Modeling the response of small multi-purpose reservoirs to hydrology for improved rural livelihoods in the Mzingwane catchment: Limpopo Basin

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Abstract

Determination of the impact of small reservoirs on improved and sustainable rural livelihoods in semi arid regions of Zimbabwe remains a largely unknown and peripheral issue. Small reservoirs contribute to the overall development of the area because they provide an opportunity for the community to deal with inter-year rainfall variation by providing storage for a significant quantity of water . Water resources literature suggests that computer based models have the potential to provide useful information in facilitating water resources planning and management, as well as the decision-making process. An understanding of catchment hydrological parameters is paramount to obtaining useful results for planning, development and management of small multi-purpose reservoirs.

An Integrated Water Resources Management (IWRM) tool, the Water Evaluation and Planning (WEAP) system model was to be calibrated and used to evaluate and simulate the various livelihood issues at play in the Siwaze subcatchment of the Mzingwane catchment within the Limpopo basin on the Zimbabwean side. The quality of model performance depends on the quality of data used, as well as who collected the data and for what purpose. The data that is required for input into the WEAP model is extensive. These limitations on the model performance cannot be ignored in its calibration.. The study represents an initial attempt to apply WEAP model as a means of addressing planning issues in water stressed Limpopo basin. However, tools can be found to better plan, develop and manage small multi-purpose reservoirs, in order to improve on decision-making capacity in determining rural livelihoods levels that are sustainable through optimal small reservoirs development and management.

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List of Acronyms

AREX ------ Agricultural Extension services

DDF ------ District Development Fund

GIS ------ Geographical Information System

IWRM ------ Integrated Water Resources Management

MDG ----- Millennium Development Goals

MoW&ID---- Ministry of Water & Infrastructure Development

NGO ------ Non Governmental Organisations

SEI ----- Stockholm Environmental Institute

UZ----- University of Zimbabwe

WRM ----- Water Resources Management

ZINWA--- Zimbabwe National Water Authority

RDC ---- Rural District Council

WEAP --- Water Evaluation And Planning

RMS --- Root Mean Square

CHAPTER 1: Introduction

1.1 Background

The effect and synergies of small multi-purpose reservoirs to catchment hydrology and their impact on rural livelihoods remains largely unknown in the semi-arid regions of Zimbabwe. The Mzingwane catchment lies in one such region which experiences water scarcity due to low rainfall and high loses to evaporation. The average rainfall in the catchment ranges from 300 to 600mm/year with a coefficient of variation of 120% is insufficient to sustain water related rural livelihoods. Runoff is limited and depends on the rainfall intensity, frequency and duration (LeRoy, 2005), as well as land use and other geo-topographical parameters. It is necessary therefore that the little runoff which is generated during the short wet season from October to March, be captured and stored for use during the dry seasons of the year. Small reservoirs are providing this function of being a source of water for the rural population during the dry period.

The people in this region depend on rain fed agriculture, which is unable to sustain livelihoods as a result of poor and erratic nature of rainfall (Mtisi, 2002). Small reservoirs support livelihoods such as providing water for domestic water supply, livestock watering, small-scale irrigation, fishing, brick making and the largely ignored environmental functions of supporting wild life and the ecosystem.

However, the development of small reservoirs in Zimbabwe is primarily an unplanned and adhoc activity (Dube, 1999). Their development is usually in response to community requests, or imposed upon by the funding agent. The Government of Zimbabwe passed a new Water Act in 1998 which is based on Integrated Water Resources Management (IWRM) principles. The Act is restricted only to the definition of small reservoirs but does not address the issues of planning, development and management of small reservoirs. Developers and Government organisations like the District Development Fund (DDF), Agricultural Research Extension as well as Non –Governmental Organisations (NGOs), local communities and other donor organisations, in most cases did not coordinate in the provision and development of small reservoirs (Bourdillon, et al, 2001).

1.2 Problem Definition

Determination of the impact of small reservoirs on improved and sustainable rural livelihoods in semi arid regions of Zimbabwe remains a largely unknown and peripheral issue.

1.3 Justification of Research Area

The importance accorded to IWRM. in sustaining rural livelihoods in Zimbabwe provides opportunities for coordinated planning, development and management of small reservoirs through the aid of decision making support tools like water resources systems models.

1.4 Objectives of the Study

1.4.1 Main objectives

To improve on decision-making capacity in determining rural livelihoods levels that are sustainable through optimal small reservoirs development and management in a defined catchment.

1.4.2 Specific Objectives

- To calibrate a water resources system model (WEAP) for analysing hydrological and rural livelihoods issues for the catchment.
- To simulate scenarios, using WEAP model, to support options and recommendations on optimum sustainable rural livelihoods levels.
- To study and assess the impact of simulated scenarios for improved rural livelihoods.

1.5 Hypothesis

- Tools can be found to better plan, develop and manage small multi-purpose reservoirs for improved and sustainable rural livelihoods.

1.6 Research Questions

- How effective or beneficial is modeling as an aid to decision making processes with regard to small reservoirs.

- What is the impact of small reservoirs on catchment hydrology and rural livelihoods?

1.7 Organisation of the thesis

This research study proceeds in the rest of the presentation as follows:

Chapter 2 – Literature review
The literature review for this research focuses on definition of small reservoirs, small reservoirs and the rural (poor) livelihoods as well as the hydrological system components. This chapter will also introduce the issues on modeling as a tool for improved planning and decision-making.

Chapter 3- -Study area
The area of study was in the Mzingwane catchment of the Transboundary Limpopo basin, in a sub catchment called Insiza and a sub-sub catchment called Siwaze.

Chapter 4 – Research methods and materials

This chapter covers the methods and techniques that were used in the course of the research. Activities that took place in Boston, such as training on WEAP, will be briefly demonstrated as well as the activities undertaken during the field study. The last few weeks of the thesis research were spent arranging the received information and calibrating the model. The scenarios were then simulated which lead to a number of results.

Chapter 5 – Results and discussions

The hydrological responses are largely dependent on the physiographical data and climatic data collected and inputted into the model. The scenarios simulated and are based on results from the calibration of the model

Chapter 6 – Conclusion and recommendations

Conclusions and recommendations on models and small reservoirs impacts on hydrology and livelihoods are drawn from the study.

CHAPTER 2: Literature Review

2.1 Definitions: Small Reservoirs

A small reservoir (commonly called small dam) is any artificial dyke, levee or other barrier, together with appurtenant works, which is constructed for the purpose of impounding water on a permanent or temporary basis, that raises the water level by 1.8 metres or more above the usual, mean, low water height when measured from the downstream toe-of-dam to the emergency spillway crest or, in the absence of an emergency spillway, the top-of-dam (www.smallreservoirs.org).

The Zimbabwe National Water Authority (ZINWA) ACT of 1998 defines a small reservoir as “a structure constructed together with abutments, appurtenant works and foundation and is capable of diverting or storing water and which—

a) has a vertical height of less than eight metres measured from non overflow crest of the wall-----
b) is capable of storing less than five hundred thousand at full supply level---.”

Table 2.1: Classification of dams in Zimbabwe

Description	**Capacity (m^3)**	**Dam wall height**	**Responsibility**
Major/ large dam	>1 – 100 million	>15 metres	ZINWA, MoW&ID
Medium dam	0.5 -1million	8-15 metres	DDF, NGOs/ ZINWA
Small dam	< 0.5 million	< 8 metres	Communities/ZINWA

Source: ZINWA (1998)

ZINWA has recently acquired has responsibility over all water resources including small dams found in the farms through the new Water Act. These dams have been gazetted under a statutory instrument.

2.2 Purpose of small reservoirs

Small reservoirs contribute to the overall development of the area because they provide an opportunity for the community to deal with inter-year rainfall variation by providing storage for a significant quantity of water (Poolman, 2005). The stored water can be used during the dry-season for irrigation, livestock watering and domestic use. Small reservoirs can aid the community in development issues as local communities are given the opportunity to grow crops all year-round (Stevenson, 2000). This means that the livelihoods of the people will become more stable because they will have a more constant

food supply and receive some income during the entire year. It is therefore in the interest of all stakeholders to look at how planning, development, maintenance and operation of small reservoir systems can be improved.

2.3 Small reservoirs and livelihood issues

The concept of 'livelihood' embraces all aspects that influence the way people make a living and organize their lives (Bourdilon M, et al, 2001)

The concept of livelihood which is defined as *"means of living or of supporting life and meeting individual and community needs"* - provides new perspectives on developing healthy sustainable societies that provide people with secure and satisfying livelihoods (Singh, 1996). Sustainable livelihoods have been defined as "capacities to generate and maintain their means of living, enhance their well-being and that of future generations." (Singh, et al ,1996).There are five types of capital that affects the livelihoods of the rural people, namely natural, economic, financial, human, and social

Natural capital relates to land holding and ownership as well as access to natural resources like water, firewood pastures and forests. Economic capital covers assets while financial capital deals with the access to cash either from the financial institutions or from the sale of agricultural produce or livestock. Human capital involved the issues of education level, employment and family size as a source of labour. On the other hand, Social capital refers to community groups, association, kinship, leadership and institutional structures.

There is an array of solutions that could be used in order to solve the problems that are related to development of small reservoirs as a means of improving livelihoods. The most appropriate solutions, however, vary from place to place and are dependant on a wide range of circumstances, and can be found in traditional life or as modern solutions.

2.3.1 Uses of small reservoirs in Mzingwane catchment

The most common uses of small reservoirs in the Mzingwane catchment are shown on Figure 2.1, with livestock watering being the top most. Agriculture is in the form of small vegetable gardens in the vicinity of the small reservoirs. Only 65% of the population use these small dams for drinking (Sithole, et al, 2005). This has more to do with perception on quality of open water (surface) reservoirs. Cattle are the most common livestock kept by the people of Siwaze, with some households owning up to 20 head of cattle.

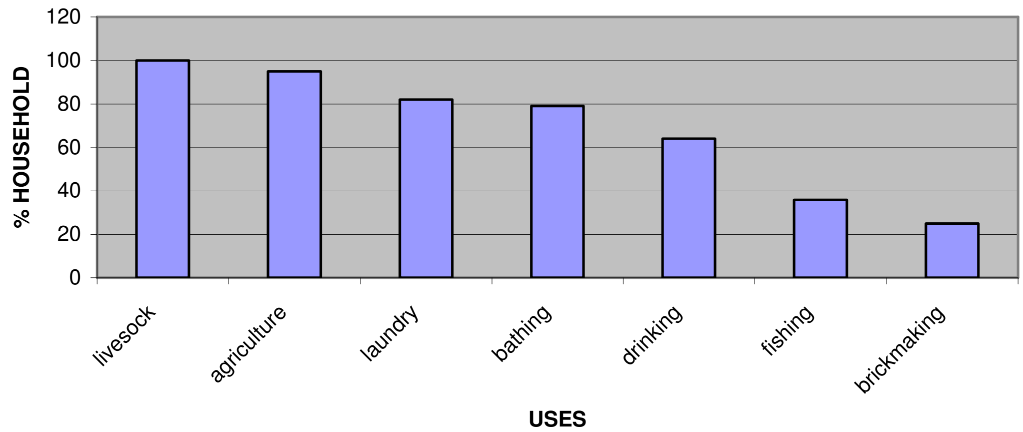


Figure 2.1: Uses of small reservoirs (source: Sithole 2005)

The following photos (Figure 2.2) captures the dependence of the community on small reservoirs, ranging from small garden irrigation, livestock watering, domestic uses and fishing activities (respectively) in the Siwaze catchment. The uses of small reservoirs are apparent. Livestock watering constitute the largest consumer of water from these reservoirs. Drinking is not high on the list. This can be attributed to the level of water quality. Agriculture comes second after livestock watering.

Figure 2.2: Water uses and support for livelihoods

In these communities there is no formal employment and livestock enterprises are one of the major sources of income. The livestock are valued as a source of wealth and as an investment. The livestock are sold to cater for all basic needs which include fees (e.g. for health and education), purchase of food stuff.

2.4 Availability of water

At both regional and national levels, water resources in Southern Africa are highly unevenly distributed (FAO, 2004). This unevenness is both spatial and temporal. Rainfall is largely seasonal and most rainfall is received during a five-to-six month's period in most areas. Most water resources conflicts are as a result of users refusing to share the scarce commodity. This leads to inflexibility on the part of those with the resource, which in turn results in civil unrest. High levels of evaporation due to high temperatures and persistent draughts also add to water scarcity (Thompson, 2005). Figures as high as 1000mm/annum of evaporation has been recorded compared to an average rainfall of 600mm/annum.

The Dublin Statement and Conference Report provide a framework for water-related actions and serves as a "holistic, comprehensive and multi-disciplinary approach [to water resources problems worldwide]." (Solanes, et al, 1999) The framework is based on four principles that cover social, political and economic issues at hand:
- Fresh water is a finite and vulnerable resource, essential to sustain life, development, and the environment …

- Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels ...

- Women play a central part of the provision, management and safeguarding of water …

- Water has an economic value in all its competing uses and should be recognised as an Economic good

These principles were established at the 1992 International Conference on Water and the Environment now form a basis of the Millennium Development Goals (MDGs). Just like the MDGs, the Dublin Principles are dynamic and should be adjusted according to the situation wherein they are applied.

The third Dublin principle is more relevant to small reservoirs, and emphasizes the role of women as major stakeholders in the provision and management of water resources. For this reason it is important that the small reservoirs be planned and managed for sustenance of rural livelihoods with women on board, as the constitute the majority of people in need of safe water..

2.5 Planning processes for small reservoirs

Water scarcity is one of the conditions that prompt water resources planning of reservoirs for the improvement of livelihoods. One definition of planning reads: “Planning is the process that converts data and information into a decision”. The role of water resources planners is to develop alternatives and evaluate the impact of these alternatives in terms of their economic, social, political and environmental values. However, the majority of the small reservoirs are unplanned and usually in response to community needs and donor interests.

Water resources management is fraught of political implications, tensions and interference. Poor governance in terms of accountability, transparency, participation and rule of law characterizes most southern African countries and intensifies the challenges of water resources management. Across much of the region, water is often at the top of needs of the poor communities.

Even though Engineers and Planners play an important role in the decision making process, it is the politicians who are, or at least be responsible and accountable for the decisions that involve various public interest and concerns: and water is no exception (Loucks, et al, 1981).Good planning emanates from good data and information processing. Consequently the managing of information or data is fundamental to the planning process.

Data and information systems (physical, technical, socioeconomic, etc) relating to water resources in terms of quality, quantity and accessibility and use are generally inadequate in Zimbabwe. Hence data collection and processing need further improvements through better technology, trained human resources and capital. Local capacity needs to be developed for the continuous updating of pertinent data for planning and monitoring. Data and information is usually of historic nature. However the information is not available for sufficiently long-term records to make more accurate predictions and decisions. Reasons for absence of data include absence of monitoring stations at appropriate locations, missing data at monitoring stations and unreliable data collection processes.

Lack of adequate data has serious implications to planning and decision making on water resources, both at national and international levels. However absence of sufficient and reliable data does not take away the need to make decisions on water resources management.

2.6 Development and maintenance of small reservoirs

Small reservoirs are constructed in most cases from earth materials and often suffer from different types of failures as a result of poor or lack of maintenance (Nelson, 1996). Three types of failures are common for small reservoirs namely, h*ydraulic failure seepage failures, structural failure.* The apparent role and responsibilities of maintaining these small reservoirs, to attend to the failures above, have been left to the community, but the community has limited, or no capacity or resources to deal with these failures.

The uncoordinated approach by different water users and agencies (e.g. District Development Fund, Rural District Councils and Non Governmental Organisations amongst many) in constructing small reservoirs lead to numerous problems associated with planning, development, management and maintenance for sustainable uses of the scarce water resource (www.smallreservoirs.org,2005).

2.7 The hydrological cycle and mass balance

A lot of decisions are made in the water resources planning; management and development, and these should take into account all aspects of the hydrological cycle (water in the atmosphere, surface water and groundwater).Figure 2.3 shows the pre development of a hydrological system and the post development hydrological bio-physical possibilities.

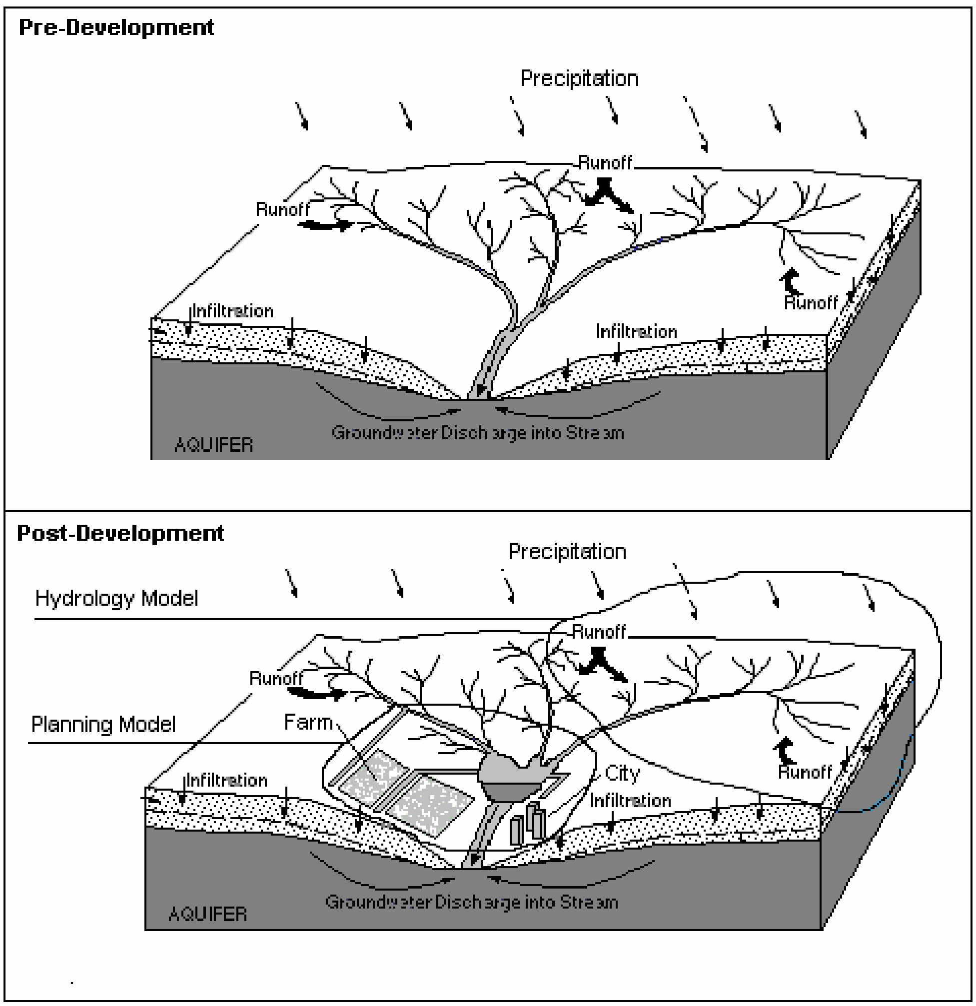


Figure 2.3: Characterization of watershed development: hydrologic cycle.

