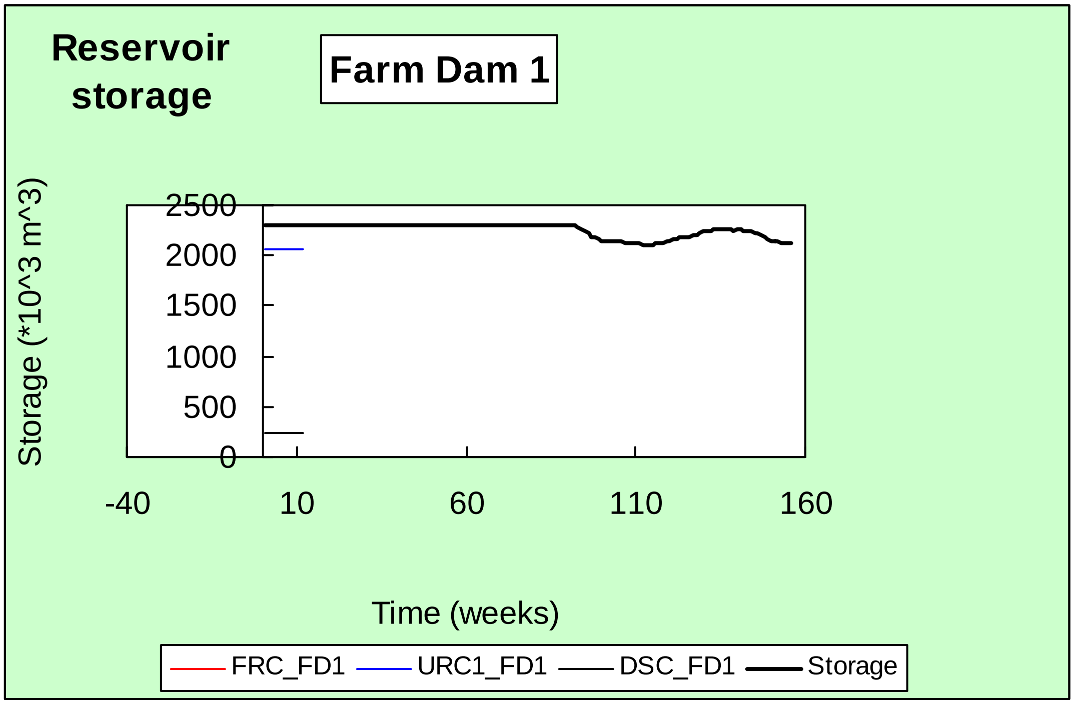

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

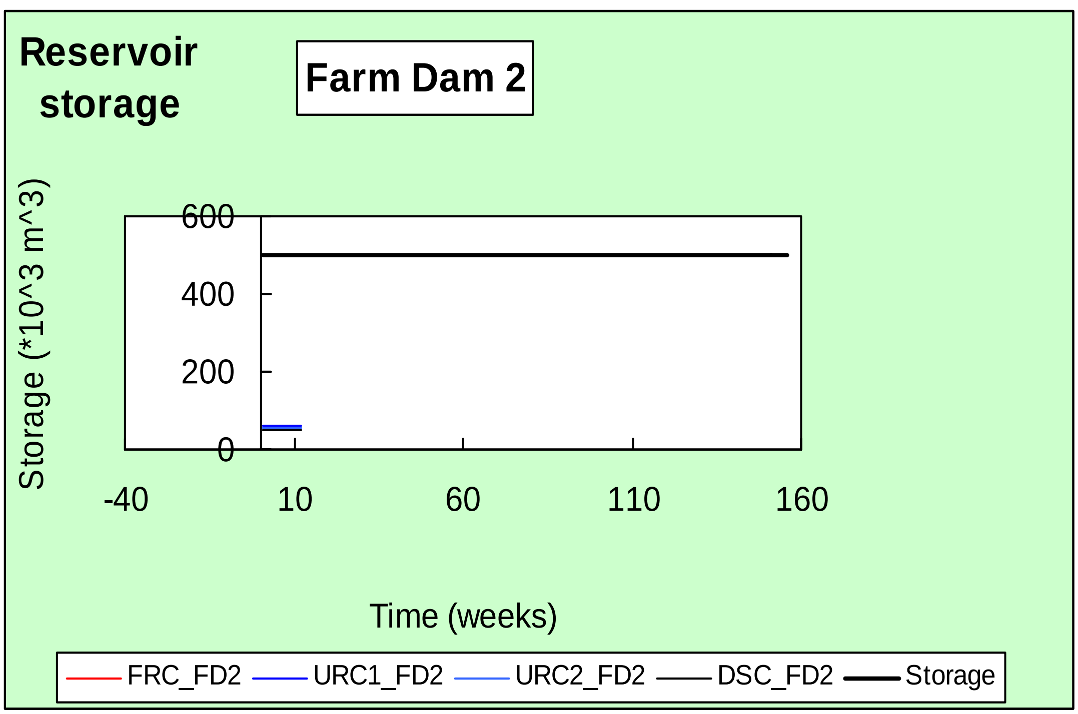

Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 18: Model Results for Scenario 2

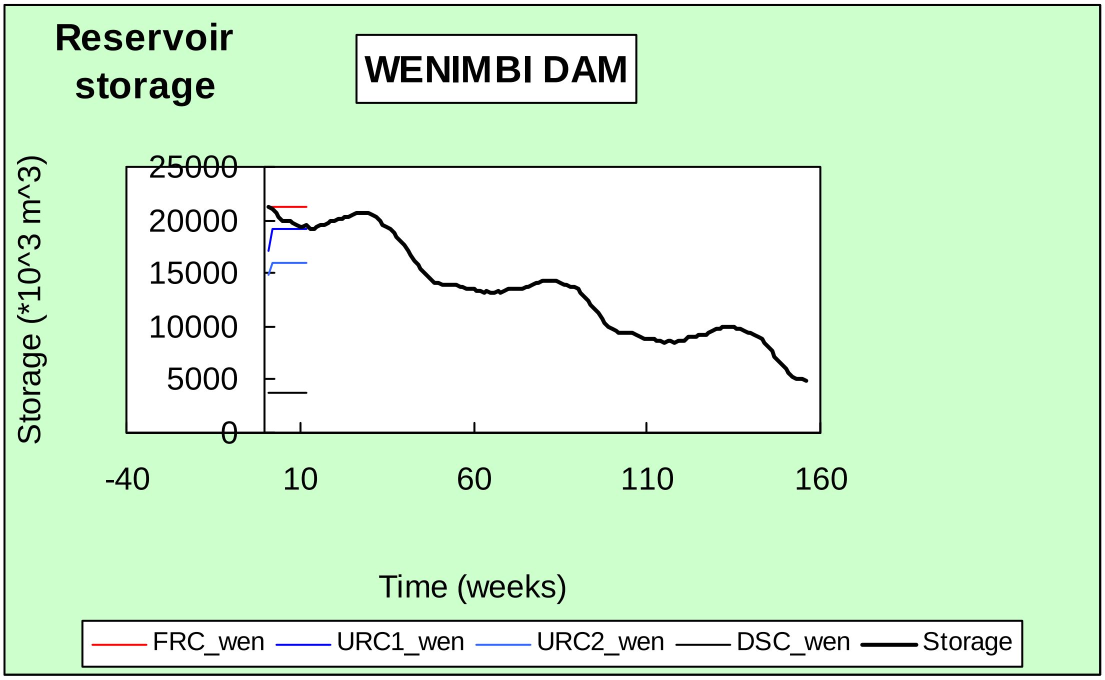


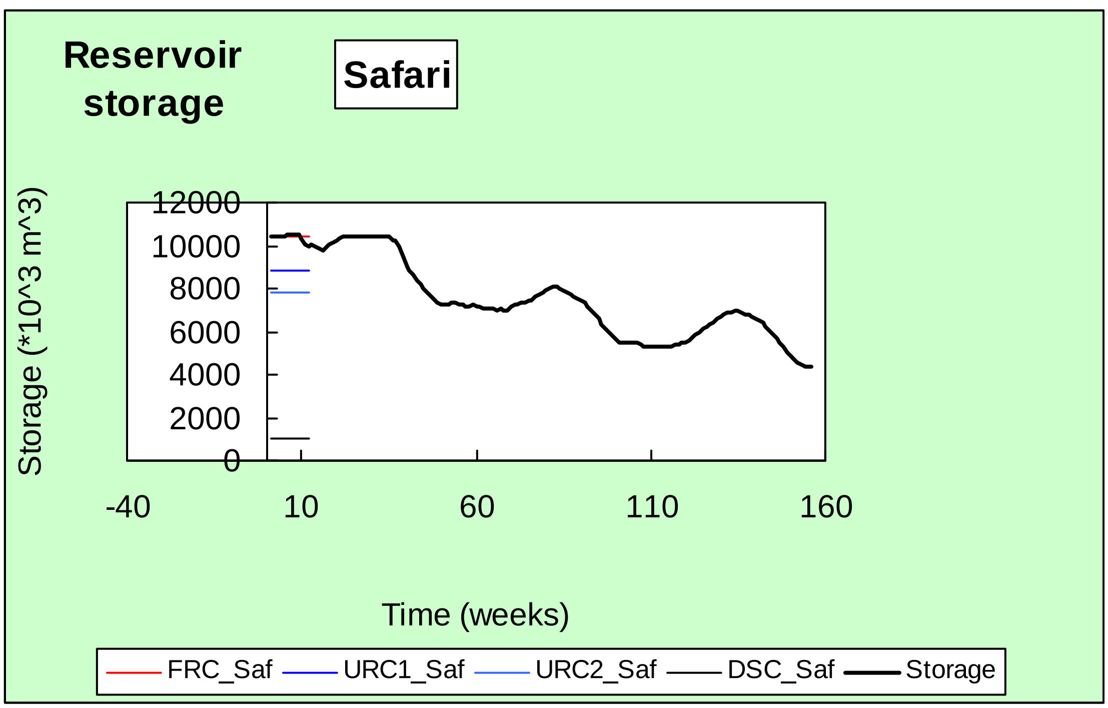


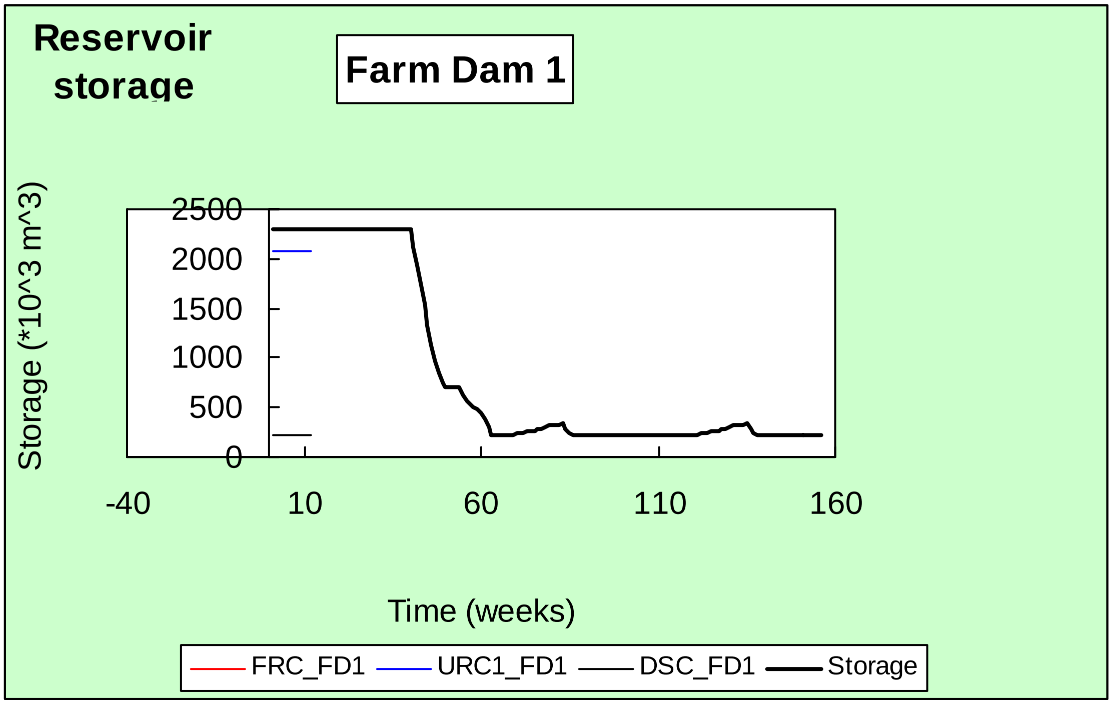

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

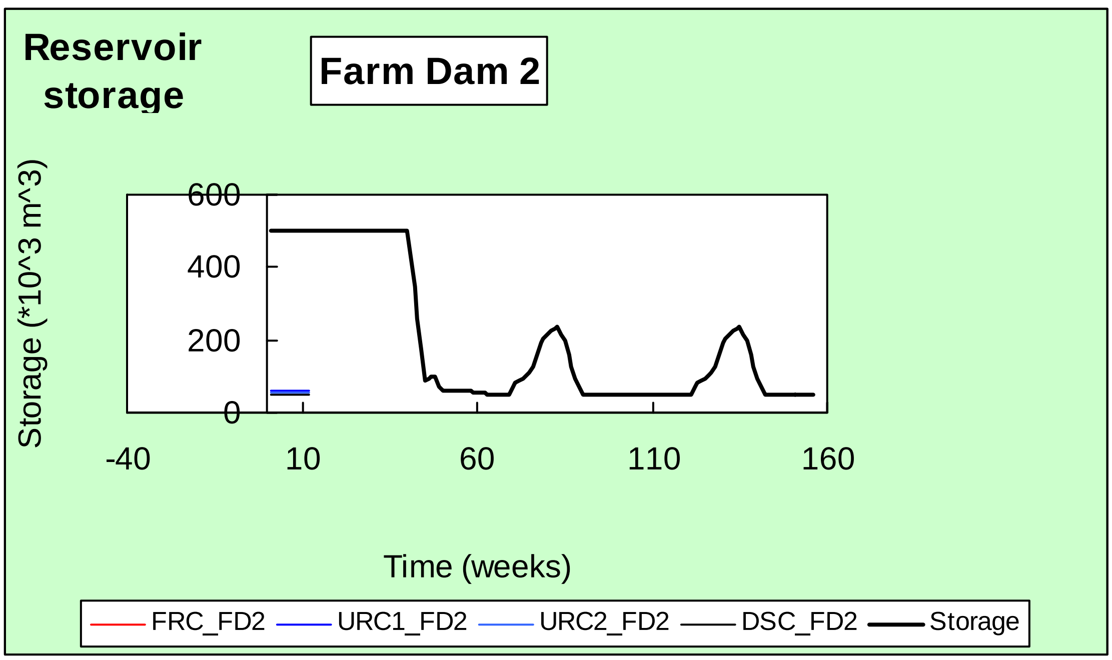

Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 19: Model Results for Scenario 3