Source: WEAP 21, model characteristics

The hydrological cycle is the pathway of water as it moves in its various forms through the atmosphere to the earth over and through the land, to the ocean and back to the atmosphere (Schulze, 1995). Water is transferred from one environment to another, through a system that involves evaporation, transpiration, transportation as water vapour, condensation or transformation from water vapour to rain which then falls on the surface of the earth and the cycle repeats (Shaw, 1983)

The implication of small reservoirs on the hydrological system are two fold:

- the prolonged residence of water in the dam recharge the ground water
- and secondly the stored water provide for evaporation back to the atmosphere which in turn could lead to condensation and hence precipitation.

2.8 Water resources models

Water resources literature suggests that computer based models have the potential to provide useful information in facilitating water resources planning and management, as well as the decision-making process. Most of these models are based on the water balance equations. The planning of water resources hinges on capacity building and strengthening of data collection and information systems. More user friendly tools for use by water managers are required to assist in planning and simulation of various scenarios, with better precision. The credibility of a model must be established over a period of time and is influenced by the following factors: a) initial stage of model development (clear model purpose), b) reliable data, and c) adaptive to the dynamic changes which the physical system might undergo.

The WEAP model used in this study illustrates the potential of modeling as a dynamic and flexible tool to assist in the planning and decision making of water resources at catchment level. Water resources models are basic tools for planning, design and management of water resources (Dube, 1999). A model is a systems methodology approach and helps to define and evaluate numerous alternatives that represent various possible compromises among the conflicting groups, values and management objectives and trade offs (Singh, 1995). These models are increasingly becoming indispensable tools for planning, design and management of hydrologically related infrastructure. Decision makers can also use these models to improve on the quality of decision and formulation of policies. Their development is closely linked to the increasing processing capabilities of computer power. These models are now an indispensable tool for planning, design and management of hydrologically related infrastructure. They can greatly improve understanding, which is required for decision-making and policy analysis and formulation of legal framework (Mohammadi, 2001).

A model is a simplified or idealized description of a particular system or process that is put forward as a basis for calculations, predictions or further investigation. A model should contain those elements of reality that are needed to solve the problem.
The least necessary model is the best possible model for the purpose. A model is an

imitation of reality which stresses those aspects that are assumed to be important and omits all properties considered to be nonessential. A model is like a caricature of a real system (Kindler et al, 1994).

In acknowledging the role of systems methodology in water resources planning process, one should recognize the inherent limitations of models as representations of any real problems (AIT paper CE 09.23, 2004). The input data, including assumptions and objectives, may be controversial or uncertain. Of course these inputs affect the output

Future events are not known with certainty and knowledge concerning water resources systems is limited. One should not expect, therefore, to have the precise results of any quantitative system study to be accepted or implemented.

There are several modeling techniques used to evaluate the storage capacity of reservoirs from the water balance equations and other energy balance relationships. This development is closely linked to the advancement in the computer processing capabilities.

Models are increasingly used in hydrology to simulate changes in catchment management, to extend data sets and to evaluate the impacts of external influences (such as climate change). Whilst there are many simulation models in use, the skill is in selecting the right model for the job and balancing data requirements against the cost of model implementation (FAO Drainage paper,1994). There is wide expertise in the development and application of hydrological models at a range of spatial levels, from plot to catchment, and temporal scales from event based models to annual water balance models.

There are two basic modeling approaches:

- Simulation models (methodology/ conceptual)
- Optimization models (mathematical)

A simulation model relies on trial and error to identify near optimal solutions. Decision variables are set and the resulting objective values evaluated (Loucks, et al, 1981). Simulation models are highly non-linear; however they are able to solve water resources system planning issues. Examples of simulation models that are common include Pitman, HEC 5 and of recent WEAP. These models seek to simulate reservoir operations to (1) minimize downstream flooding; (2) evacuate flood control storage as quickly as possible; (3) provide for low-flow requirements and diversions; and (4) meet hydropower requirements.

Optimization techniques include linear programming, Lagrange multipliers, geometric and quadratic programming among others. Optimization models are highly mathematical

e.g. GLSNET and HSPF models. They analyse reservoir using residual techniques to estimate a regional regression equation to predict flow characteristics at ungauged sites.

The water resources system is a complex system with great heterogeneity in input responses, both in time and space. Much remains unknown about this heterogeneity, which often averaged or lumped. When linking model components it is important that each routine and or process representation be at a comparable level of complexity and conceptualization because in hydrological modeling the 'weakest link in the chain' concept holds true. The model is only as good as its weakest process representation albeit its best routines (Mohammadi, 2001).

2.9 Selection of an appropriate model

Selection of an appropriate model depends on the objectives of the study, function and level of spatial and temporal resolution. The criterion is also related to the nature of the problem being investigated and the resources available (Loucks, et al, 1981). Water resources model specifications depend on:

- ✓ Objectives of the analysis
- ✓ Data requirements
- ✓ Time, money and computational facilities
- ✓ The modelers knowledge and skills

The number of water resources models available has increased in recent years so much that it now a relatively hard task to choose from amongst them.

Some of the reasons for modeling a hydrological system include: -

- o To make efficient and cost effective quantitative estimates of water related variables at ungauged locations under varying climatic and land use conditions.
- o To generate useful information from limited or missing data or to replace inaccurate data.
- o To synthesis hydrological data and hence assist in producing coherent and holistic view of the behaviour of the entire system.
- o To prove the economic justification of a project and optimize the design of a water resources system
- o To identify and evaluate alternatives, trade-offs, objectives and interests
- o To predict impacts and important assumptions on water resources
- o To enhance judgements on water resources issues

(Schulze, 1995)

2.10 The WEAP Model

The Water Evaluation and Planning (WEAP) System is a water resources model developed by the Stockholm Environmental Institute (SEI) Boston as a water allocation tool, that allows decision makers to interactively change water allocations to best fit their goals

This study uses the WEAP (Model) system as a investigating tool for water resources planning, development and management of small reservoirs within the context of integrated water resources management. The model uses the rain fall runoff component as shown in Figure 2.5 flow diagram, to simulate runoff and applies the reservoir operating rules for the storages in the dams.

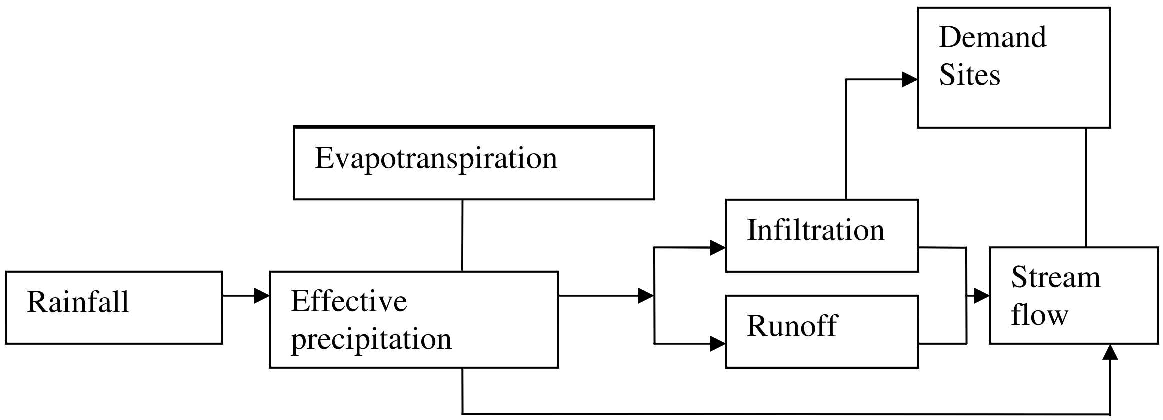


Figure 2.5: Flow diagram of WEAP rainfall-runoff component
(Source: LeRoy 2005)

The method presents a water balance model formulated to account for the dynamic hydrological components (Le Roy, 2005). The model represents the physical system using a demand, supply, abstractions, and storages and incorporates water balance components such as rainfall runoff, evaporation, infiltration, and percolation and surface storages (Yates, et al, 2005).

It is imperative that any such model developed should be of a complexity that is commensurate with available data, financial and other resources like computer resolutions.

WEAP provides a comprehensive, flexible and user-friendly framework for policy analysis. A growing number of water professionals are finding WEAP to be a useful addition to their toolbox .Data required for input into the WEAP model is four fold i.e. geo-physical, climatological, water quality and socioeconomic data. The advantage of WEAP is that it is compatible with windows and GIS, which makes it easy to use. This model has been applied to other basins in the world with satisfactory results, of note, is the Olifant basin in South Africa. It is also being applied in Brazil and Ghana to study the impact of small reservoirs on rural livelihoods.

CHAPTER 3: Description of the Study Area

3.1 Geographic and physical

The Limpopo River basin forms part of the northern boundary of South Africa on its border with Zimbabwe. It separates South Africa, Zimbabwe and Botswana before it enters into Mozambique and drains into the Indian Ocean. The basin is therefore shared between the four countries (Figure 3.1).

Figure 3.1: Map showing the Limpopo basin

The Limpopo River Basin is demarcated by latitude 24°S, longitude 25°E and latitude 26°S,longitude 34°E. The annual runoff of the Limpopo is 5500 Mm^3/ annum significantly small in comparison to other major basins, but the river is important because of its strategic value for water to the four countries (Pallet, 1997).

Mzingwane catchment is one of the seven catchments of Zimbabwe and forms part of the Limpopo River Basin located on the Zimbabwe side. It is estimated that there are 1000 small reservoirs on the Zimbabwe side of the Limpopo Basin (Zirebwa et al, 1999). The catchment lies in region V and experiences low and variable rainfall, spatially and temporal, whose distribution is characterized by droughts. Figure 3.2 shows the catchment zoning for Zimbabwe. Each of the catchments are managed by a Catchment Manager though a catchment council which is responsible for the overall water resources

management from planning, regulating and granting of water permits as well as ensuring that the proper compliance with the Water Act.

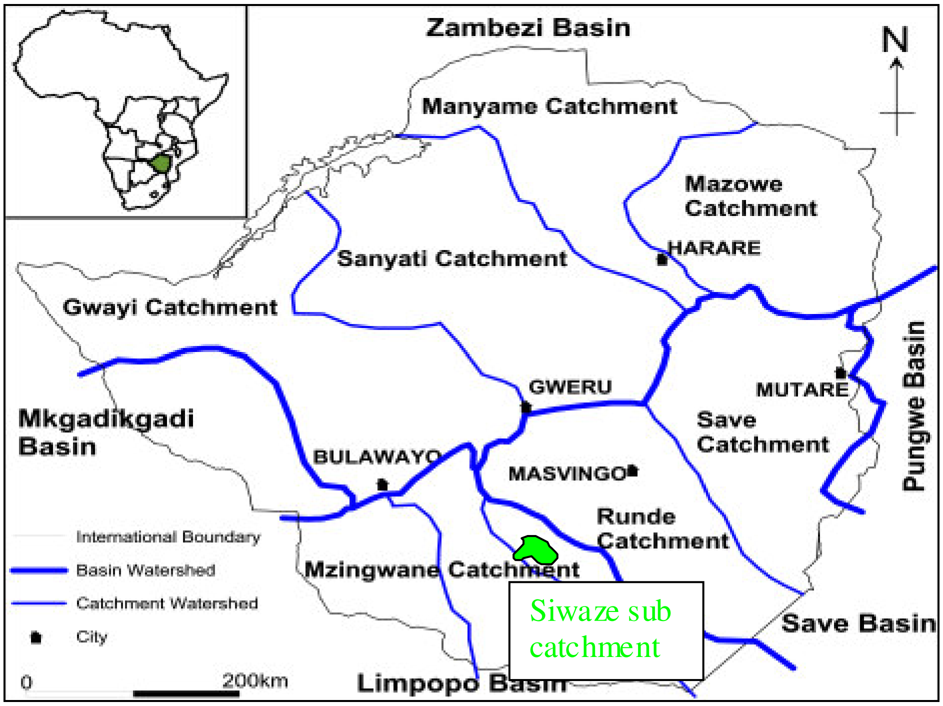


Figure 3.2: Map showing catchment boundaries in Zimbabwe

The study area was delineated spatially through satellite images and was a limited to a fairly small area (Siwaze) of about 50Km^2 due to lack of sufficient time and resources. Siwaze sub catchment was selected because it can be identified hydrologically as a unit.

Figure 3.3 shows the river network in the Mzingwane catchment and it associated sub catchments and settlements. The catchment is divided into four sub-catchments, namely, Shashe, Upper Mzingwane, Lower Mzingwane, and Mwenezi. The network flows towards the Limpopo basin. The rivers flow to the southeastern direction into the river Limpopo as shown on the map.. In certain parts of river courses, flow occurs only during the wet months, while during the dry months the riverbed is a sandy alluvial bed.

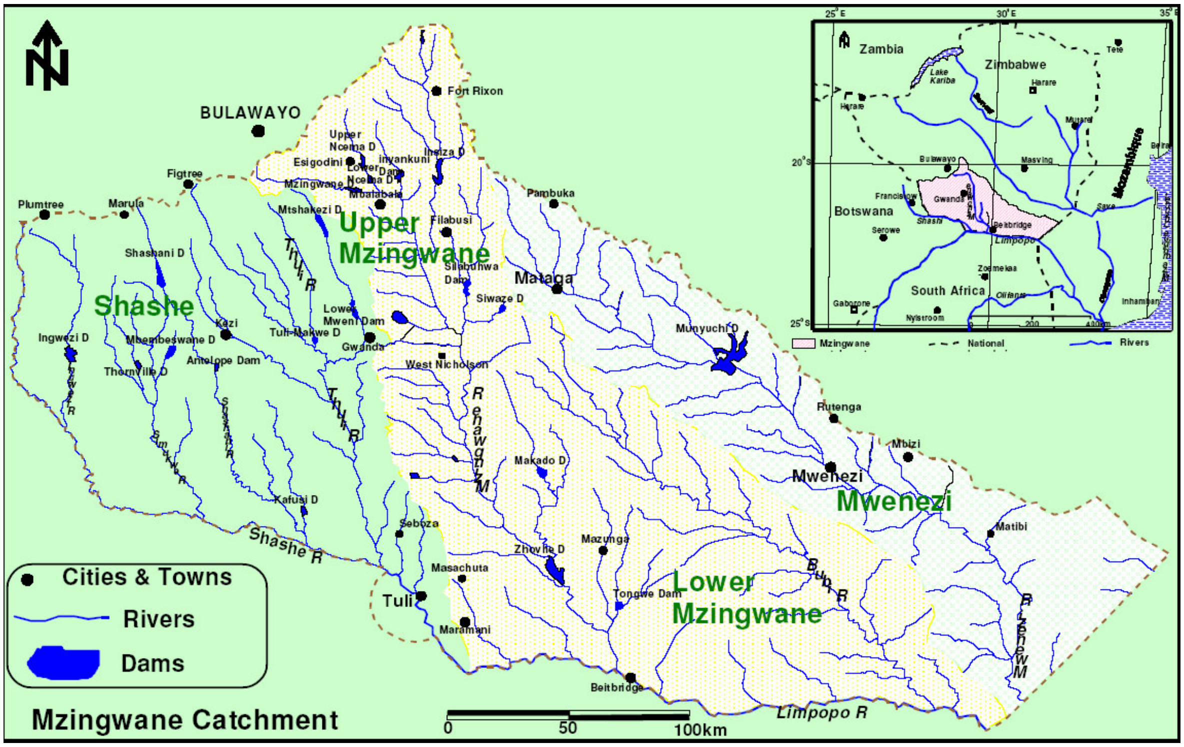


Figure 3.3: Map showing Mzingwane Catchment

3.2 Climate

The climate of Siwaze is predominately dry with two distinct seasons namely wet summer and dry winter. The wet season starts in October and ends in April with intermittent rains. Runoff depends on the rainfall intensity but is generally short lived.

Climate variability in the region raises the specter of endemic drought. Recent trends indicate progressive drier rainfall regimes and temporal variations in rainfall in especially drought prone zones (Sharma, et al, 1996) like Zimbabwe.

The average annual rainfall is 600mm and it is highly seasonal, with most rains falling between October and March. The highest rainfall recorded was in 1977/78 rainy season at 860mm and the lowest was in 1990/91 season at 110mm for the year (AREX- Insiza). The rainfall is generally on the lower side of this range. Rains occur almost exclusively in the form of convective thunderstorms, resulting in an erratic temporal and spatial pattern of precipitation.

Figure 3.3 shows a typical graph for the annual rainfall pattern for the study area. It is clear that the rainfall is concentrated in the summer season of October to April. Whilst, the winter season receives insignificant rains.

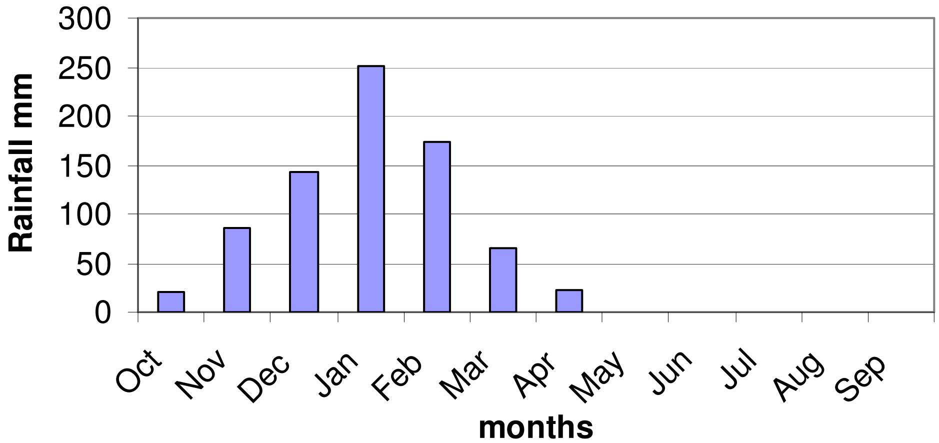


Figure 3.4: Mean monthly rainfall in Siwaze (1977-2005)

The temperatures in the study area are predominately very high in summer (25 °C and above), while the winter temperatures ranges from 10°C to 15°C.The humidity varies with the seasons between 40% in winter and 60% in summer. The wind speed averages 2 m/s for an annual time step. Evaporation is high due to high temperatures, averaging 4-5mm per day.

3.3 Topography

The topography of the sub-catchment is such that the hills to the North form the water divide and all the water flows towards Siwaze River. In turn Siwaze River flows into Insiza river which feeds into Mzingwane River. Most rivers are able to provide water only for short periods of time each year in the catchment. The vegetation is dominated by the indigenous Mopane trees

Four active small dams (Bhova, Avoca, Sifinini and Majelimane) are situated in the sub catchment feeding into one large dam (Siwaze Dam). However there are three other small dams which have silted to storage levels that do not warrant consideration. Only Siwaze dam is operated while the small dams are not operated. A reservoir that is operated is one that is controlled in terms releases downstream.

The characteristics of the small reservoirs are tabulated (Table 3.1). The four small dams range from about 18 000 m^3 to 41 000 m^3 in capacity. Different interest groups constructed these dams at different times. Two were constructed by the government and two by DDF, while the other was constructed by an NGO. The major use for all the four small reservoirs pertains to garden irrigation and livestock watering. While Siwaze dam in addition also support an irrigation scheme downstream.

Table 3.1: Characteristics of the study dams

Dam	Siwaze	Bhova	Avoca	Sifinini	Majelimane
Year built	1993	1955	1940	1992	1986
Built by	Government	DDF	Government	Christian care (NGO)	DDF
Management	ZINWA	Community	Community	Community	Community
Capacity * 10^6 (m^3)	2.4	0.31	0.41	0.50	0.18
Major uses	1. Irrigation 2. Domestic supply 3. Livestock watering 4. Clean water supply :Avoca growth point	1. Gardens 2. Livestock watering	1. Gardens 2. Livestock watering	1. Gardens 2. Livestock watering	1. Gardens 2. Livestock watering
Max. Depth(m)	5.2	1.6	2.4	3.1	1.5
Catchment Area (m^2)	5000	800	1500	1500	1200
Problems	Pollution levels are high	Spillway destroyed	Capacity reduced due to siltation	Dam dries out: years of low rains	Dam dries out: years of low rains

(Source: Sithole, et al 2005)

3.4 Socio- economic issues

The people in Siwaze mostly practice dry-land farming. However limited small-scale vegetable garden irrigation is being practiced near small storage reservoirs. Small reservoirs are a source of water related livelihood. Therefore the shortage of water poses a threat to their lives and well being (FAO, 1984). The several small reservoirs in Siwaze contribute significantly to poverty reduction for this rural population. Poverty is widespread and people are extremely vulnerable to the effects of drought or crop failure (WRMS, 2000).

The community's livelihoods emanate mainly from livestock rearing mostly cattle (Sithole, 2005). Cattle provide food in the form of meat and milk. Cattle are also financial resources as these can be redeemed for cash in times of crisis. The livestock herds include cattle, donkeys, goats, sheep and chickens. When the communities are under stress it is the small stock (goat, sheep) that they dispose of first through exchange for grain and cash. The small stock is also used to acquire cattle and donkeys through barter trade. Livestock is used as a barometer for wealth; it can be sold for cash (which is then used

for buying food, sending kids to school, etc). Livestock is also used for fetching water in addition to fetching firewood and drought power in the fields

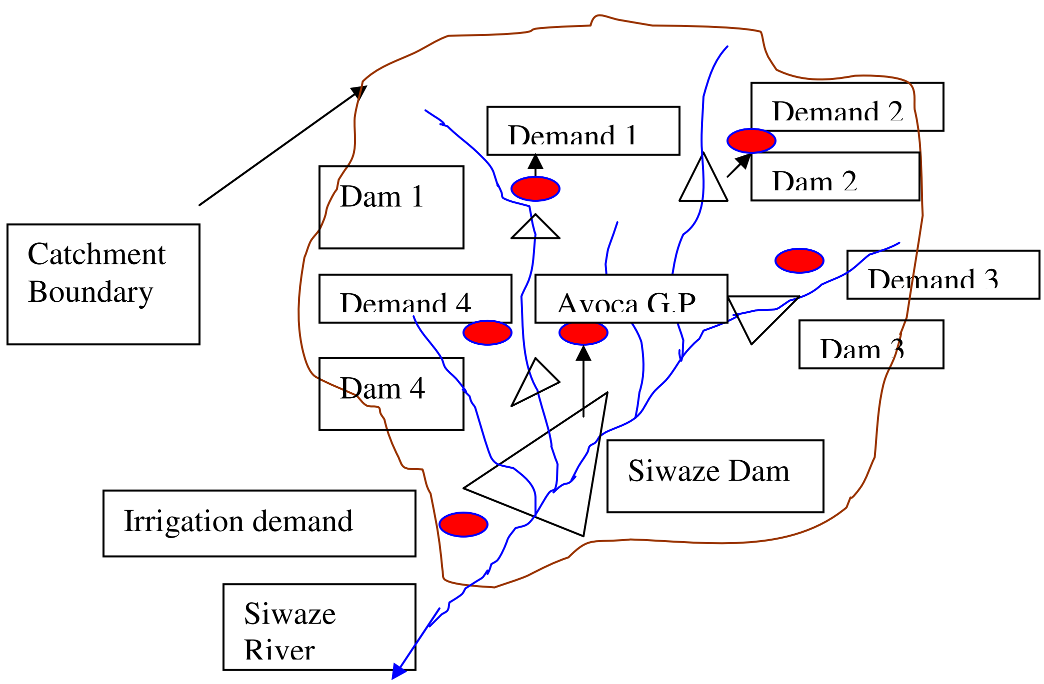
Of particular interest to livelihood issues is “Amacimbi” (a tree borne butterfly lava) which is one of the best relishes and provides income to most people in the subcatchment. These are often harvested and sold, hence improving on community livelihoods in terms of health and income.

CHAPTER 4: Research Methods and Materials

A hydrologically delineated (isolated) catchment was selected as the study area and field data was collected to verify the assumptions that the historical data obtained applied equally and correlate to the whole catchment. Field visits and data collection was necessary for ground-truthing purposes. The Water Evaluation and Planning (WEAP) model was to be calibrated and used to simulate various hydrological and livelihood issues. The model was applied in this study as it is user friendly and windows compatible, making it easily accessible (especially to developing countries).

4.1 Physical hydrology system outlay

Figure 4.1 shows the conceptualised catchment of the study area with dams 1 to 4 being small reservoirs while Siwaze dam is the receiving large dam. The river network in the subcatchment area is shown within the hydrological boundary.



KEY:
Dam 1---Avoca Dam 2---Majelimani Dam 3---Sifinini Dam 4---Bova

Figure 4.1: Subcatchment hydrological system model

The demand sites are represented and are lumped up, so are the supply sites, which are represented by catchment head flows. The arrows to and from the supply sites show the transmission links. Ground water recharge is only considered downstream of the large

dam Siwaze since it does not dry out through the year. There is no return flow from Avoca growth point back to the Avoca River upstream of Bhova dam.

4.2 WEAP Model structure

4.2.1 Theoretical background

The WEAP model was developed as a water resources system model based on bio-physical parameters (climate, topography, land cover, surface and ground water hydrology, soil type, demands and allocations).

4.2.2 Reservoir mass balance model

The governing equation for the reservoir operation for a closed system is given as:

Input (I) – Output (O) = Change in storage (ΔS)   (Spaans, 1995)

Where Inputs are
- precipitation (P_e)
- Runoff
- direct Inflows and
- ground water influent

and the Outputs are
- Evaporation
- Abstraction for irrigation
- domestic use
- livestock watering
- releases down stream, as well as
- Seepage.

Inputs into the reservoir are constituted by direct precipitation, inflow from upstream and dam catchment. Outputs are made up of direct withdrawals (abstractions), evaporation and downstream outflows.

4.2.3 Hydrological data

4.2.3.1 Reservoir inflow

Local reservoirs by definition are modeled independently of river stream flow. The monthly inflows entered did not include return flows from demand sites and wastewater treatment plants the model calculates the inflows from return flows separately.

Runoff is generally determined on the basis of water level recordings in combination with a rating curve (stage discharge relation curve). A unique relationship between water level

and river discharge was obtained in a stretch of the river where the riverbed is stable and flow is slow and uniform i.e. the velocity pattern does not change in the direction of flow.

Inflow measurements were done using floats in conjunction with gauge plates and rating curves derived from previous study (Saunyama, 2005).

A position was chosen in the stream that was tranquil with no rapids. A cross section of the stream was taken using a leveling staff. Then a float and a stopwatch were used to measure the velocity of the water in the stream. Several readings were taken of the velocities and an average of the readings was used (Figure 4.2).

The Simpson's rule method was used to calculate the cross sectional area of the stream and discharge was obtained by multiplying the area with the velocity. However due to the temporal variations of the rainfall, the data collected for stream flow measurements was only used to verify the model output, against the gauge plates readings (inflows) into the dams.

Figure 4.2: Stream flow measurements

The rating curve was represented by an equation of the form:

$$\mathbf{Q = a\ (H\text{-}H_0)^b} \qquad \text{Eq. 4.1}$$

Where Q is the discharge in m^3/s, H is the water level in the river (m), H_0 is the water level at zero flow and a and b are constants.

H_0 was determined as equal to zero since these stream were dry riverbeds as the zero flow.

Taking H at spillway level and H_0 at dry river bed and equating $(H-H_0)^b$ to 1 it was possible to calculate the values of a and b for each dam, giving the values of Q for each dams. The rating curves for each of the five reservoirs in this study are shown in Appendix C.

The values from the rating curve were compared with those obtained from the Manning's formula where the cross sectional area A, and hydraulic radius R are functions of $(H-H_0)$.

$$\mathbf{Q = A/n\ R^{0.666}\ S^{0.5}} \qquad \text{Eq. 4.2}$$

Where A is the cross sectional area channel (m^2), R is the hydraulic radius A/P and S is the bed slope and P is the wetted perimeter (m), n is the coefficient of roughness of the channel.

4.2.3.2 Reservoir Storage Capacity

The Storage Capacity represents the total capacity of the reservoir, while the Initial Storage is the amount of water initially stored at the beginning of the first month of the Current Accounts year. The model maintains a mass balance of monthly inflows and outflows in order to track the monthly storage volume (Appendix A).

Gauge plates were installed at all four small reservoirs namely Avoca dam, Sifinini Dam, Majelimane dam, Bhova dam, using leveling instruments (Figure 4.3). While the ZINWA gauges were used at Siwaze dam. These gauge plate readings were used to calculate reservoir storage capacities.

The spillway level was taken as the 100.00 m arbitrary bench mark.

Figure 4.3: Installation of gauge plates.

4.2.3.3 Reservoir Volume Elevation Curve

The points on the Volume Elevation Curve define this function. Values between the points are interpolated. At least one point, corresponding to the total storage capacity of the reservoir, was defined. Refer to Appendix C.

4.2.3.4 Reservoir Priority

This determines the priority for filling of the reservoir. This priority can change over time or from scenario to scenario. Typically, this priority is set to 99 (the lowest possible priority), so that it will fill only after all other demands have been satisfied. If you had two reservoirs, you could fill one before the other by setting its priority to 98.

Reservoir storage capacities were estimated using rating curves. The surface area volume relationships developed by Saunyama (2005) were adopted for the reservoir storage volumes given as $\mathbf{C = aA^b}$
where C is the capacity in m^3 and A is the surface area of reservoir in m^2 while a and b are constants dependent climatic factors.

When one or more reservoirs are in series Outflow in the upstream reservoir is an inflow in the downstream reservoir. For the Siwaze catchment:

$O_{out1} + O_{out4} = I_{siwaze1}$ Eq. 4.3

$O_{out2} = O_{out3} = I_{siwaze2}$ Eq. 4.4

$I_{siwaze1} + I_{siwaze2}$ = total inflow into Siwaze Eq. 4.5

4.2.3.5 Reservoir Zones and Operation

Reservoir storage is divided into four zones, or pools. These include, from top to bottom, the flood-control zone, conservation zone, buffer zone and inactive zone. The conservation and buffer pools, together, constitute the reservoir's active storage. The model ensures that the flood-control zone is always kept vacant, i.e., the volume of water in the reservoir cannot exceed the top of the conservation pool.

The Siwaze reservoir is allowed to freely release water from the conservation pool to fully meet withdrawal and other downstream requirements. Once the storage level drops into the buffer pool, the release will be restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies. Water in the inactive pool is not available for allocation, although under extreme conditions evaporation may draw the reservoir into the inactive pool.

To define the zones, the volumes corresponding to the top of each zone (**Top of Conservation**, **Top of Buffer** and **Top of Inactive**). The model uses the **Buffer Coefficient** to slow releases when the storage level falls into the buffer zone (Figure 4.4).

When this occurs, the monthly release cannot exceed the volume of water in the buffer zone multiplied by this coefficient. In other words, the buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully while rapidly emptying the buffer zone, while a coefficient close to 0 will leave demands unmet while preserving the storage in the buffer zone. Essentially, the top of buffer should represent the volume at which releases are to be cut back, and the buffer coefficient determines the amount of the cut back.

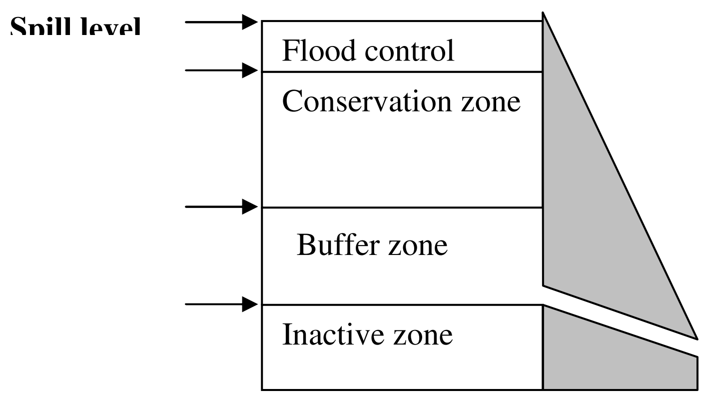


Figure 4.4: Representation of the large (operated) reservoir zones operation

However for the small (un-operated) reservoirs the buffer and conservation zones are combined since the dams are allowed to be empty during the dry seasons, while the inactive zone is when water cannot be drawn from the dam. Disregarding ground water recharge a reservoir mass balance equation for a reservoir becomes:

$P + I - E - F - O = \Delta S$ (Figure 4.5) Eq. 4.6

Where P = precipitation, I = inflows into reservoir, E = evaporation, F = infiltration /percolation, O = outflow and ΔS = change in storage, since B=0 and F= 0

The water balances equations for each reservoir are based on the principle of continuity and /or laws of conservation of mass. The governing equation for a mass balance is given by:

$\mathbf{I - O = \Delta S}$ Eq. 4.7

Where the I = inflows (inputs) and O = outflows (losses) and ΔS is the change in storage in reservoir.

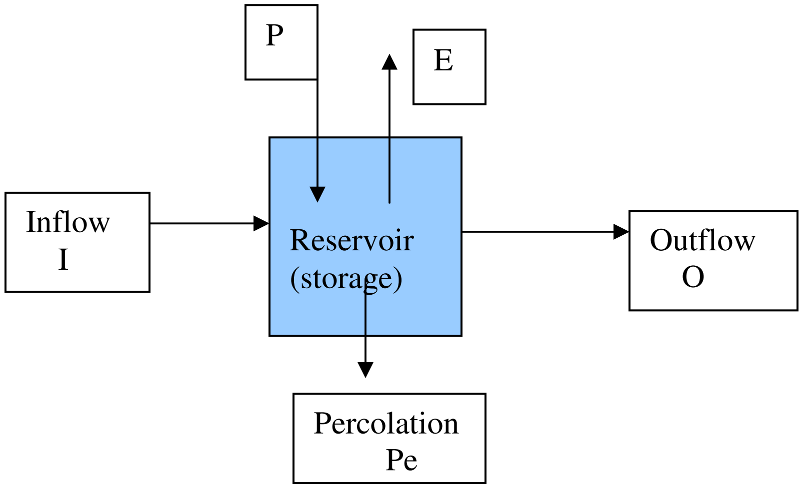


Figure 4.5 Schematic representation of water balance for a reservoir

Figure 4.6 shows typical inputs and outputs to a small reservoir in the Siwaze catchment. The equation for the generic water balance for the small reservoirs becomes:

$$I_p + I_r + I_c - O_{liv} - O_{irr} - O_e - O_{ab} - O_{out} = +/- \Delta S \qquad \text{Eq. 4.8}$$

Where I_p = precipitation, I_r = river inflows, I_c = catchment inflows, O_{liv} = livestock demand, O_{irr} = irrigation demand, O_e = evaporation, O_{ab} = household abstraction, O_{out} = outflows/spillage and ΔS = change in storage.

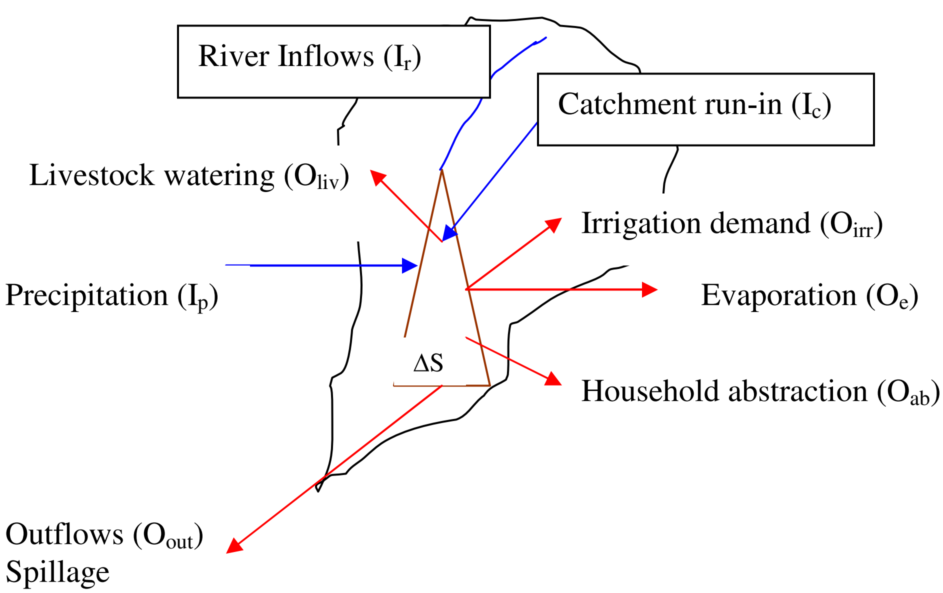


Figure 4.6 Representation of inflows and outflows in a small reservoir

Now for time step 1 - January:

$I_p + I_r + I_c – O_{liv} – O_{irr} – O_e - O_{ab} - O_{out} = + \Delta S_1$ Eq. 4.9

Since inflows exceed abstraction and losses, the change in storage is positive and results in increased reservoir capacity. The other factor is that the demand from livestock and irrigation is reduced since water is collected in depressions and the irrigation demand is reduced.