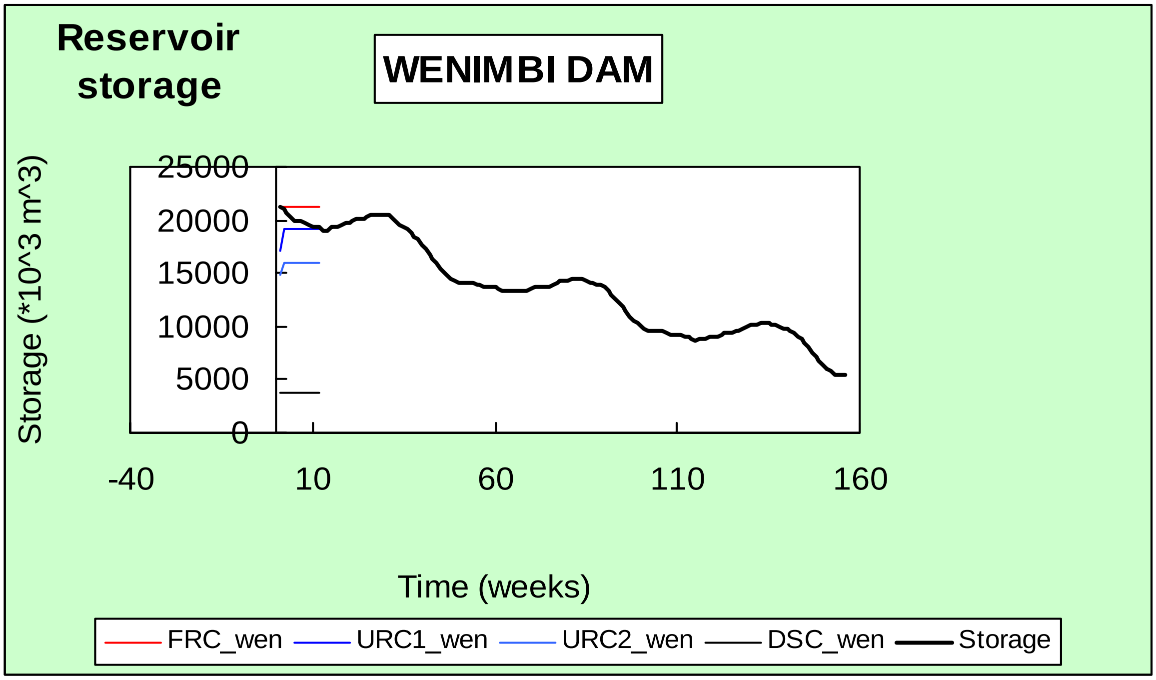


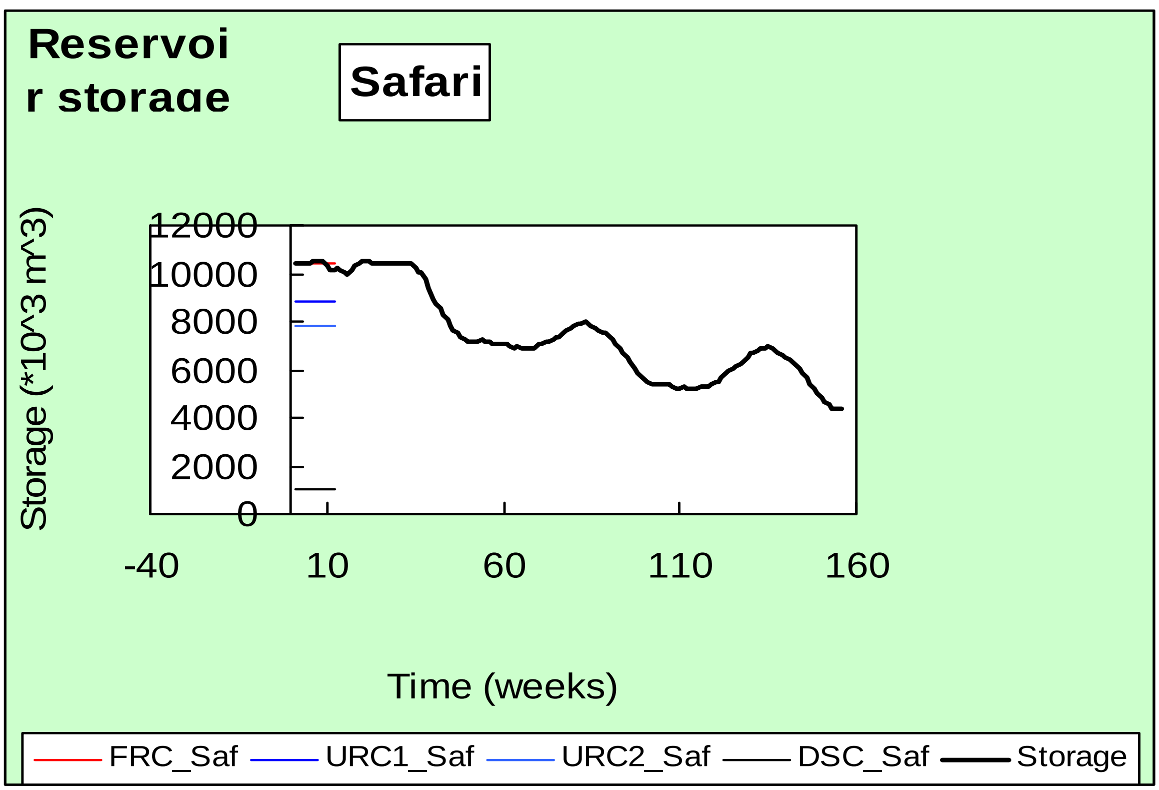


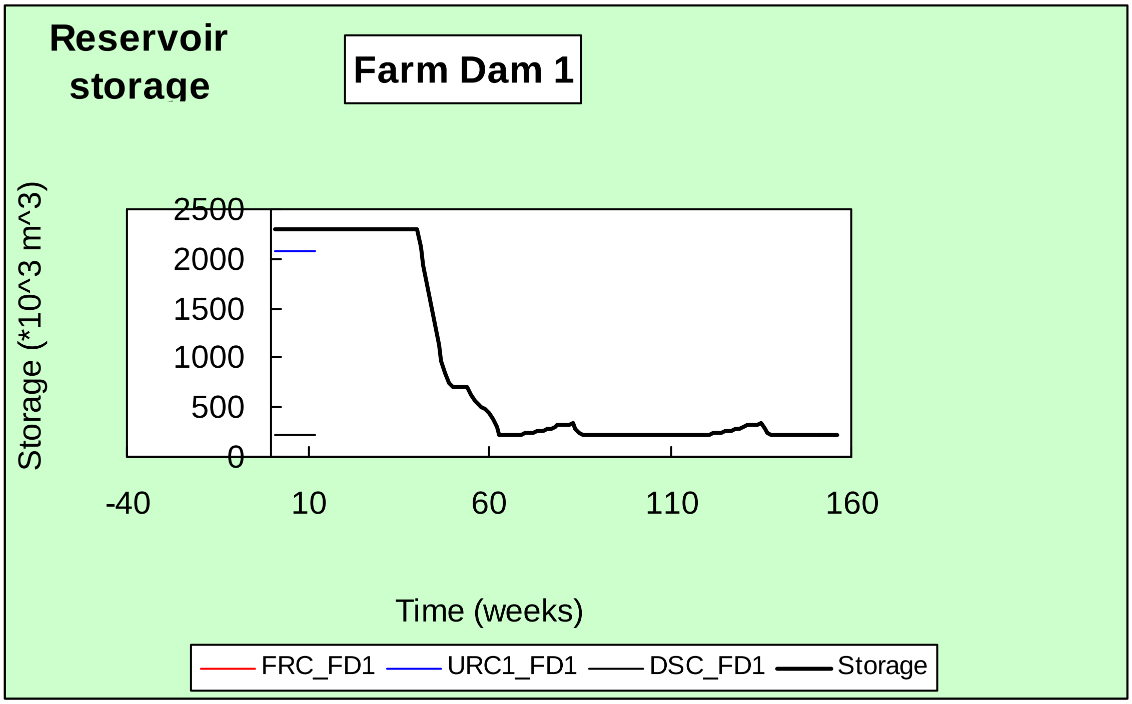

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