For time step 2 - February:

$\Delta S_1 + I_p + I_r + I_c – O_{liv} – O_{irr} – O_e - O_{ab} - O_{out} = + \Delta S_2$ Eq. 4.10
Etc,etc

For time step 6 – June:

$I_p = 0$, $I_{irr} = 0$, $I_c = 0$ the equation then becomes:

$(- O_{liv} – O_{irr} – O_e - O_{ab} - O_{out}) = - \Delta S$ Eq. 4.11

Storage is depleted in the small reservoirs during the dry season resulting in reduced yield capacity.

The iteration equation then becomes:

ΔS_n + --- = ΔS_{n+1} Eq. 4.12

Where $1 < n < 12$

4.2.4 Runoff calculation

. The generic water balance equation for a catchment can be written as

$\mathbf{(P-E)*A-Q = \Delta S/\Delta t}$ Eq. 4.13

Where: P = precipitation, E = evaporation, A = area, Q = discharge and $\Delta S/\Delta t$ = change in storage over time

(De Laat et all, 1996)

The hydrological cycle water balances is based on the principle of continuity and /or laws of conservation of mass (Spaans, 2001).The following equation represents the hydrological water balance for a catchment :

$$\mathbf{P + R + B - F - E - T - O = \Delta S} \qquad \text{Eq. 4.14}$$

Where P = precipitation, R = runoff, B = subsurface flow, F = infiltration,
E = evaporation, T = transpiration, O= outflow and ΔS = change in storage volume
This equation is disregarding inter-catchment transfers.

The Soil Moisture Model (Two–bucket model) represents the catchment runoff and subsequent inflows into the reservoirs. It is represented as having two soil layers. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Base flow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes.

Runoff Flow Routing specifies the fraction of runoff generated by the catchment that is sent to each runoff flow destination. These flows must sum to 100% since they are a fraction of outflow. Illustrated in Figure 4.7 is the physical representation of the "Two-bucket model" for surface runoff which represents inflows into the reservoirs.

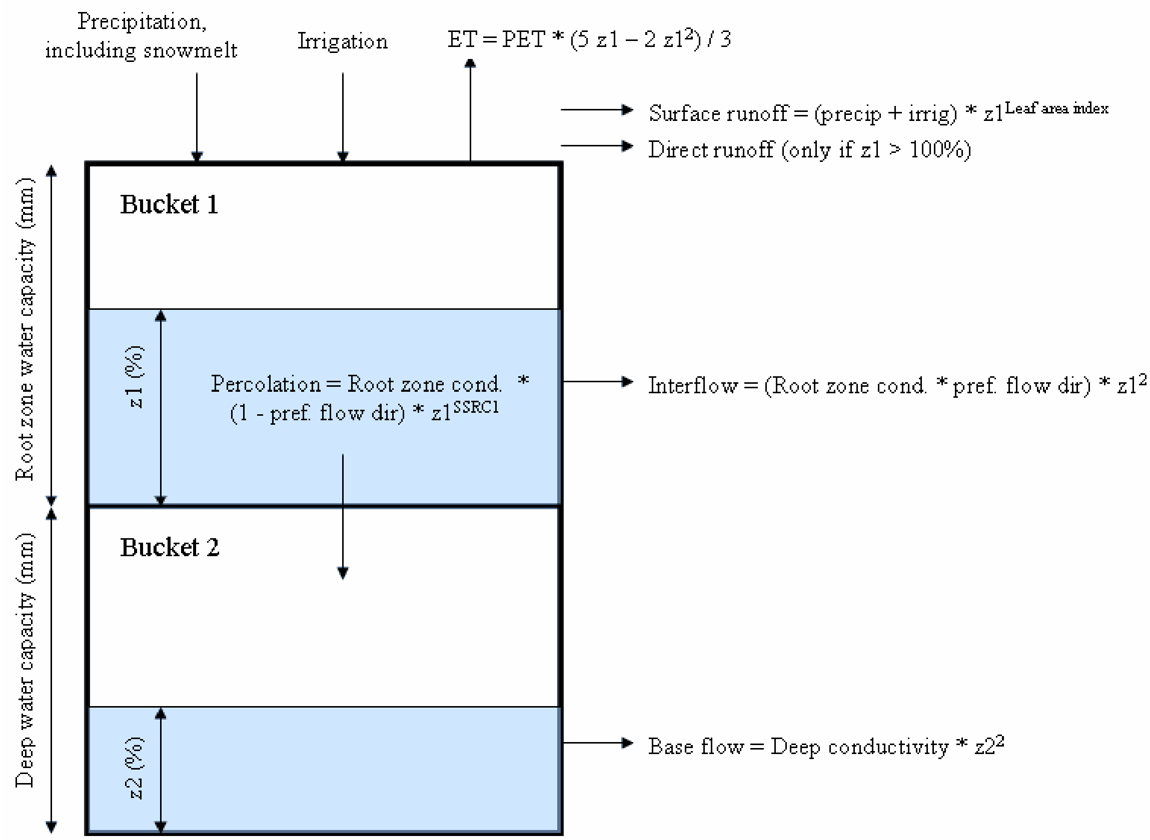


Figure 4.7 Conceptual representation of the 2- bucket model

where the precipitation and irrigation are inputs into the bucket and evapotranspiration (ET), surface runoff are losses to the bucket..

$ET = f(Z_1, Kc, PET)$ Eq. 4.15

only a part of the root zone capacity (Z_1) will be available for evapotranspiration therefore

$ET = PET^* (5Z_1 - 2Z_1^2)/3$ Eq. 4.16

Surface runoff = $f(Z_1, LAI, P_e)$

Where LAI is the leaf area index and Pe is effective precipitation, if Z_1 is 100% saturated or more then all the effective precipitation becomes direct runoff.

However P_e is also a function of precipitation duration, intensity and Z_1 soil type and Z_1 depth.

Interflow = $f(Z_1, Kc, f)$ where f is the infiltration which is also a function of soil type, rainfall duration and intensity of the storm.

The equation then becomes:
Interflow = (root zone conductivity* preferred flow direction)* Z_1^2 Eq. 4.17

Deep percolation = f(Z_1, Kc, f) where the higher the infiltration rate and the lower the interflow the higher the percolation.

The equation then becomes
Percolation = Root zone conductivity *(1 – preferred flow direction) *Z_1 Eq. 4.18

The second bucket (Z_2) translates to deep water capacity (mm) and contributes to the hydrology through base flow. Only a percentage of the Z_2 is useful to the base flow. The contribution of the base flow equation is:
Base flow = deep conductivity *Z_2^2

Deep conductivity relates to the geology of the second bucket, its ability to transmit water, porosity, rock type, permeability, storage capacity and other geological parameters of the bucket.

4.2.5 Reservoir Evaporation

The research was interested in evaporation as it is an important component of the water balance equation. With respect to reservoir water balance, evaporation is considered a loss. Free surface water evaporation is of interest in the water balance for small reservoirs.

Evaporation pans are the most common instruments for measuring evaporation from small surface water bodies. Several types and version can be found but the most common type is the Class A pan, which was used in this research. The diameter of the pan is 1.21 m and the depth is 255 mm with a water level that is maintained at 50-75mm below the rim. The pan was placed on a wooden structure so that the bottom is 150mm above the ground. Evaporation is recorded from water level changes, corrected for rainfall depths.

Two evaporation pans (Figure 4.8) were installed at the following sites:
- Siwaze Irrigation scheme
- Sifinini Dam

Evaporation was measured in millimitres (mm) and converted to loss in the reservoirs as follows :-

Surface area of reservoir (m2) * mm/ 1000 = m^3

Figure 4.8: Data collection proceedings

There was an existing pan that was already being recorded at Siwaze dam site. Readings were taken for all reservoirs on a daily time step at set times for a period of three months.

The monthly evaporation rate can be positive or negative to account for the difference between evaporation and precipitation on the reservoir surface. A positive (negative) net evaporation represents a net loss from (gain to) the reservoir. Evaporation data from Siwaze dam was obtained from the records at the dam and is shown (Figure 4.9).

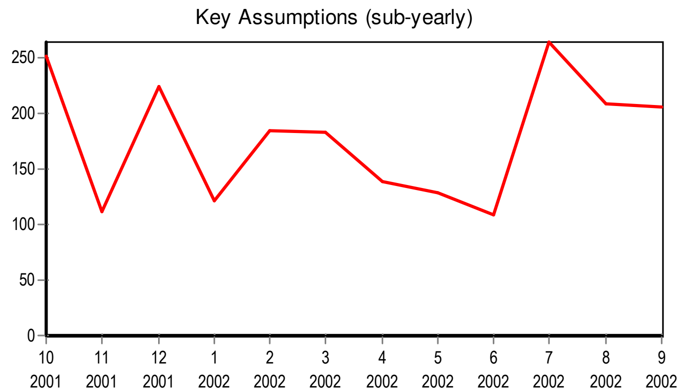


Figure 4.9: Reservoir evaporation in mm: Siwaze dam (2001-2002)

4.2.6 Model hydrological schematic

Figure 4.10 is the schematic of the catchment hydrological system as represented in the WEAP model. Reservoirs demand sites, head flows and known gauging stations are shown (including the positions where filed stream flow measurements were done). The drag and place operations of the windows based model allows this schematic to be generated and formulate hydrological relationships within the catchment.

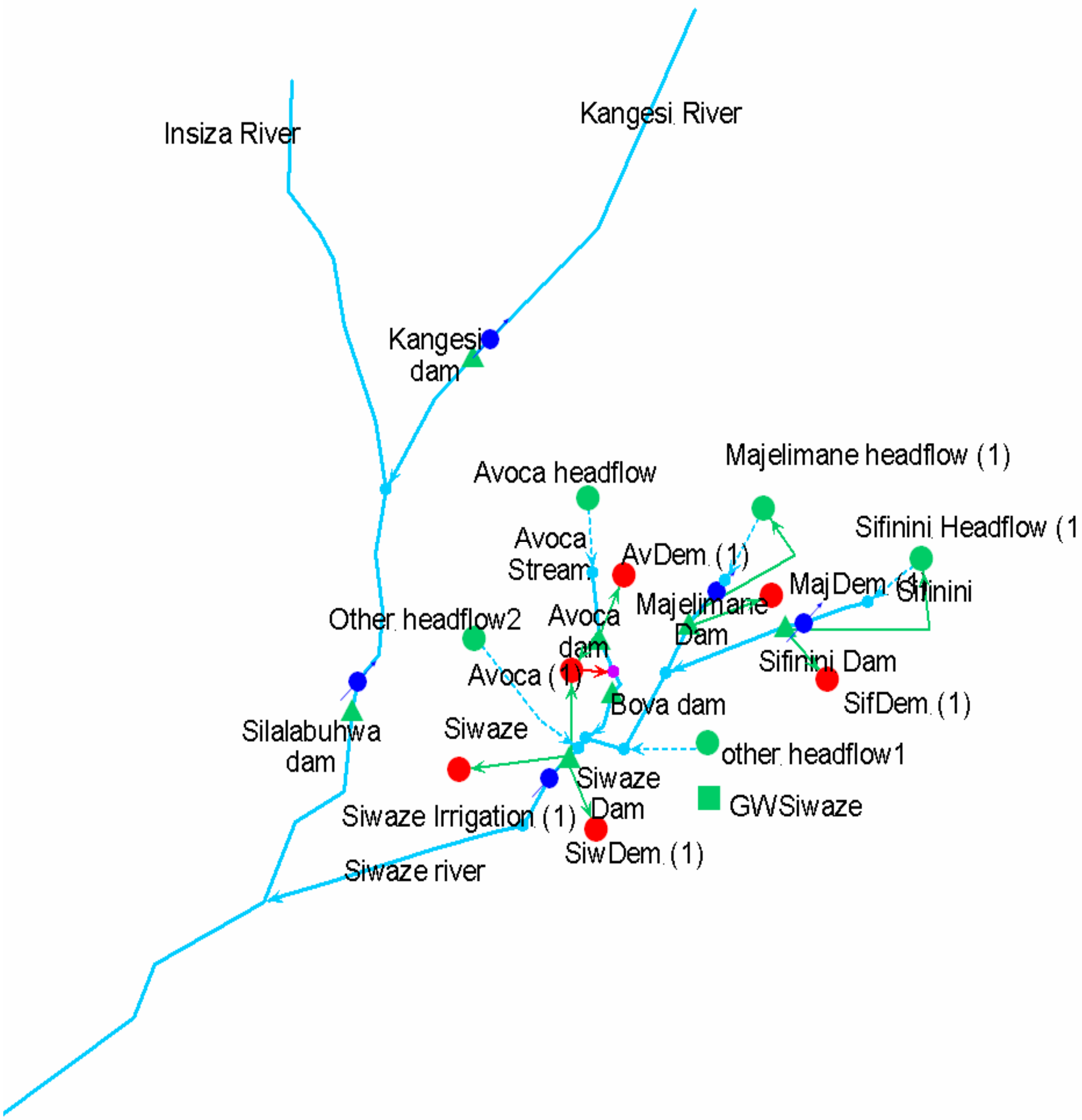


Figure 4.10: Siwaze subcatchment WEAP model Schematic

Key: Demand site
Head flow
Dam site
Ground water

4.3 Input Data

The graph shown under each input data is displayed in the data view of the model. ONLY key parameters are discussed briefly.

The following data was inputted into the model:

4.3.1 Set current accounts (or base year)

Our base year for the model was set for year October 2001- September 2002. This was selected after observing that the year had sufficient data, correctly recorded with minimum missing data. The quality of data was checked for errors through the Meteorological office data quality section.

For the current year it was important to classify as a normal year, dry or wet year under the hydrology water year method (refer to WEAP User guide)

4.3.2 Physical and geographical data

4.3.2.1 Demand sites: water use

Two demand site are prevalent for the large dam Siwaze, namely demand from the growth point, which is supplied with clean water processed at a ZINWA owned treatment plant, and delivered to the centre as well as demand from the irrigation scheme. Avoca has a fairly constant demand while the demand from Siwaze irrigation varies with the season. The demand from the irrigation is much higher in the dry months of May to October(as shown in Figure 4.11).

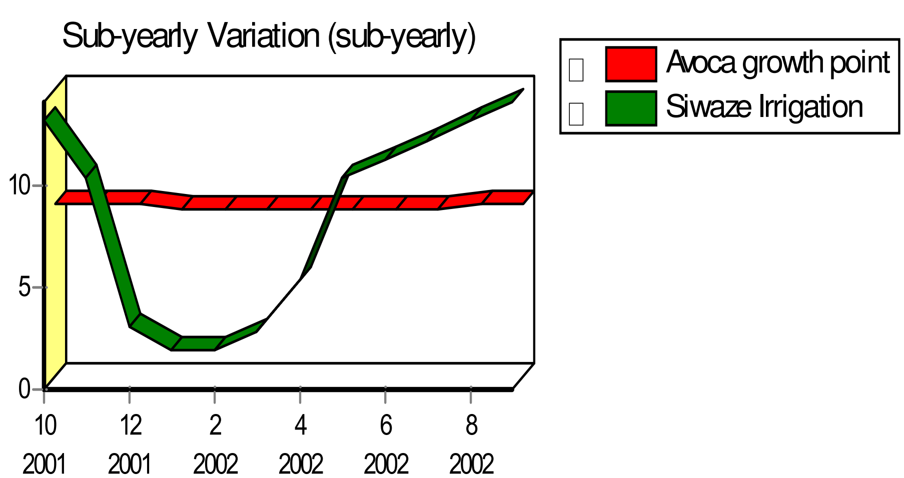


Figure 4.11: Average monthly water use

The average daily water use was obtained from literature of the area under study and is estimated at 25 litres/day/ livestock unit and 140 litres/day/ capita/ household for

domestic use A livestock unit was taken as one which weighs 350 Kg. That means that all livestock were converted to a beast of that size (Zirebwa et al, 1999)

Conversions to a livestock unit (Mtisi, 2002) were as follows:
5 goats = 1 unit
1 donkeys = 1 unit
1 cow = 1 unit

A typical water demand calculation is illustrated for Avoca dam for average daily water use is as follows:

Dam: Avoca
Capacity: $40.87 * 10^3\ m^3$

Table 4.1 Livestock conversion (numbers)

Number of cattle	925
Number of goats (after conversion)	720
Number of sheep (after conversion)	422
Number of donkeys (after conversion)	197
Total livestock unit	2264

Source: AREX (2000)

Average = (50+11.5+23)/4 = 25litres/day

Therefore Livestock demand D_l = 25l/day *2264*365 days/ 1000 = 20 659 * $10^3\ m^3$/annum

<u>Domestic demand</u>

Number of households : 200
Demand/ household : 140 litres / day

Therefore domestic demand = 140*200*365 days /1000 = 10 220 * $10^3\ m^3$/ annum

<u>Irrigation demand</u>

Taken as 15 000* $10^3\ m^3$/ha/annum (Singh, 1996)
Hectarage supported by the dam : 1 hectare

Total water demand for the specified dam then becomes
(20.659 +10.220 +15.000) *$10^3\ m^3$ = 45.88 *$10^3\ m^3$/ annum

Note well that the demand is higher than the supply, which explains why the dams dry out in the winter season.

4.3.2.2 Land Use

This relates to land area for land covers class within catchment. Pastures dominate the land cover at 50%, while the crops take up 30% and the remainder is used as untapped forests. The forests provide firewood and cover non cultivated hills and mountains. Figure 4.12 shows the % shares for each type of land use. The whole catchment was assumed to have the same portioning for each head flow.

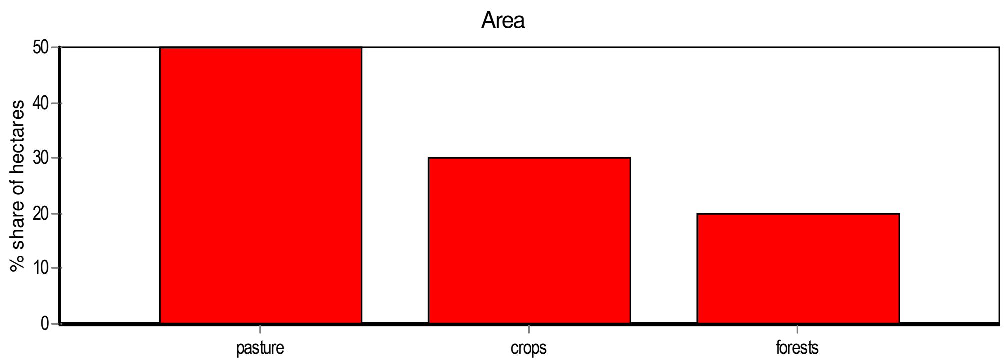


Figure 4.12: Land use activities

4.3.2.3 Land sizes

Land sizes for each sub-sub catchment are input parameters. Land sizes were derived from geographical maps of the area. These parameters are used in the calculation for runoff generation, since runoff is generated over an area. The basis for the calculation is the empirical formula

$$Q = CIA \qquad \text{Eq. 4.19}$$

Where Q is the runoff in cubic metres, A is the catchment area in square metres, I is the rainfall intensity in metres and C is a coefficient of land use and terrain. Figure 4.13 shows the hectares per catchment head flows (upper to the reservoir).

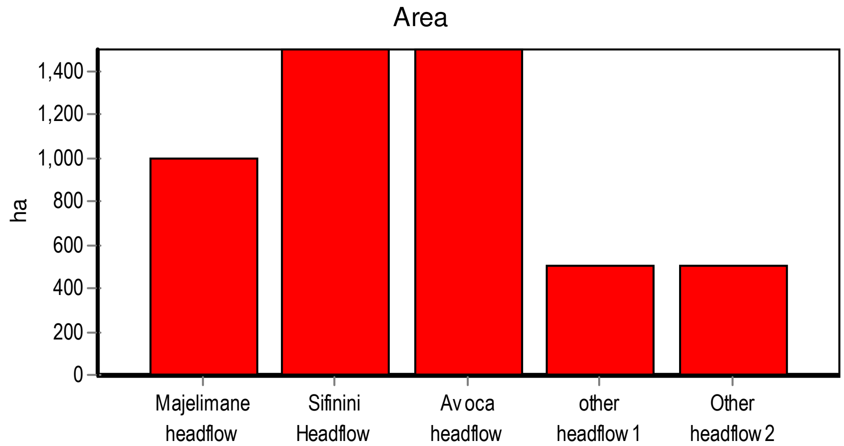


Figure 4.13: Land sizes per subcatchment

The area for each head flows was estimated using geographical maps and is as shown on the Figure 4.13 . Sifinini and Avoca headflows are the largest with 1500 hectares each.

4.3.2.4 K_c Crop coefficient

The crop coefficient is relative to the reference crop, for a land class type. This depends on the crop type and crop stage. Therefore it would vary with time steps. Figure 4.14 shows the Kc values per crop type which varies with the time of cropping and stage of crop.
The equation for the input is:

$$ETm = K_c * ETo \text{ (mm/day)} \qquad \text{Eq. 4.20}$$

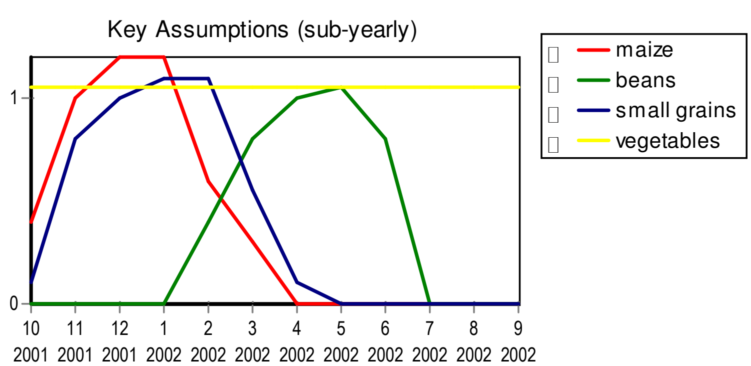


Figure 4.14: K_c for crops in Siwaze Irrigation

The irrigation scheme is unique in its operation as the Siwaze dam supplies the scheme with water through out the year.

4.3.2.5 Soil water capacity

The soil water capacity depends on the type of crop which all have varied root zone depths and therefore their uptake of water within the soil determines which type of loss occurs in the first bucket. Losses in the first bucket occur through evapotranspiration and deep percolation as well as interflow. The soil water capacity also depends on the texture of the soil itself.

The root zone for the crops was obtained from literature and differs for each type of crop. The vegetables and beans set at 350mm and the maize set at 450mm and small grains at 800mm.

4.3.2.6 The cropping pattern: Small reservoirs

The cropping pattern for the catchment is influential to the hydrology of the catchment as it imparts on the demand for water e.g. demand from an irrigation scheme. Figure 4.15 shows the percentage share of each crop for all arable land.

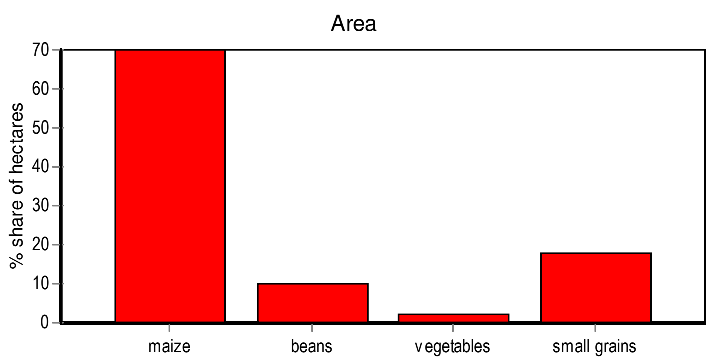


Figure 4.15: Percentage share per crop

It is typical of all head flows in the sub-catchment, that the predominately cultivated area has maize as the most grown crop. Therefore 70% of all the cultivated land would be set aside for maize. Meanwhile, the remaining cropping area was left for vegetables and small grains like sorghum.

4.3.2.7 Cropping pattern: Siwaze irrigation

Siwaze, which has an irrigation scheme, had a cropping pattern that differed slightly from the other dams. Figure 4.16 shows that the predominant crops still remains the maize crop at about 70 % (source AREX)

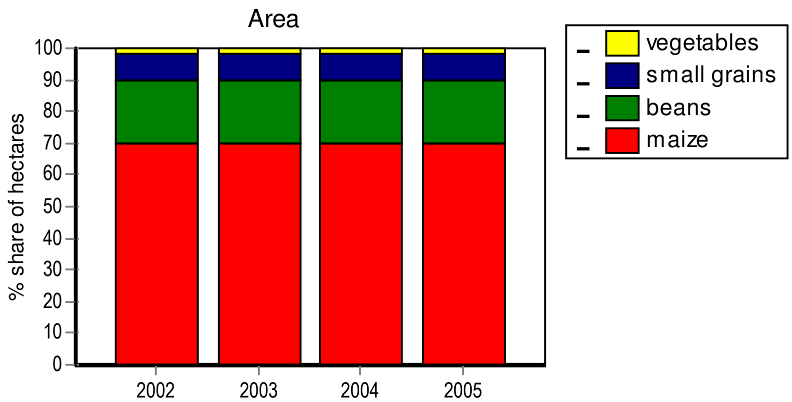


Figure 4.16: Siwaze irrigation cropping pattern

4.3.2.8 Root Zone Water Capacity

This represents the effective water holding capacity of the top layer of soil, represented in mm. This is represented by the first "bucket". The soil water depth was set at 300mm for pastures and 1000mm for the forests meaning that grass roots take up water within the first 300mm and the tall trees root zone is set at 1 metre depth. The root zone water capacity applies to the area that is not under cultivation, since runoff generated in the forest differs from that generated in the fields.

4.3.2.9 Deep Water Capacity

This is the effective water holding capacity of lower, deep soil layer (bottom "bucket"), represented in mm. This is given as a single value for the catchment and does not vary by land class type. The final assumption made for this study catchment was that the deep water capacity is set at 1000mm below ground level.

4.3.2.10 Deep Conductivity

This represents conductivity rate (length/time) of the deep layer (bottom "bucket") at full saturation (when relative storage $Z_2 = 1.0$), which controls transmission of baseflow. This is given as a single value for the catchment and does not vary by land class type. Baseflow will increase as this parameter increases.

4.3.2.11 Leaf Area Index (LAI)

The leaf area index LAI is used to control surface runoff response. Runoff will tend to decrease with higher values of LAI (range 0.1 to 10). This parameter can vary among the land class types. Leaf area index for crops in Siwaze catchment is shown below (Figure 4.17) for the most commonly grown crops.

LAI determines which of the evaporation types will take place. If the LAI is high it means that the leaves cover a substantial area leading to a predominance of the interception from the leaves. Interception of rain by the leaves imply increased evaporation off the leaves.

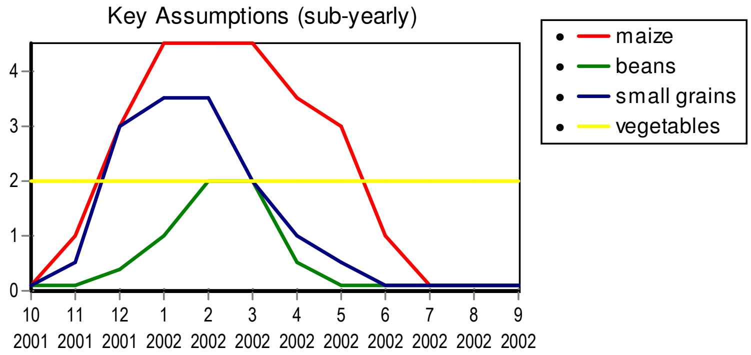


Figure 4.17: Leaf area index per crop

4.3.2.12 Root Zone Conductivity

Root zone conductivity accounts for the root zone (top "bucket") conductivity rate at full saturation (when relative storage Z_1 = 1.0), which will be partitioned, according to Preferred Flow Direction, between interflow and flow to the lower soil layer. This rate can vary among the land class types.

4.3.2.13 Preferred Flow Direction

This is used to partition the flow out of the root zone layer (top "bucket") between interflow and flow to the lower soil layer (bottom "bucket") or groundwater. This value varies among the land class types. However for the parameter a key assumption was made that through the year the preferred flow direction remained constant at 0.2.

The value 1.0 = 100% horizontal flow while 0 = 100% vertical flow.

The flow direction the water prefers to take was assumed to be more horizontal that towards groundwater recharge.

4.3.2.14 Initial Z_1

The initial value of Z_1 is stated at the beginning of a simulation. Z_1 is the relative storage given as a percentage of the total effective storage of the root zone water capacity.

4.3.2.15 Initial Z_2

The initial value of Z_2 is stated at the beginning of a simulation. Z_2 is the relative storage given as a percentage of the total effective storage of the lower soil bucket (deep water

capacity). This parameter is ignored if the demand site has a runoff/infiltration link to a groundwater node. This rate cannot vary among the land class types.

4.3.3 Irrigation data

The following irrigation-related variables will require input (Soil Moisture method) for the catchment.

Irrigated Area *- The percent of area that is irrigated.*

Lower Threshold *- Irrigate when soil moisture falls below this percent level.*

Upper Threshold *- Cease irrigation when soil moisture reaches this percent level.*

Figure 4.18 shows the variation of the irrigation scheme at Siwaze in terms of the % share of water available for irrigation. The rainy season is depicted by a reduced demand for irrigation water.

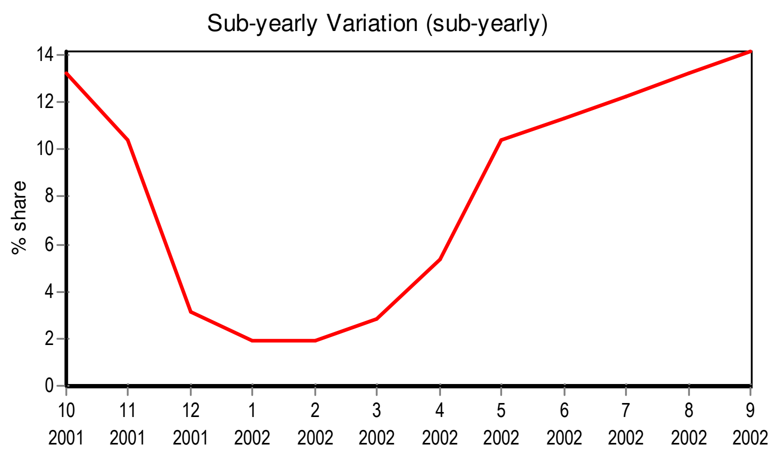


Figure 4.18: Siwaze Irrigation scheme water (2001 -2002

4.3.4 Climatic data

4.3.4.1 Precipitation

The traditional way of measuring rainfall has been rain gauges. Standard sizes depend on the frequency of readings, e.g. monthly or daily. The static (beaker) type was used in this

Figure 4.19 Data collection proceedings

study. The rain gauges were installed away from any obstructions like buildings and trees. The reading frequency was daily at set times (Figure 4.19).

Four rain gauges were installed at the following sites:

- Bhova dam(Siwaze Irrigation scheme)
- Sifinini Dam
- Majelimane Dam
- Avoca Dam

For rainfall to generate meaningful runoff the following parameters should be noted:

1. Duration of precipitation in second or minutes or hours: hence intensity or rate of precipitation: the depth of water per unit time in mm/min or m/s
2. Frequency of occurrence, usually expressed by the return period e.g. once a day.

However, the study could not capture these accurately due to lack of appropriate equipment.

The monthly flows/runoff time series was obtained from records within ZINWA for Siwaze dam, while for the catchment the data from the Metrological station at West Nicholson (32 kilometres from the Siwaze subcatchment). Figure 4.20 shows the precipitation for the current year (base year) for the catchment

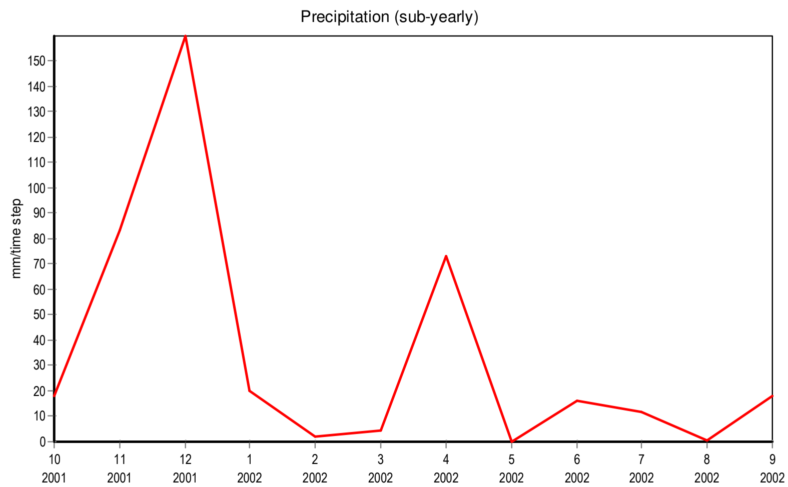


Figure 4.20: Precipitation data (2001 -2002)

4.3.4.2 Temperature

This was inputted as the weighted mean of high and low temperature on a monthly basis set and inputted for the base year (2001/2002)

4.3.4.3 Humidity

For the average monthly relative humidity, data obtained from Meteorological station was used**.** Figure 4.21 shows the time series variation for the base year..

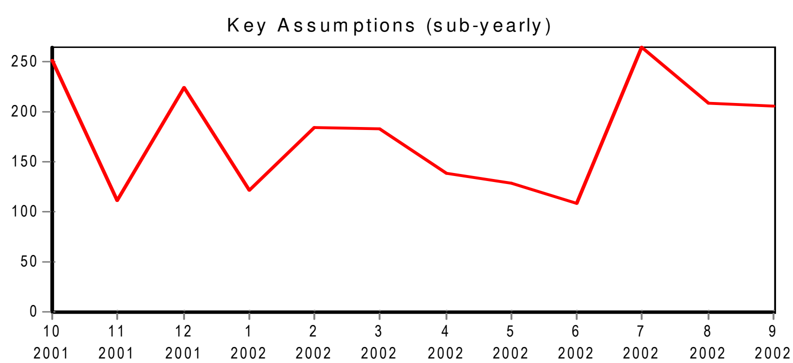


Figure 4.21: Humidity data (2001 -2002)

4.3.4.4. Wind

This was taken as the average monthly wind speed in m/s. This data set was obtained through the West Nicholson meteorological station and inputted per time step, assumed to apply to the study area. However this assumption is researchable and debatable.

4.3.4.5 Latitude

This was taken as the latitude for the area under study (in degrees). This parameter does not change for a given catchment For Siwaze catchment this was obtained form the Digital Elevation models taken from the satellite images and set at 1400 metres above sea level.

4.3.4.6 Key Assumptions and Other Assumptions

Other Key Assumptions that create variables for major modeling assumptions, especially those that varied from scenario to scenario and are very important. These are:

- Root zone conductivity: important as it stipulates the soil water that is taken up by the vegetation, and is not available for runoff or interflow.
- Ground water outflow
- reference potential evaporation/ transpiration
- priority of demands

4.4 Model calibration and sensitivity analysis

The model calibration was done manually via trial and error, seeking to minimize the root mean square (R^2); maximizing the correlation coefficient, R; and reproducing the average monthly reservoir elevation levels of Siwaze, which can relate to dam capacity level. Historical data obtained from ZINWA and meteorological unit was used to calibrate the model (from field observations). The model results were compared to the actual readings taken for the dam Siwaze over the year Oct 2001 to Sept 2002. Field data collected over the two year period represented different agro meteorological conditions encountered under the basin rainfall pattern and land use scenarios. The observed or recorded readings were plotted against the modeled results. For the model sensitivity analysis of the model, several key assumptions were made and estimated.

Model calibration consisted of changing values of model input parameters in an attempt to match field and observed conditions within some acceptable criteria. This required that field conditions at a site be properly characterized. Lack of proper site characterization could result in a model that is calibrated to a set of conditions, which are not representative of actual field conditions.

Step 1: Initial calibration
The initial estimates of the key parameters are shown (Table 4.2):

Table 4.2: Initial calibration assumptions

Parameter			
Initial	**Pastures**	**Cropped area**	**Forests**
Leaf area index (LAI)	Varies with season	Varies with crop type	Varies with season
Root zone depth (Rd)	600mm	Varies with crop type	1500mm
Kj	600mm	800mm	1000mm
Kc	Varies with season	Varies with crop type	Varies with season
Z_1	200mm	300mm	300mm
Z_2	500mm	400mm	1000mm

Figure 4.22 shows a strong relation between precipitation and modeled storage capacities. Precipitation is followed by increase in storage in the reservoir. The precipitation (rainfall) evidently displayed the input into the reservoirs namely direct precipitation and inflow from the dam catchment, as well as inflows from upstream.