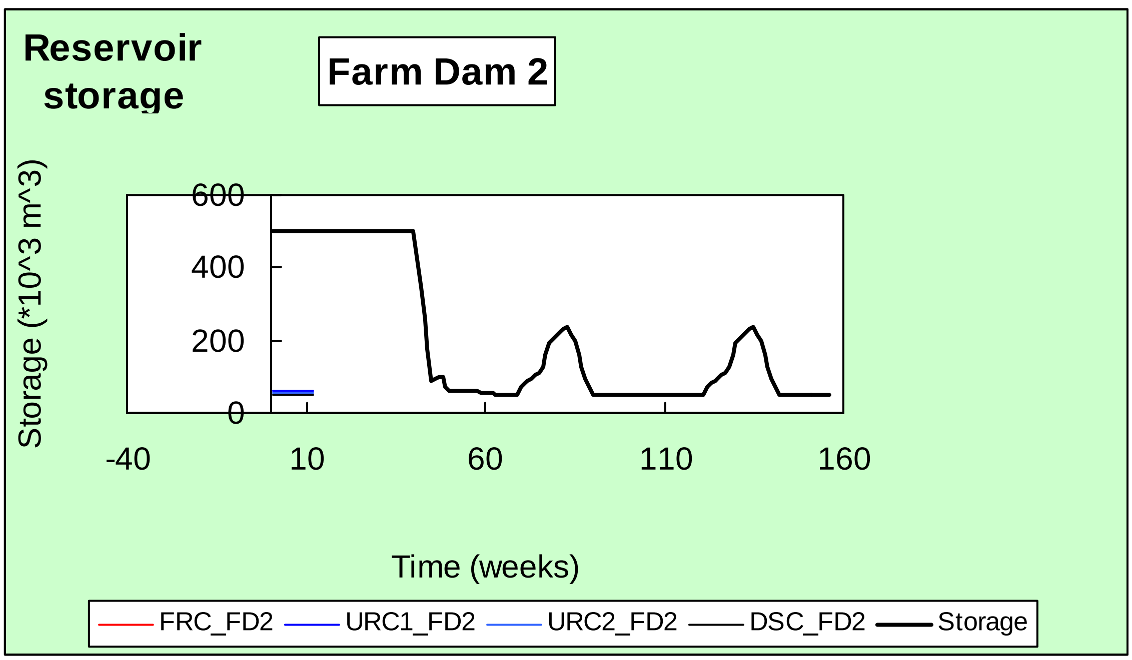

Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 20: Model Results for Scenario 4

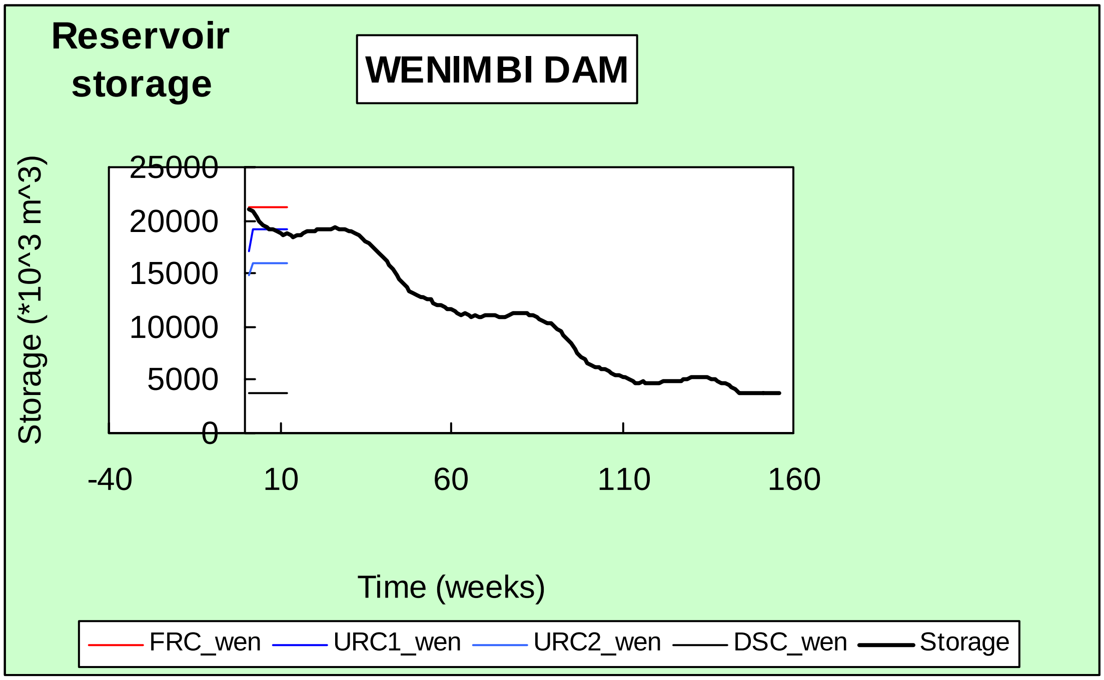


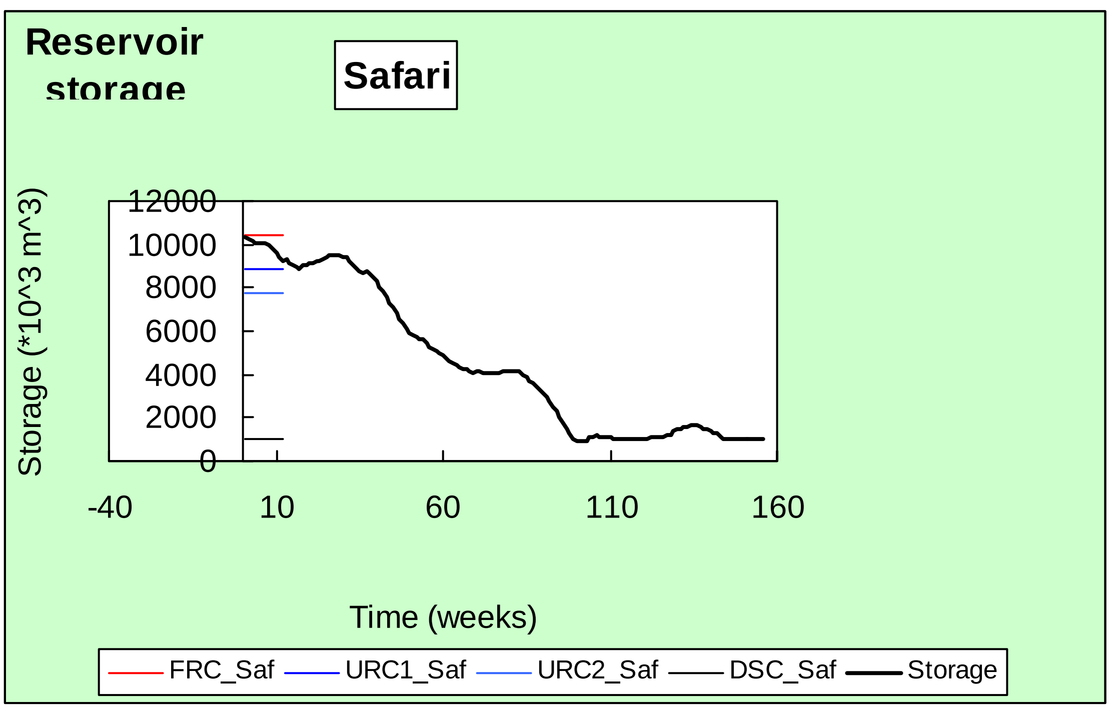


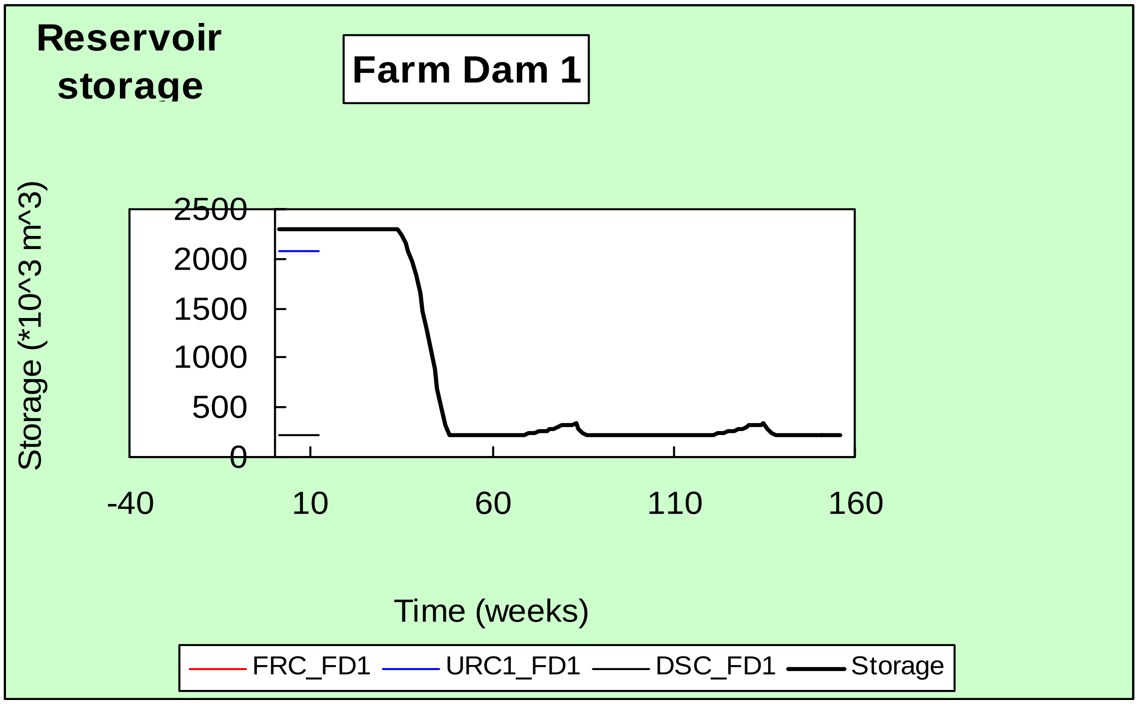

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

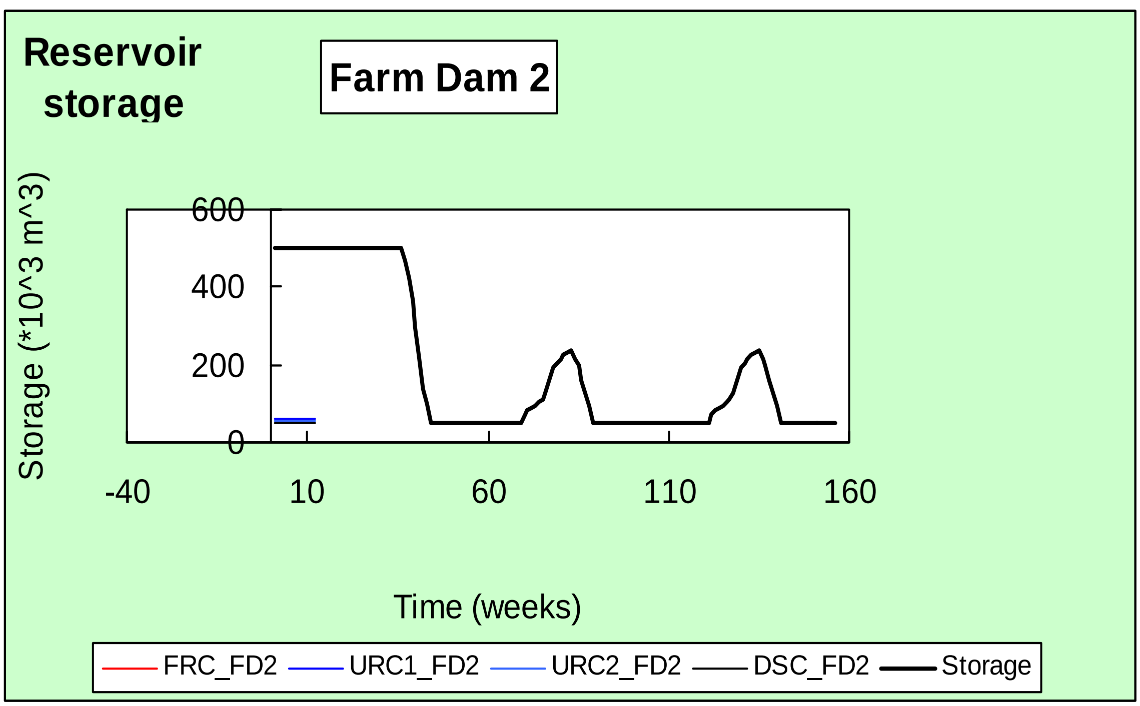

Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 21: Model Results for Scenario 5