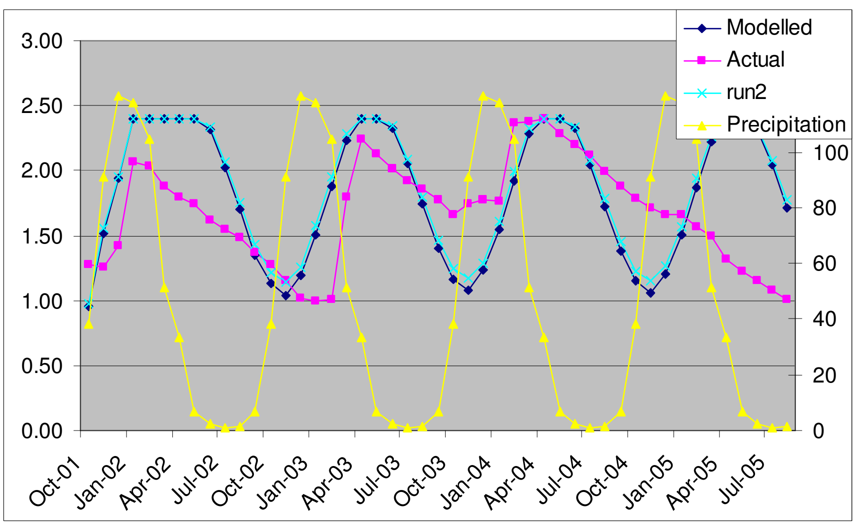
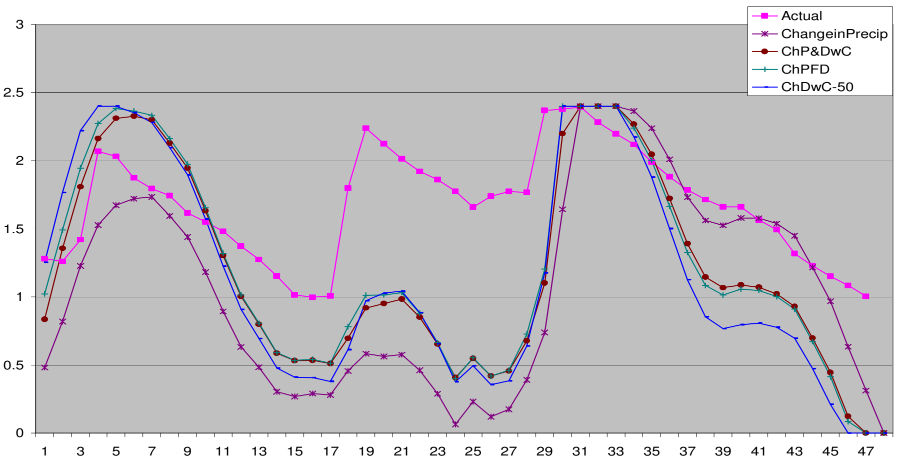


Figure 4.22: Precipitation vs. storage in reservoir Siwaze Dam

The sensitivity analysis was conducted for the data inputted. These included varying the sensitive parameters like deep-water capacity (Two-bucket model). This parameters determines how much will percolate into the second bucket and will not be available as interflow. So, therefore the surface reservoirs cannot account for this water.

Figure 4.23 plots the change in the assumption of this deep water capacity and preferred flow direction. There still remains a fairly weak correlation between the actual and actual observed values.



Legend: ChP = Change in precipitation
ChDwC = Change in deep water capacity
ChPFD= Change in preferred flow direction

Figure 4.23: Initial sensitivity analysis graphs

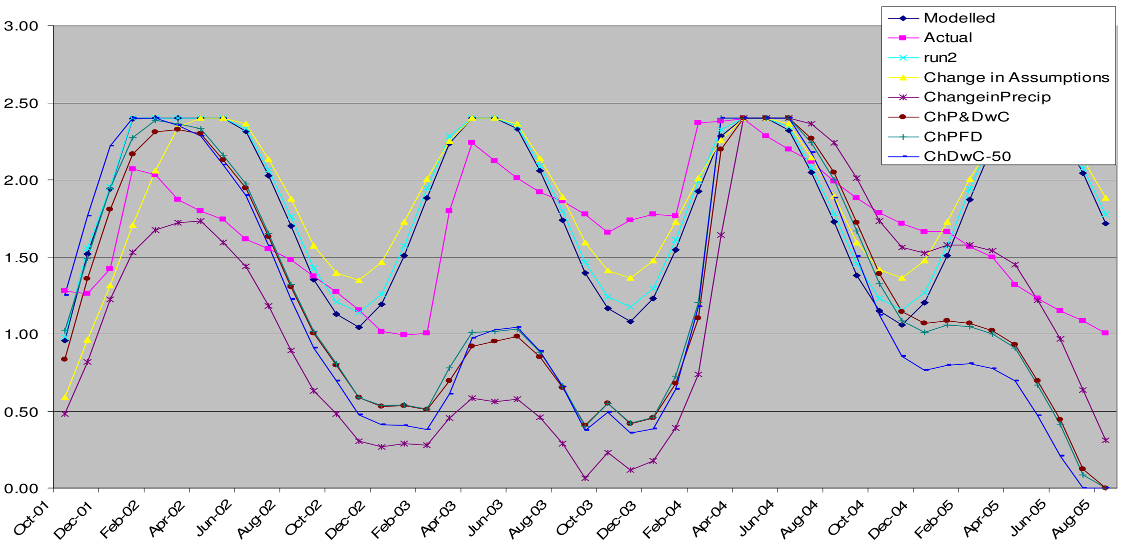
Step 2: Changing preferred flow direction and deep water capacity

A change in precipitation and preferred flow direction affected the model output, Figure 4.24 illustrates how sensitive the model is to these parameters.

Since this model is based on the concept of two buckets, its sensitivity is very high in response to the soil water capacity, the root zone, deep-water capacity and preferred flow direction The soil water capacity impacts on the interflow from the first bucket into the stream for eventual storage in the dams. Meanwhile the deep-water capacity does not release water into the surface water reservoirs.

The changes in the preferred flow direction relate to the geological parameters as to whether the flow is percolating or flowing horizontally. The deep water capacity is the capacity of the soils to store water in the second bucket.

These parameters were continuously varied, testing the various responses and comparing with the actual measured values. The aim was to achieve the graph that would best describe the actual measured series. It became increasingly obvious that these parameters are very sensitive to the model and there required accurate and reliable data. However this data could not be obtained and hence the model runs were not going to be accurate or reliable too.



Legend: ChP = Change in precipitation
ChDwC = Change in deep water capacity
ChPFD= Change in preferred flow direction

Figure 4.24: Final sensitivity analysis graphs

Step 3 : Final parameters

The final estimates of the key parameters for calibration are shown below (Table 4.3):

Table 4.3: Final calibration assumptions

Parameter			
Initial	**Pastures**	**Cropped area**	**Forests**
LAI	Varies with season	Varies with crop type	Varies with season
Rd	300mm	Depends on crop	1000mm
Kj	300mm	600mm	1000mm
Kc	Varies with season	Varies with crop type	Varies with season
Z_1	300mm	400mm	600mm
Z_2	750mm	500mm	1500mm

If a a strong correlation had been obtained then it could have been concluded that the model can now be used to run different scenarios. This process could take a very long time since various experiments and filed data collection techniques are required to obtain input data that would calibrate the model to the optimum. But for the purpose of this study the final calibration data was taken as tabulated in Table 4.3.

4.5 Model verification

A preliminary verification of the model was attempted and three key parameters were investigated namely: temperature precipitation, relative humidity and reservoir evaporation. Historical data from the 2001 to 2005 was used. This data had been cleaned from the meteorological station and the reservoir evaporation was obtained from ZINWA. Figure 4.25 shows the comparison between the relative humidity from the observed against the modeled.

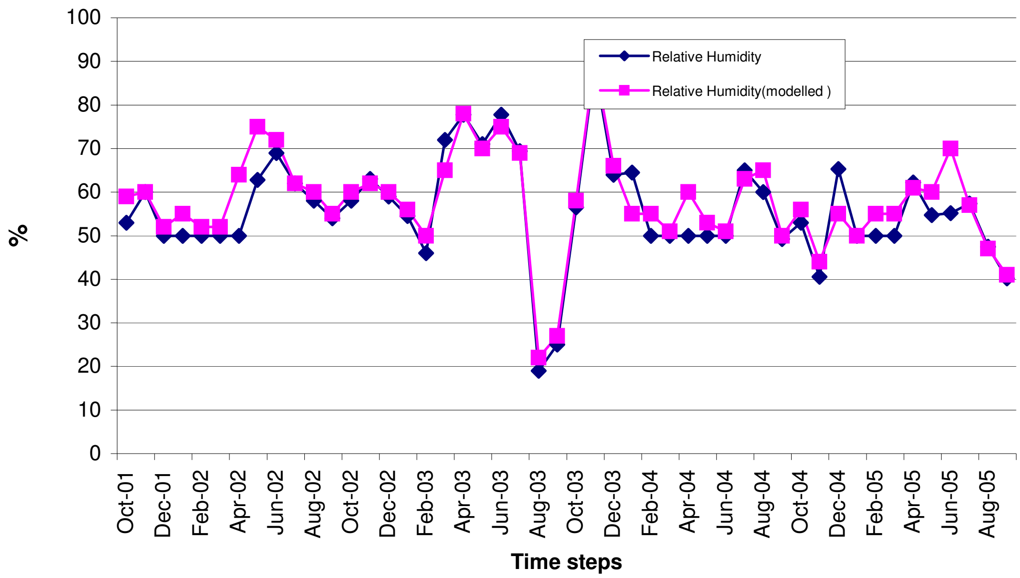


Figure 4.25: Relative Humidity

Model verification seeks to establish the performance of the model. The accuracy of transforming a problem formulation into a model specification or the accuracy of converting a model representation from a micro flowchart form into an executable computer program is evaluated in model verification. The process of model verification requires more extensive data and requires a much prolonged period of study and research.

Similarly the model validation process involves a regression analysis of the observed data against the modeled results. However, this requires a different set of data, which was not available and hence no attempt was made to validate the model.

4.6 Assessment of the scenarios on livelihoods impact.

Through observation and review of previous studies in the area, a number of social, cultural and traditional aspects relating to livelihoods were also "discovered" or rather experienced (Sithole, et al, 2005). Though, these are not necessarily made explicit in the research because they were not directly linkable to hydrology but were however linked to livelihoods. The assessment on livelihoods also served as an outlet for indicating dilemmas that are also of importance especially to organizations such as the Small

Reservoirs Project and ZINWA to understand the "problems" that a decision-maker could be faced with when wanting to implement a development project like a dam or take part in a participatory approach. To ZINWA and the government the dilemmas may also be of importance to understand that, for example, donor assistance also brings with it a number of negative aspects that may not be desirable.

A total of four scenarios were considered for simulation, those that impacted the most on the livelihood of the catchment communities:

1. *Add one more new reservoir with same capacity as Avoca Dam(constructed upstream of Siwaze dam to total 5 small reservoirs).*

   This was an inference from the AREX officials that adding a new reservoir of the size of Avoca in the catchment would improve significantly the availability of water in the catchment. This then means that there would now be five small reservoirs in the catchment. This would possibly prolong the availability of water in the other reservoirs, and possibly allow for increase in livestock numbers and agricultural activity, which relates very much to improving livelihoods.

2. *Increase Avoca growth-point from rural water demand to urban demand*

   This an inference from ZINWA which wishes to simulated a rapid increase in the population at Avoca growth point, removing it from its growth point status demand to a full scale urban center demand. This scenarios would create employment for the local population but hydrological deplete the water resources.

3. *Increase livestock numbers by a growth rate of 5% per annum.*

   As the population of the area increases the demand for drought power increases and there is bound to be an increase in livestock numbers. Increasing the livestock numbers at a rate of 5% annually, has an impact on the livelihoods and water resources especially the small reservoirs.

4. *Increase irrigated area by 100%*

   This is also an inference from AREX which wishes to simulate a rapid increase in the irrigated agriculture to improve livelihoods and alleviate poverty. This scenario would create employment for the local population and provide food for the population all year round as well as cash crop production.

CHAPTER 5: Results and Discussions

The results and output of the model were benchmarked against a known station (Siwaze) which had historical data and information which could be confirmed. Siwaze was taken to be the control station for calibration and simulating scenarios. These results are compared only to dam levels in Siwaze Dam which is the only dam in the sub-catchment with recorded readings taken by ZINWA. The results and discussions therefore are dependent largely on the data quality and the level of accuracy of the readers at the ZINWA station and the degree of calibration of the model.

5.1 Demand and supplies

The demand on the reservoirs could only be translated in relation to livestock and domestic populations and consumption levels. The water demand from the two major users, that is the irrigation scheme and Avoca growth point, from the dam Siwaze was observed to be very high in the drier months of the year. This decreases in the wet season, as irrigation crop water requirements reduces. Demand on the other small dams tend to remain steady over the whole year since irrigation is negligible and most demand is from livestock watering and domestic consumption. Majelimane reservoir dries out completely during the winter months, from over abstraction and evaporation.

Water supplies of clean water came from Siwaze dam which has a treatment plant to supply water to the nearby growth point at Avoca. Water supply to Avoca has a consistent demand for domestic use by the residents.

5.2 Data evaluation

The relevance and appropriate use of the data used in calibration was evaluated by field measurements. Field observation with respect to calibration of the model was sort through the observations of dam levels by gauge plates readings installed at all reservoir sites. There is a relation in the recorded results for precipitation for all the studied dams in the month of January through to March (Figure 5.1). The highest rains fell in January for the catchment. The average variance for the months is 15mm. This poses difficulty in asserting confidence that the data used to calibrate the model for the catchment based on Siwaze data can be relied upon with some scientific reliability. However, there is sufficient assumptions and confidence in the use of data from Siwaze Dam for calibrating the model.

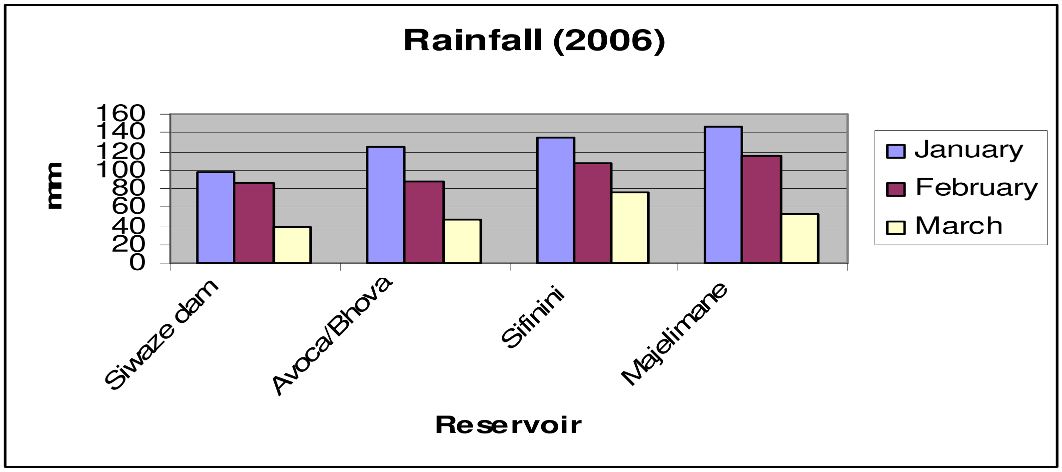


Figure 5.1: Recorded monthly precipitation

Figure 5.2 shows the relationship between the dam levels for each of the dams as recorded in the field work. The observation are that the fill up as the rainy season progressing with some of them spilling. The shape follows that of a typical hydrograph. Based on the data colleted in the field it was assumed that the hydrological occurrence of events in the catchment can be taken as generic to Siwaze dam , hence model output should behave as observed through readings taken at Siwaze over the years..

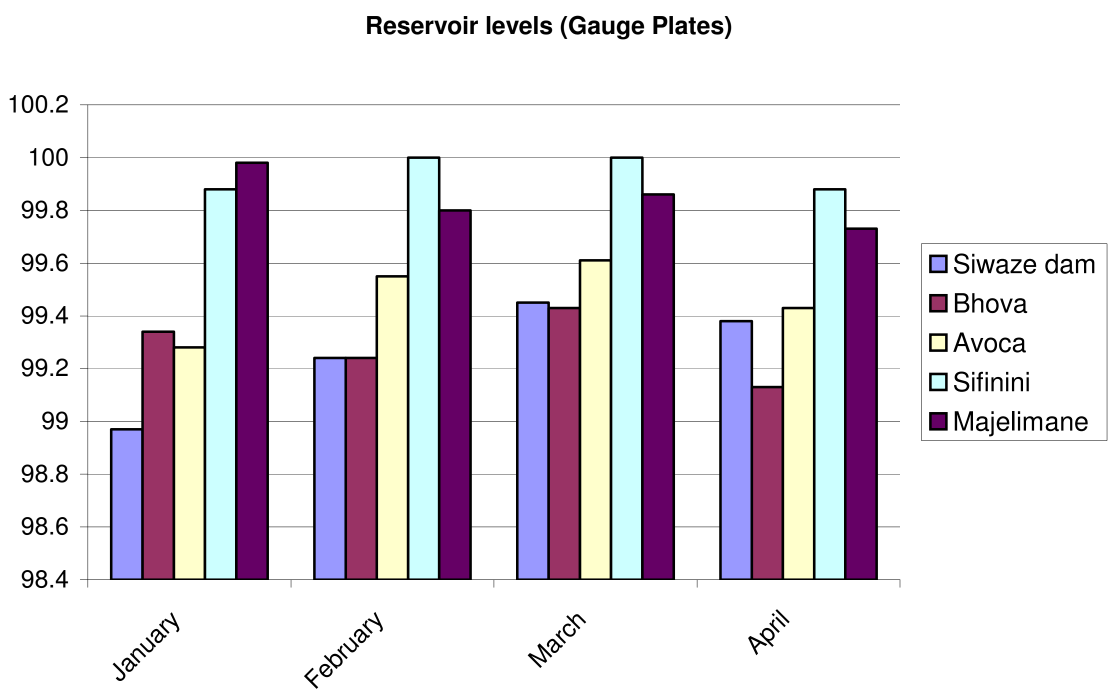


Figure 5.2: Monthly average gauge plate reading per dam site

5.3 Model calibration Results

WEAP model calibration requires that the data be of high quality and of sufficiently long period to achieve the best fit curves. Figure 5.3 shows the mean monthly-observed elevation (storage capacities) levels for the Siwaze dam against the modeled results. Initially it revealed very poor correlation. The poor results indicate the inadequacy of the calibration level or degree.