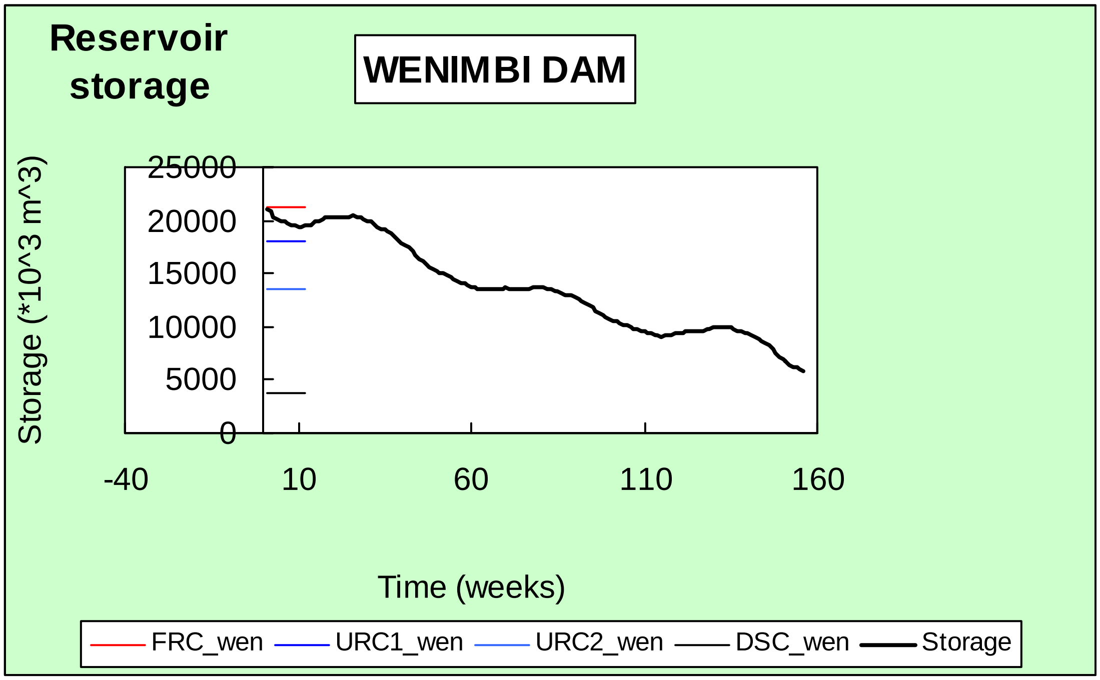


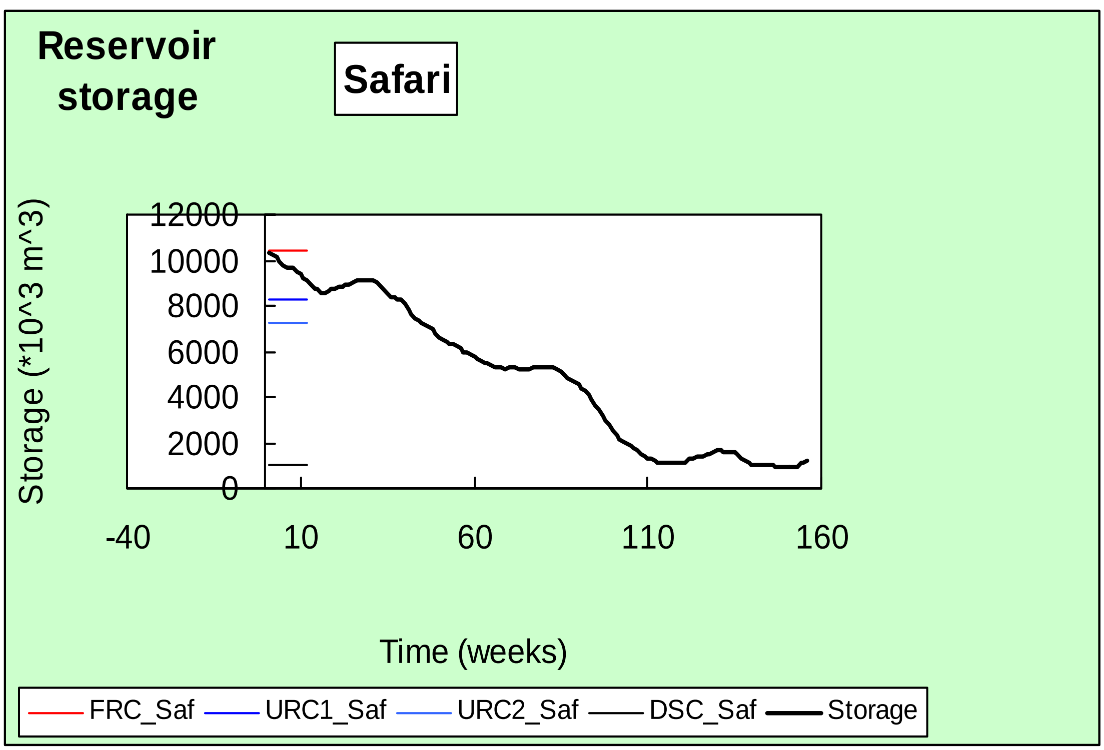


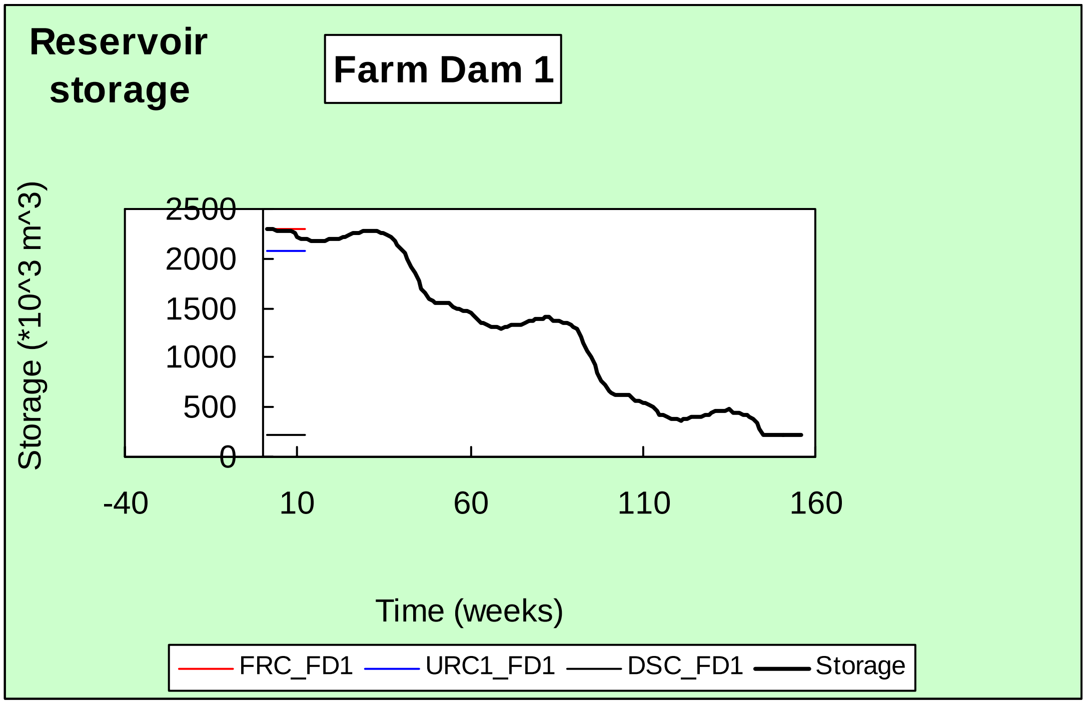

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage


Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

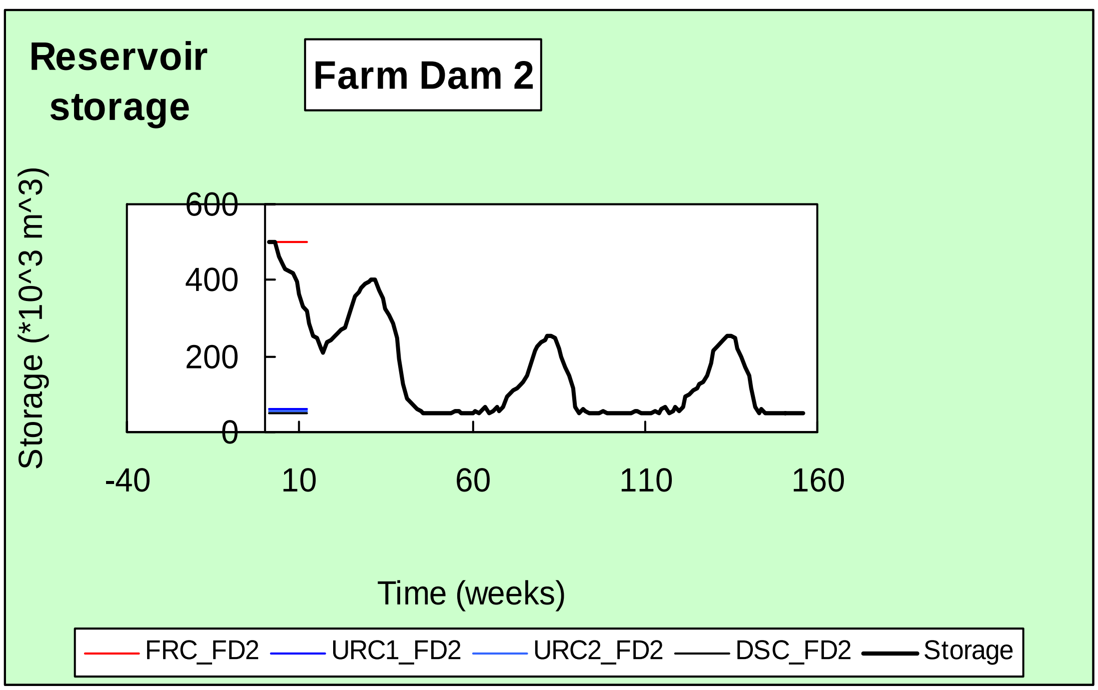
Appendix 22: Model Results for Scenario 6





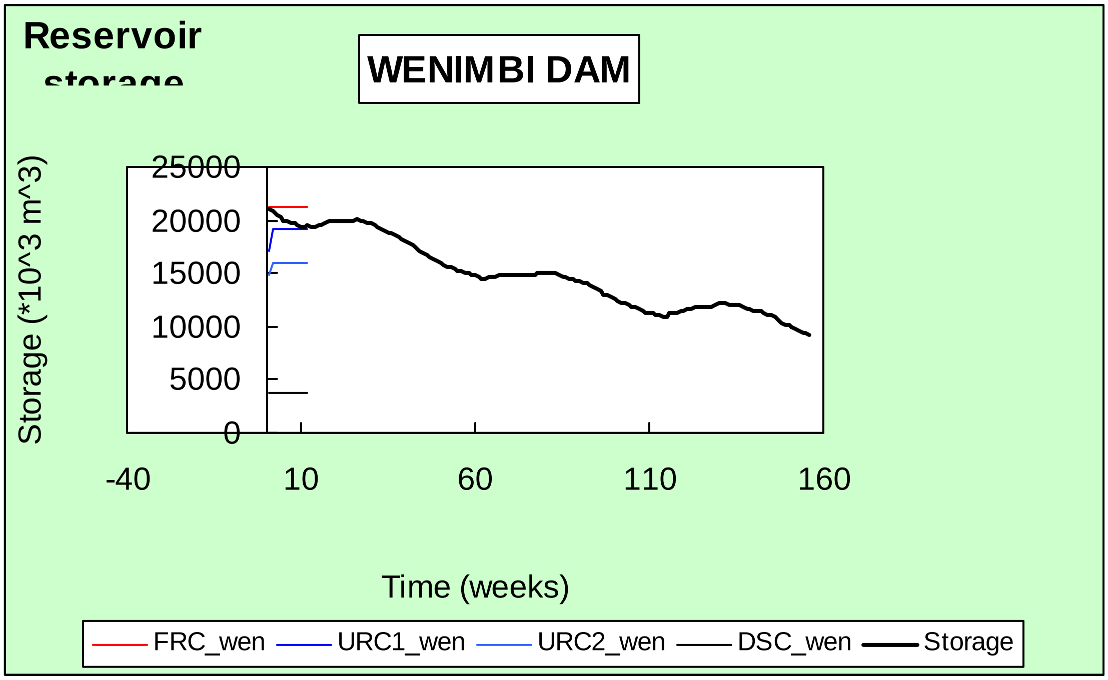


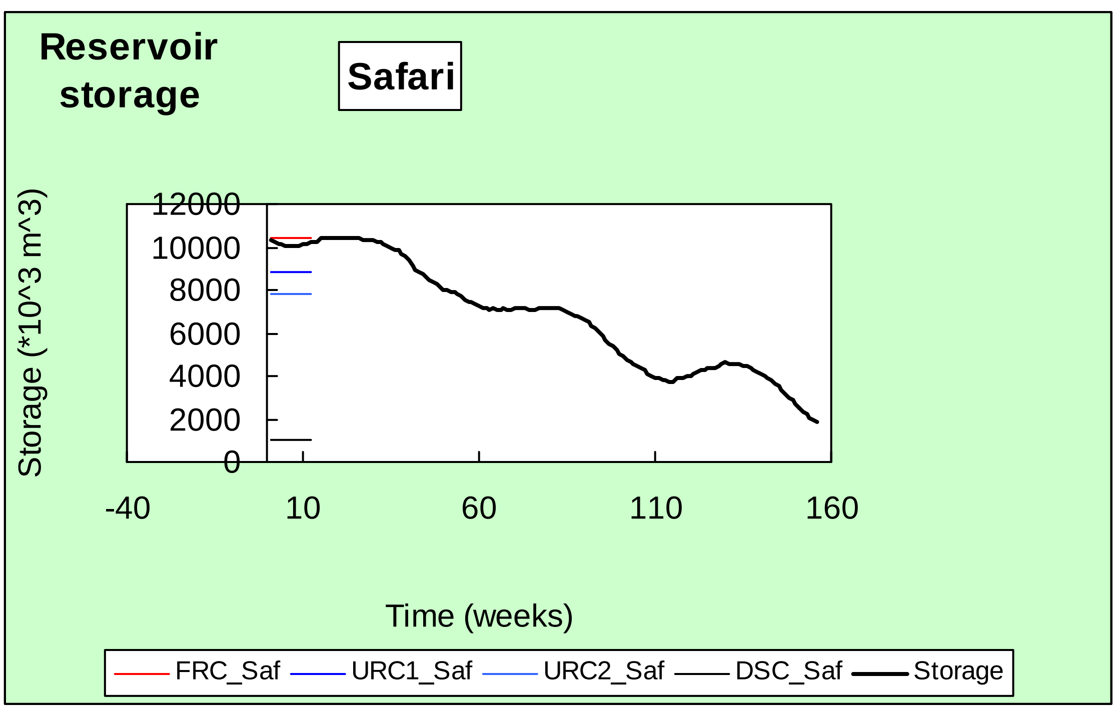
Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

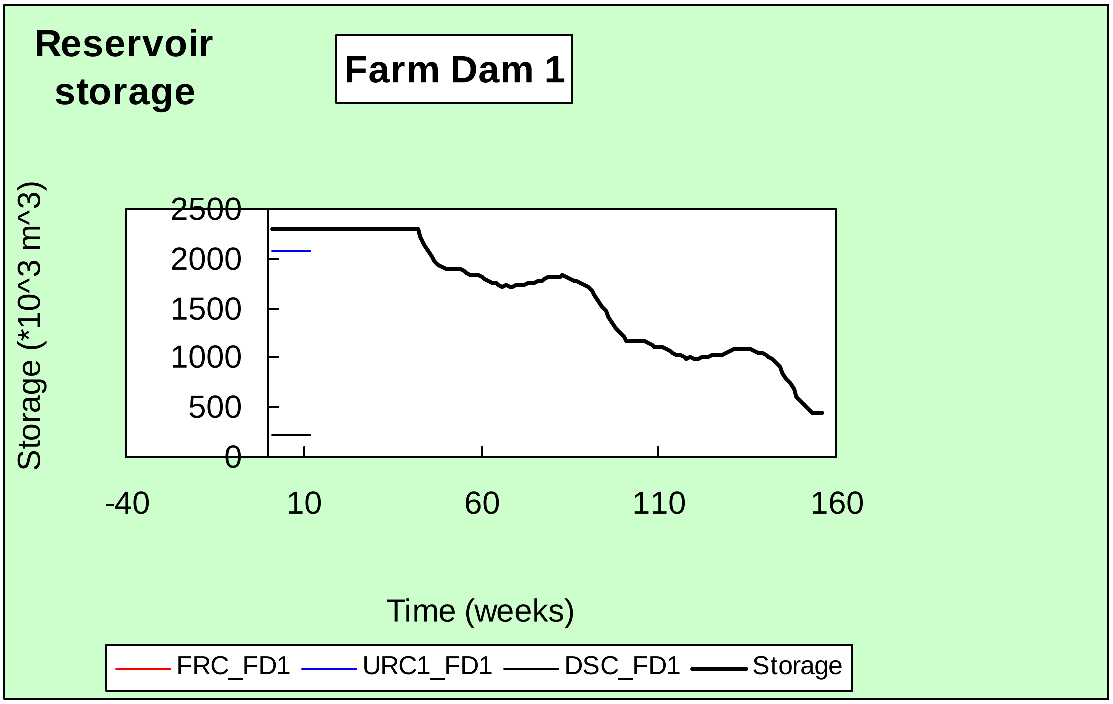


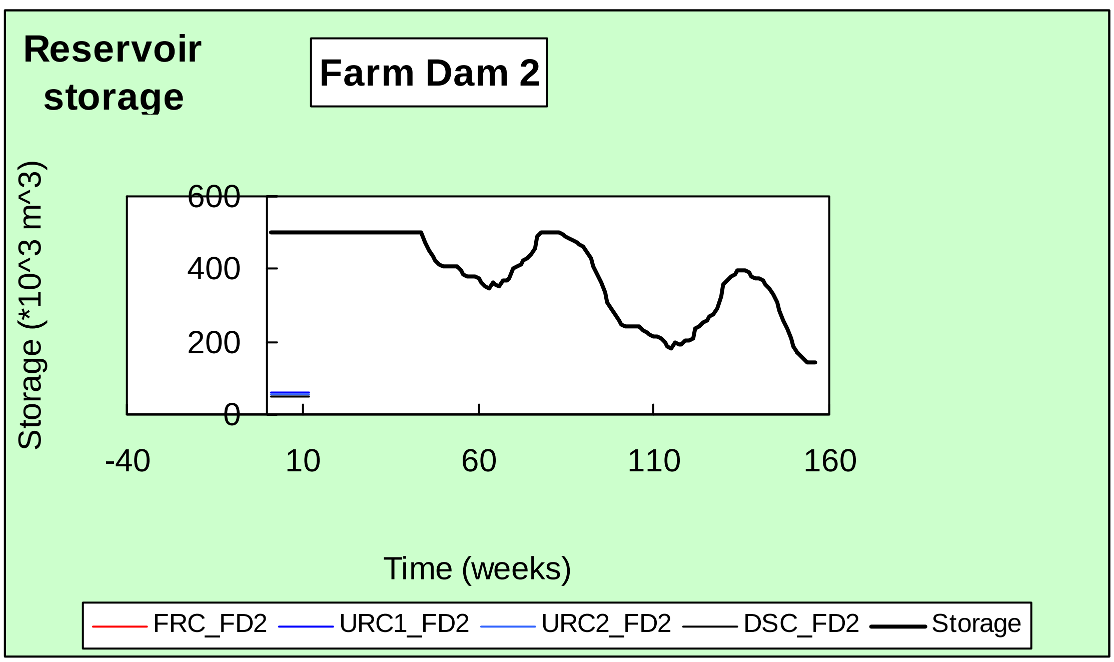
Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 23: Model Results for Scenario 7