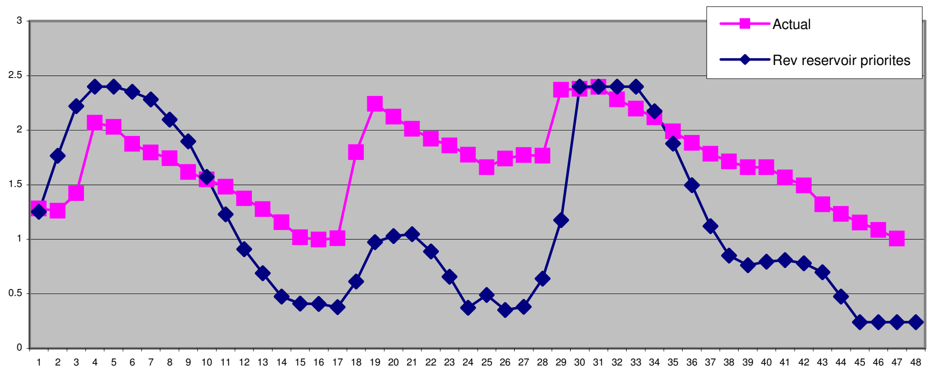


Figure 5.3: Actual vs Modeled reservoir storage capacity of Siwaze dam

The error (deviation) between the observed actual and the modeled translate to need for further review of assumptions. Figure 5.4 shows the dam levels for the modeled and observed at initial stage of calibration of dam levels.

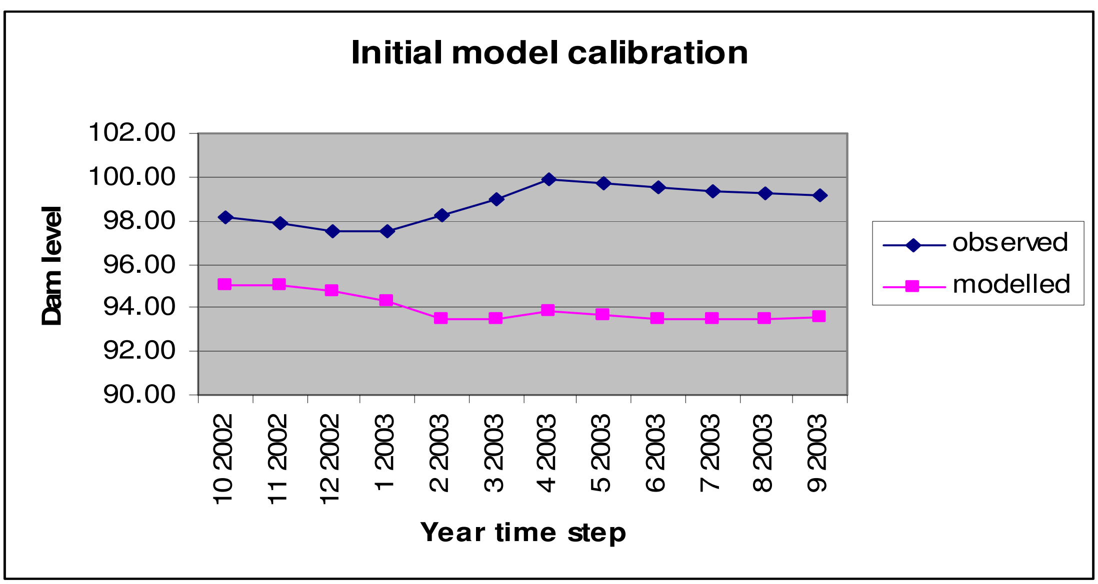


Figure 5.4: Initial model calibration results

Further assumptions continued to be tested in order to improve and attempt to obtain the best fit curves, especially assumptions that were observed to be very sensitive to the model.

Figure 5.5 shows the greatly improved calibrated results on graph as modeled 2. Only two points coincided with the model output, however this was a great improvement from the initial results.

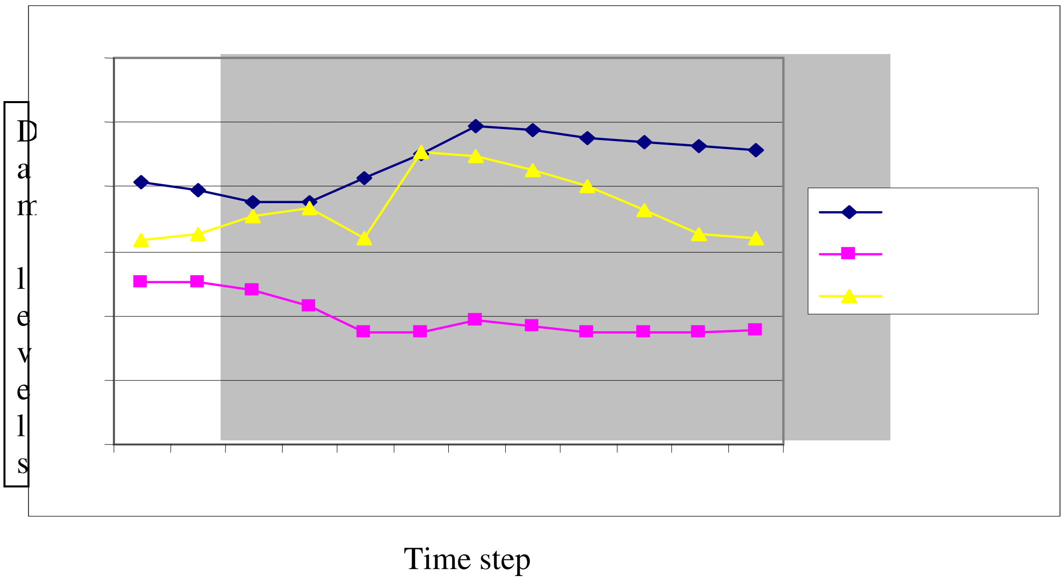


Figure 5.5: Final model calibration results

5.4 Model calibration limitations

Some local factors that are not easy to capture and complicate the model output and calibration are root zone depths, leaf area indices (LAI) and others such as sedimentation. Figure 5.6 shows and demonstrates the problem of sedimentation in the catchment. These problems affect the model output and leads to complication in simulating scenarios. Hence WEAP needs to be evaluated to take into account sedimentation, which is prevalent in the catchment. Much more work is required to establish WEAP sensitive parameters that impart on the calibration of the model. Some of these parameters like Deep water capacity, preferred flow direction would require a study on its own to establish even for a relatively small sub catchment like Siwaze.

Figure 5.6: Extensive river sedimentation in the Mzingwane catchment

The quality of any model performance depends on the quality of data used, as well as who collected the data and for what purpose. The data that is required for input into the WEAP model is extensive. For example, as alluded previously the root zone depth for the catchment's forest is not easy to determine requiring extensive experiments in as far as spatial and temporal dimensions are concerned, hence assumptions made could be way out. Another input data that was sensitive to the model is the leaf area index (LAI), which required time and money to establish being a function of climate conditions and season. Arguments have been raised in some quarters, about the LAI when the trees have shed off their leaves and the leaves lie on the ground rather than on the tree branches. When the leaves cover the ground, moisture is preserved in the soil, so then how is soil water capacity or the root zone water capacity affected?

Going back to the 'Two Bucket" model (Fig. 4.7) there are parameters like deep conductivity, which calculates the water that percolates into ground water. This parameter could not be obtained; hence assumptions had to be made. Where literature is not available, money and time constraints are encountered, assumptions were based on intuition, whose basis can be argued as not scientific.

These limitations on the model performance cannot be ignored in its calibration. WEAP requires all these parameters to be ascertained with precision which in a developing country like Zimbabwe may take years to obtain.

5.5 Livelihood Scenarios results

5.5.1 Scenario 1: Increase reservoirs by one number the size of Avoca

The results of the scenario when one more reservoir was added (assumed to have the same capacity as Avoca dam) are shown in Figure 5.7. The results show how the storage

in the large and small reservoirs in terms of capacity are affected by this change in hydrology.

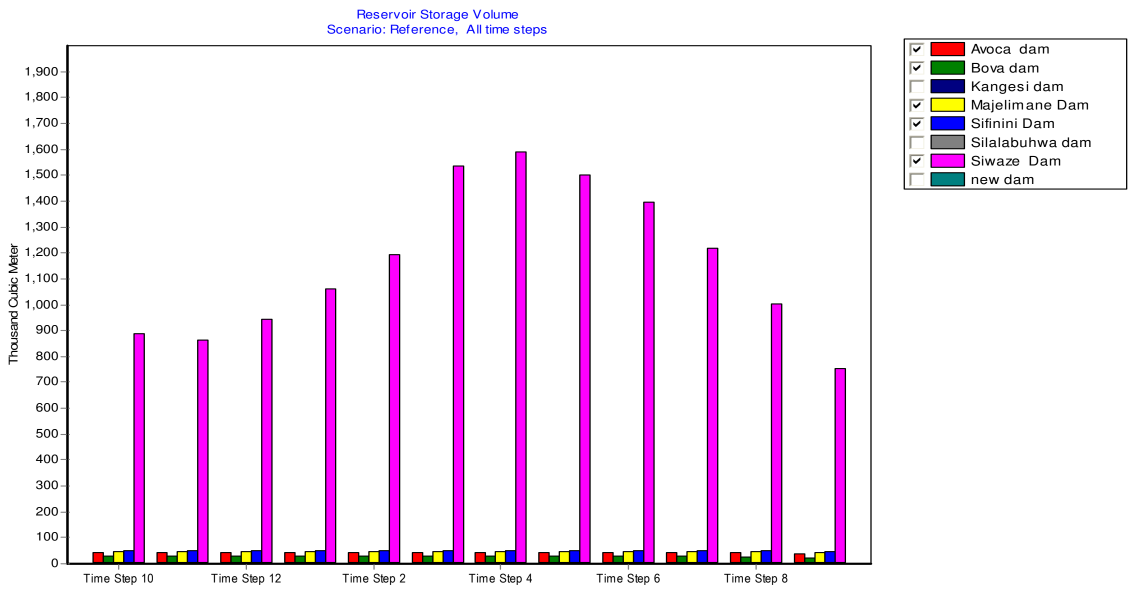


Figure 5.7: Reservoirs storage volume: new reservoir upstream of Siwaze.

The results of the addition of a new reservoir (the same capacity as Avoca dam) are such that only the large reservoir is heavily impacted by this hydrological change. The Siwaze reservoir will be depleted to almost half, and will not spill for the projected period, since more water is now being stored upstream of the dam. The more the dams are constructed upstream the less water that reaches Siwaze dam.

5.5.2 Scenario 2: Increase Avoca growth point demand

The results show that the dam Siwaze will be affected by a gradual increase in population water demand, as the population approaches that of urban consumptive water use. In 2005 the water level and hence storage capacity show signs of over withdrawal. The domestic water demand increase on Siwaze dam would impose stresses in the supply capacity.

It should be stressed that these results should be taken with care since the model calibration did not reach the desired degree of precision and accuracy.

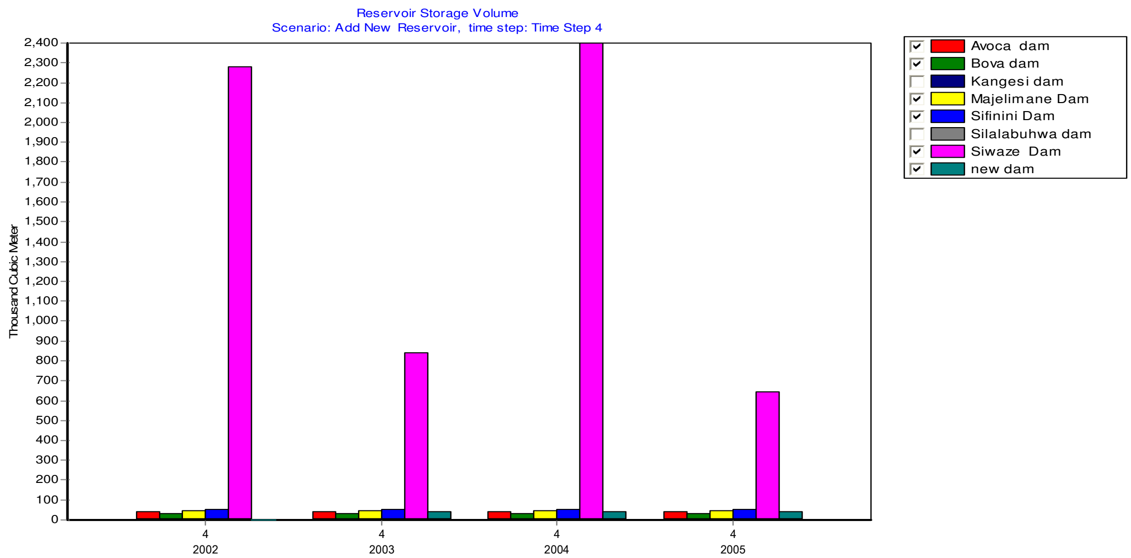


Figure 5.8: Reservoir storage volume

5.5.3 Scenario 3: Increase livestock numbers at 5% growth rate/ annum

Figure 5.9 shows the results when the livestock has been increased incrementally by 5%. The results pertain only to storage in the large and small reservoirs. It shows that the all dams will empty as early as 2005. This could be translated to imply that the area is already overstocked with livestock. Further increase in livestock numbers will not improve on reservoir storages. This scenario, when there is an increase in livestock numbers, certainly does not improve on livelihoods, but rather depletes the reservoirs and can have serious consequences on livelihoods of the community.

These results should be taken in the light of a model that could not be calibrated with best fit curves and results. If calibration had reached a high degree, these are some of the decisions that could be arrived at by planners for recommendation to the decision makers. Such are the importance of modeling tools in water resources.

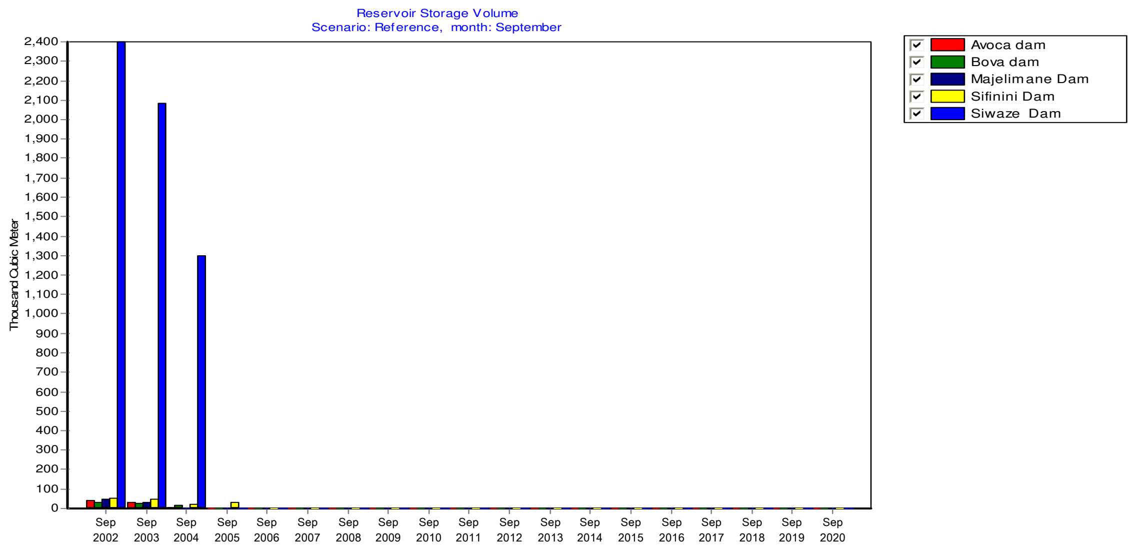


Figure 5.9:Reservoir storage elevation: all dams

5.5.4 Comparing all scenarios

Comparing all scenarios, Figure 5.10 shows that the various livelihoods issues do not affect much of the storages accumulating in all the reservoirs. These results are a manifestation of the inadequate calibration of the model due to insufficient data available for input into the model.

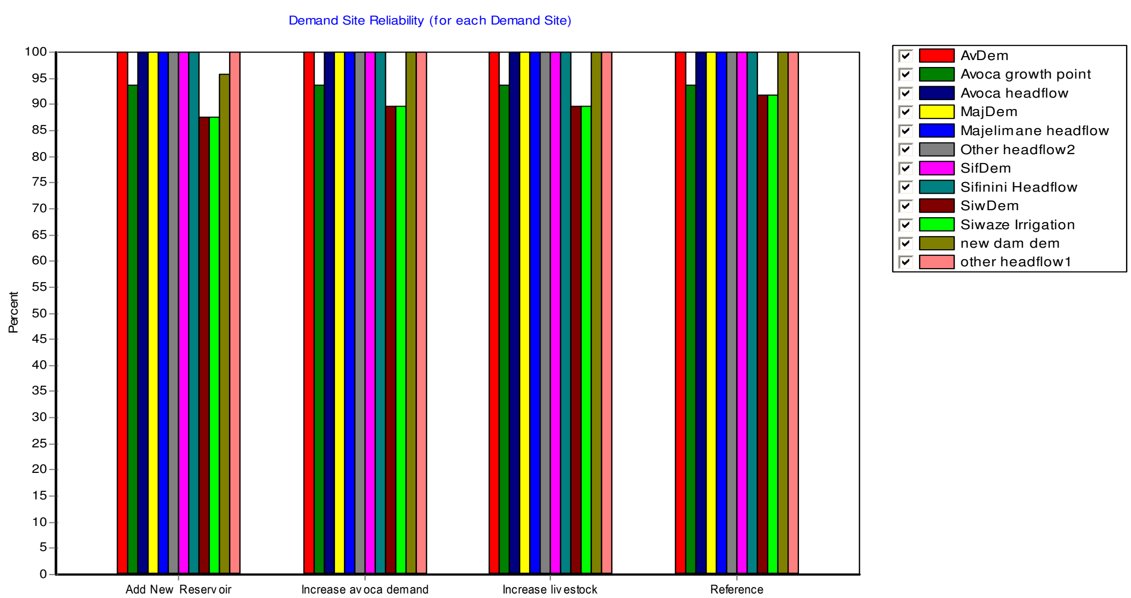


Figure 5.10: All scenarios reservoir storage volumes results

A comparison of the different scenarios and their impact on storage reservoir capacities are shown in Figure 5.11. There is no notable variance between these scenarios. This can

be attributed again to inadequate and low level calibration of the model due to non availability of sufficient data for input into the model.