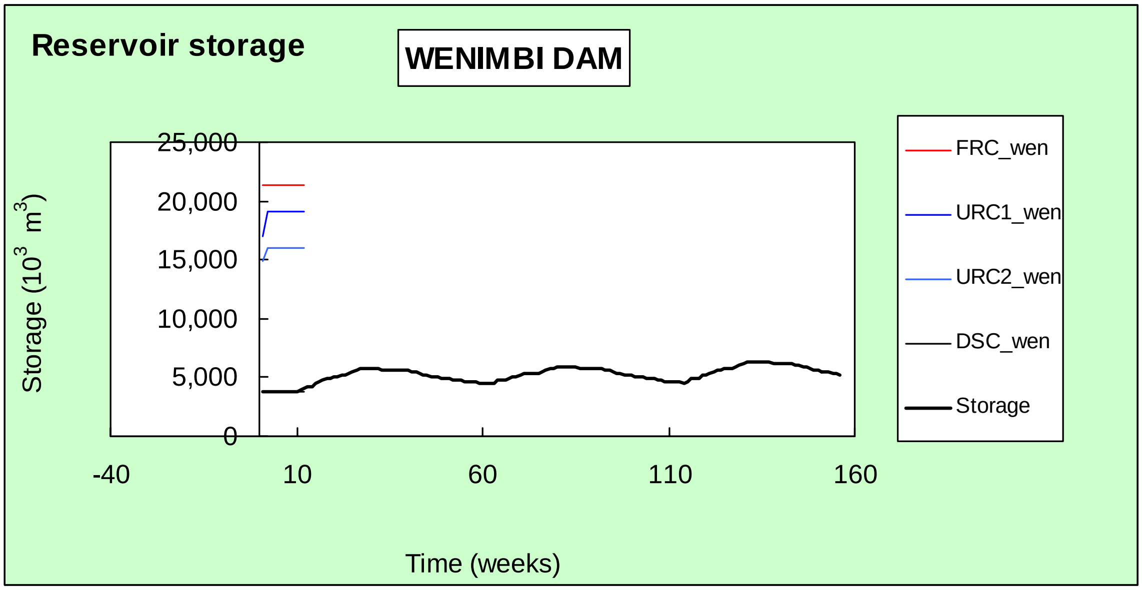


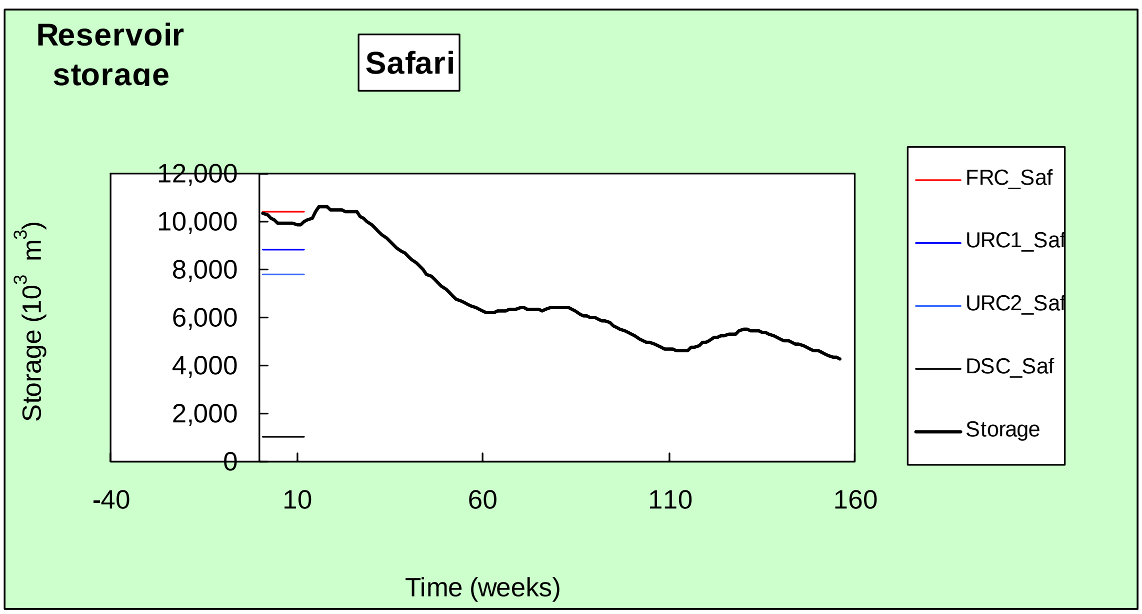


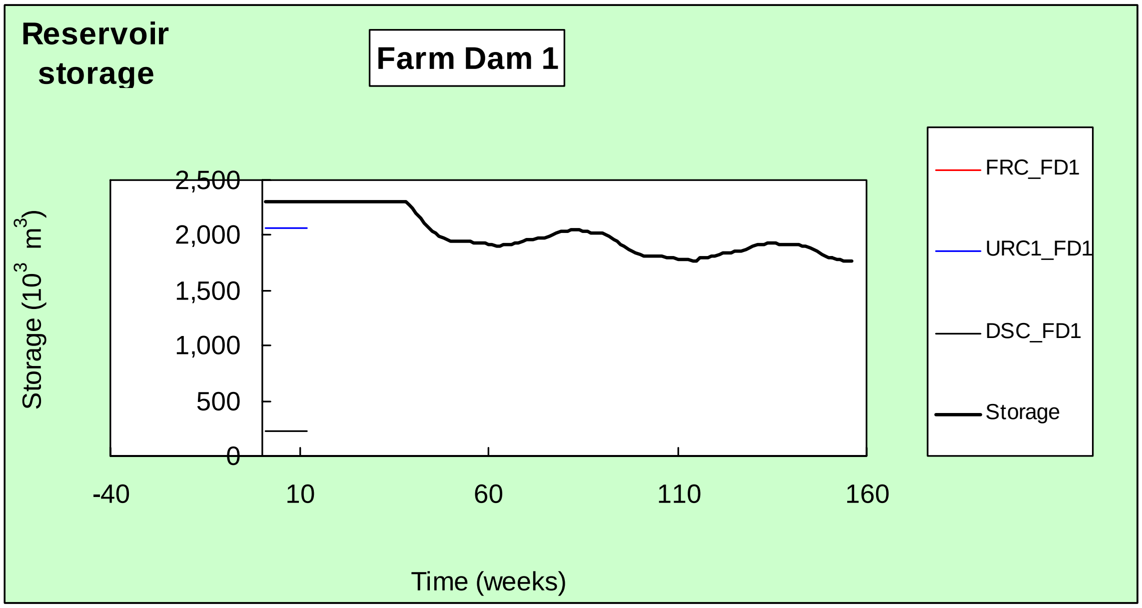

Reservoir storage
Farm Dam 1
Storage (*10^3 m^3)
2500
2000
1500
1000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage

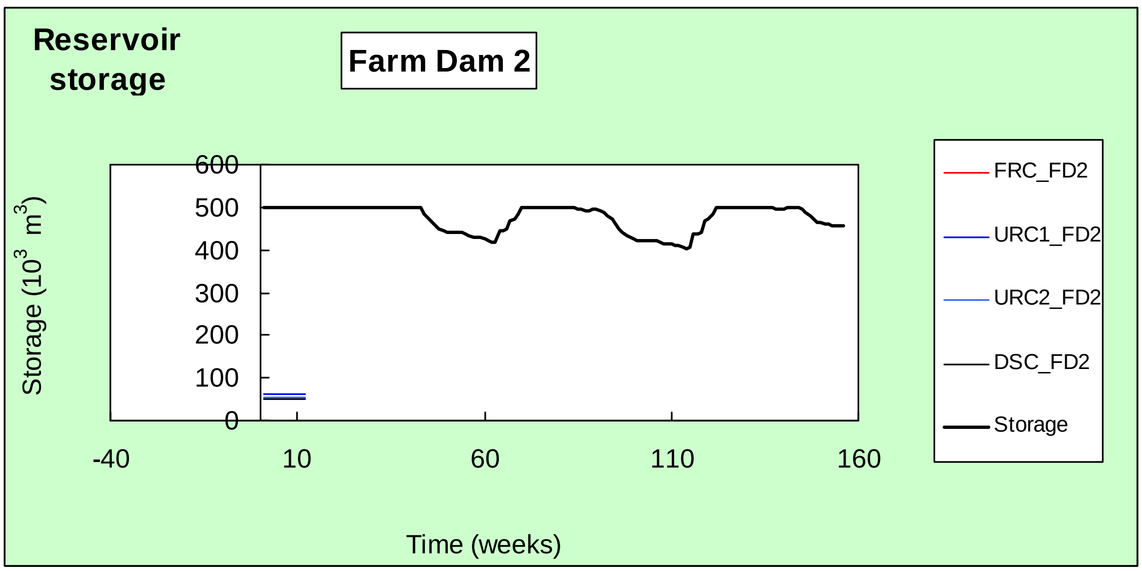

Reservoir storage
Farm Dam 2
Storage (*10^3 m^3)
600
400
200
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage

Appendix 24: Model Results for Scenario 0 (a) at 75% Irrigation Efficiency






Reservoir storage
Farm Dam 1
Storage (10^3 m^3)
2,500
2,000
1,500
1,000
500
0
-40
10
60
110
160
Time (weeks)
FRC_FD1
URC1_FD1
DSC_FD1
Storage


Reservoir storage
Farm Dam 2
Storage (10^3 m^3)
600
500
400
300
200
100
0
-40
10
60
110
160
Time (weeks)
FRC_FD2
URC1_FD2
URC2_FD2
DSC_FD2
Storage