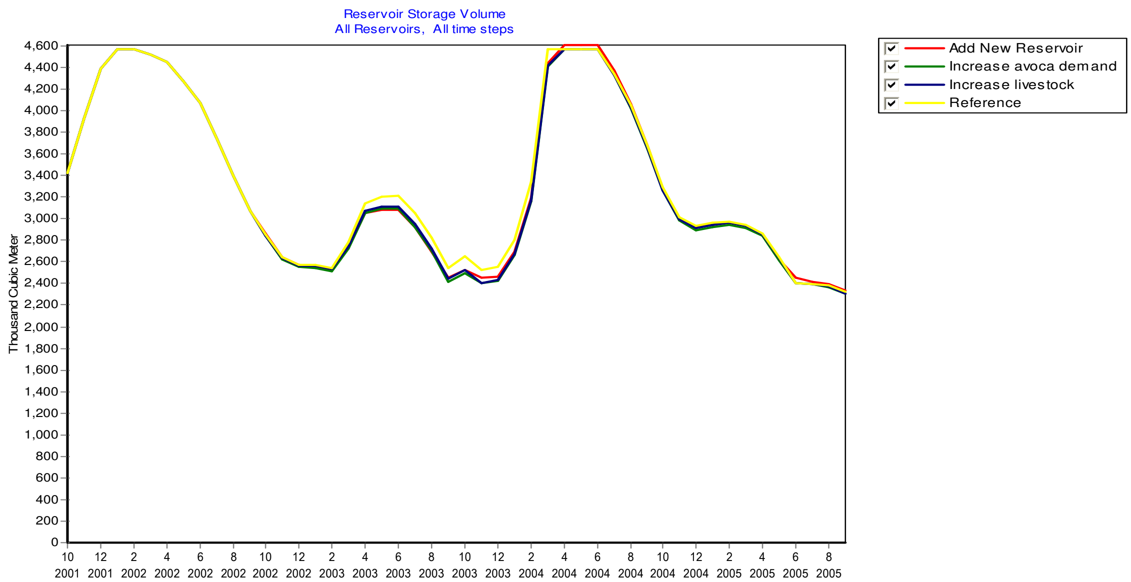


Figure 5.11: Reservoir storage volumes: all scenarios

It is evident that as the small reservoirs fill up upstream of Siwaze dam the more water is available, and the nearer Siwaze it gets to filling up. A projection into year 2020 shows that a combination of all the scenarios would not yield desirable results to the hydrology of small reservoirs. The model shows that all the reservoirs will be depleted to zero capacity, by 2006, if the combination of all livelihood scenarios is to be effected. Such is the usefulness of the model in decision-making, if and only if high level calibration had been attained . However this cannot be conclusively drawn at this stage as the model requires further calibration and possible future verification, for its usefulness as a decision making tool.

In general the results show that the model had not reached a high level of calibration and hence more work would be required, particularly in the area of geophysical data collection and preservation.

CHAPTER 6: Conclusions and Recommendations

6.1 Conclusions

To calibrate a water resources system model like WEAP is by no means an easy task. The data required for the model to be calibrated with precision is intensive. The data would have to have been recorded over a long period with sufficient accuracy. Due to these constraints, to simulate scenarios, using WEAP model for options and recommendations on optimum sustainable rural livelihoods level could not yield reasonable results. Non-the- less the study represents initial attempts to applying WEAP model as a means of addressing planning and management issues in the water stressed Limpopo basin in Zimbabwe.

The study attempted to assess the impact of simulated scenarios for improved rural livelihoods. It failed to prove the effectiveness or benefits of WEAP model as an aid to decision making processes with regard to small reservoirs. The applicability of WEAP to the catchment requires further exploration with more data required for input and certainly more work in the form of experiments and filed work. Hence the impact of small reservoirs on catchment hydrology and rural livelihoods could not be ascertained with certainty and confidence.

However, tools can be found to better plan, develop and manage small multi-purpose reservoirs, in order to improve on decision-making capacity in determining rural livelihoods levels that are sustainable through optimal small reservoirs development and management in a defined catchment.

The WEAP model can be used with limitations (herein contained in item 5.4), provided sufficient good quality data can be obtained for input into the model. Further work is required to prove the reliability of the WEAP model and its applicability to the study area. This study brings to light some short comings of the model, due to the variable hydrological phenomena and geophysical conditions in Zimbabwe, where extremes are very common, with a coefficient of variation of 120% for such model sensitive parameters like precipitation.

6.2 Recommendations

Based on constraints experienced in the study, the following recommendations for future WEAP model development and calibration are proposed:

- Data collection and documentation should be a continuous process and should take place parallel to the model development and use.
- WEAP model should be developed to incorporate the specific river basins with well-defined objectives and specific scenarios to be simulated.
- The model development process should involve joint and continuous cooperation among model developers and potential users.

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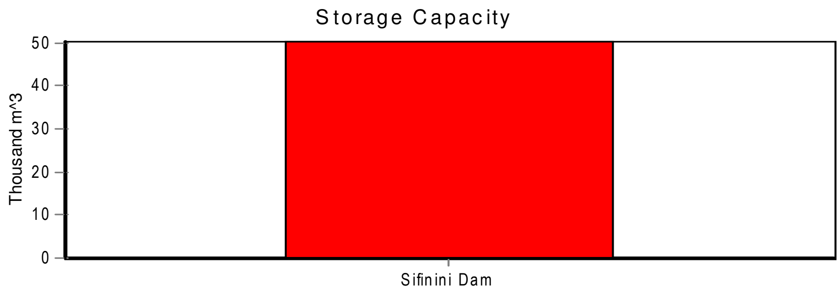
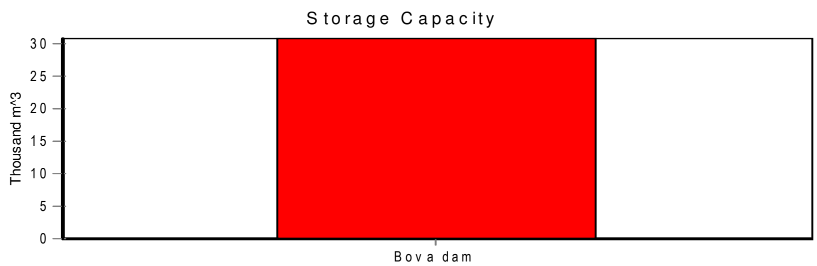
APPENDICES

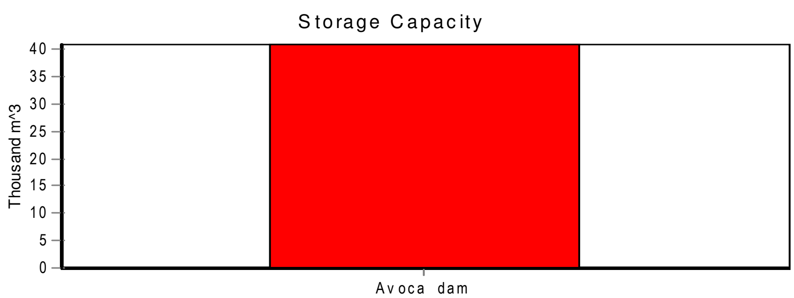
Appendix A : Reservoir storage capacities and major demands



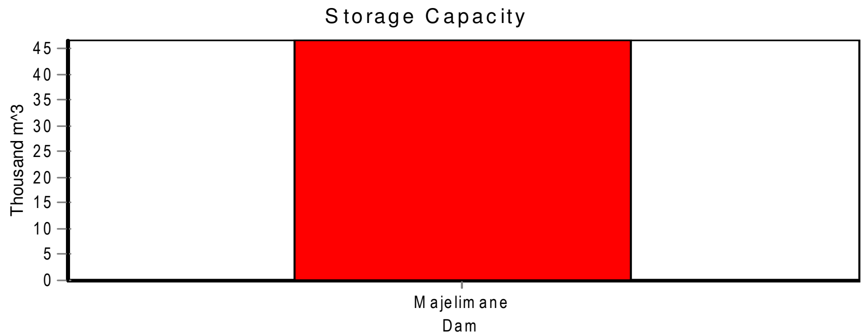
Sifinini Dam Capacity



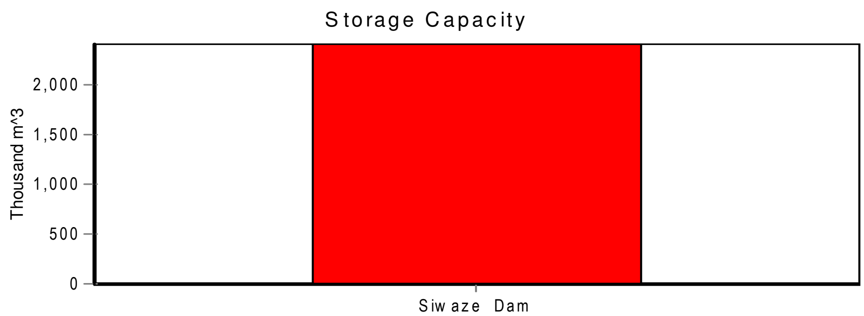
Bhova dam capacity



Avoca dam capacity



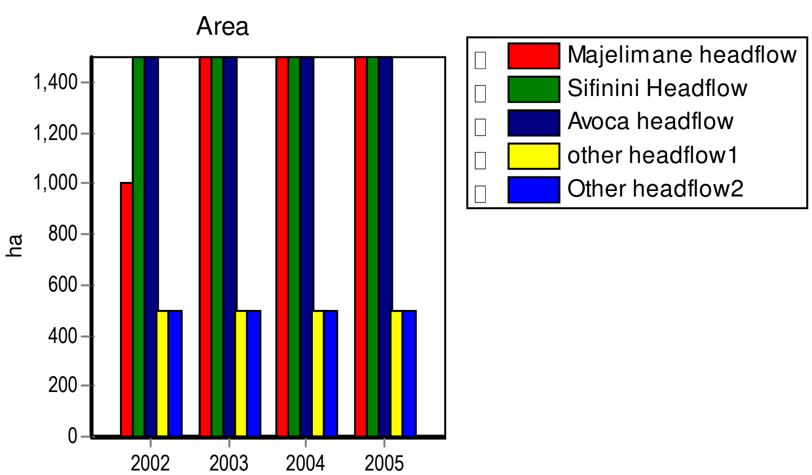
Majelimane dam capacity



Siwaze dam capacity

Domestic water consumption vs Livestock water use

Scenario: Reference 2001-2002



Scenario: Increase reservoir numbers

<u>Appendix B1</u> Raw Data

Evaporation Return NOV. 2005

Date	*Reading*	*Difference*	*Rainfall*	*Evaporation*
1	77.8 (54.1)	12.9	Nil	12.9
2	67	12.7	Nil	12.7
3	71.7 (54.1)	12.5	Nil	12.5
4	66.6	13.9	Nil	13.9
5	80.5 (54.1)	11	Nil	11
6	65.1	4	3	7
7	69.1	8.5	Nil	8.5
8	77.6 (54.1)	2.6	Nil	2.6
9	56.7	4.4	Nil	4.4
10	61.1	10	Nil	10
11	71.1 (54.1)	12	Nil	12
12	66.1	10	Nil	10
13	71.1	9	Nil	9
14	80.1 (54.1)	13.4	Nil	13.4
15	67.5	7.8	Nil	7.8
16	75.3 (54.1)	12.3	Nil	12.3
17	66.4	8.1	Nil	8.1
18	74.5 (54.1)	6.1	Nil	6.1
19	60.2	8.1	Nil	8.1
20	68.3	7	Nil	7
21	75.3 (54.1)	7.6	Nil	7.6
22	61.7		6.2	2.7
23	65.2	4	Nil	4
24	69.2	10.5	Nil	10.5
25	79.7 (54.1)	12	Nil	12
26	66.1	6.8	Nil	6.8
27	66.9		2	5.3
28	70.2	5.3	Nil	5.3
29	75.5 (54.1)	9.2	Nil	9.2
30	63.2		10.5	2.8

Total Rainfall = 21.7mm **Mean rainfall = 0.7mm**
Total Evaporation = 249.4mm **Mean evaporation = 8.3mm**
Source : ZINWA Siwaze

APPENDIX B2: Raw data

Evaporation Return DEC. 2005

Date	*Reading*	*Difference*	*Rainfall*	*Evaporation*
1	55.5	0	8.5	0
2	54.1	3	16	13
3	57.1 (spill)	5.5	5.5	11
4	51.6	0	11.5	0
5	54.1 (spill)	0	68.5	0
6	54.1 (spill)	1.1	10	1
7	54.1 (spill)	5.6	Nil	5.6
8	59.7	6.1	Nil	6.1
9	65.8	2.1	2	4.1
10	67.9	1.1	2.5	1.4
11	69	4	Nil	4
12	73.0 (54.1)	8.7	Nil	8.7
13	62.8	1.6	Nil	1.6
14	64.4	9.1	Nil	9.1
15	73.5 (54.1)	8.3	Nil	8.3
16	62.4	8.5	Nil	8.5
17	70.9	5.6	Nil	5.6
18	76.5 (54.1)	1.1	Nil	2.9
19	55.2	3.2	4	3.2
20	58.4	5	Nil	2
21	55.4	2.6	5	4.1
22	58	3.1	1.5	3.1
23	61.1	5.9	Nil	5.9
24	67	7.6	Nil	7.6
25	74.6 (54.1)	3.2	Nil	4.8
26	50.9	1.5	8	1.5
27	52.4	3	Trace	3
28	55.4	3.9	Nil	3.9
29	59.3	5.3	Nil	5.3
30	64.6	4.8	Nil	4.8
31	69.1	6.3	Nil	6.3

Total Rainfall = 143.0mm Mean rainfall = 4.6mm
Total Evaporation = 146.4mm Mean evaporation = 4.7mm
Source : ZINWA

Appendix B3 : Raw data

Siwaze Dam Capacities

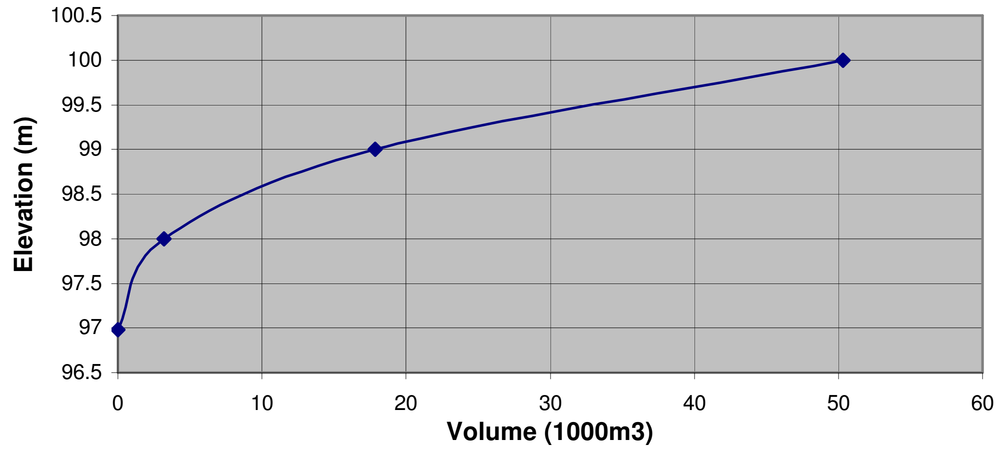
Year	Capacity(Measured)	Modelled	
Oct-01	1.28	1.20	
Nov-01	1.26	1.30	
Dec-01	1.42	1.40	
Jan-02	2.07	2.15	
Feb-02	2.03	2.15	
Mar-02	1.87	1.90	
Apr-02	1.80	1.93	
May-02	1.74	1.75	
Jun-02	1.62	1.60	
Jul-02	1.55	1.56	
Aug-02	1.48	1.50	
Sep-02	1.37	1.32	
Oct-02	1.27	1.28	
Nov-02	1.15	1.16	
Dec-02	1.02	1.05	
Jan-03	1.00	1.00	
Feb-03	1.01	1.03	
Mar-03	1.80	1.81	
Apr-03	2.24	2.30	
May-03	2.13	2.12	
Jun-03	2.01	2.01	
Jul-03	1.92	1.92	
Aug-03	1.86	1.85	
Sep-03	1.78	1.83	
Oct-03	1.66	1.65	
Dec-03	1.77	1.79	
Jan-04	1.77	1.79	
Feb-04	2.37	2.33	
Mar-04	2.38	2.37	
Apr-04	2.40	2.50	
May-04	2.28	2.40	
Jun-04	2.20	2.21	
Jul-04	2.12	2.13	
Aug-04	1.99	1.99	
Sep-04	1.88	1.89	
Oct-04	1.78	1.78	
Nov-04	1.71	1.72	
Dec-04	1.66	1.69	
Jan-05	1.66	1.63	
Feb-05	1.57	1.56	
Mar-05	1.50	1.49	
Apr-05	1.32	1.32	
May-05	1.23	1.25	
Jun-05	1.15	1.13	
Jul-05	1.08	1.09	
Aug-05	1.00	1.12	
Sep-05	0.95	0.97	

Appendix B4 : Raw data

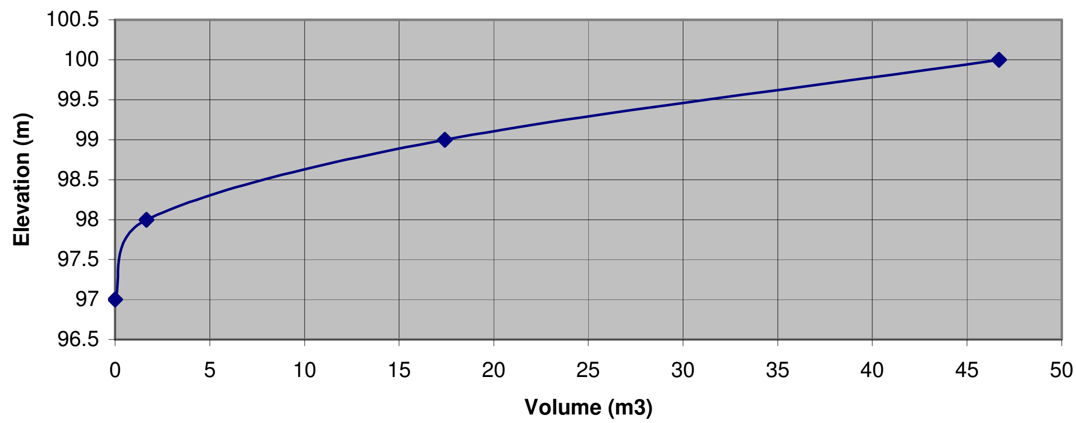
SiwazeTemperature

Year	Max Temp	Min Temp	Mean Temp	Modelled (mean)
Oct-01	31.6	15.3	23.5	26
Nov-01	30.7	18.4	24.6	24
Dec-01	30.2	18.8	24.5	22
Jan-02	34.2	17.1	25.7	24
Feb-02	33.8	16.8	25.3	25
Mar-02	33.2	16.9	25.1	22
Apr-02	30.2	13.3	21.8	21
May-02	28.3	8.6	18.5	19
Jun-02	23.3	6	14.7	15
Aug-02	27.8	8.6	18.2	18
Sep-02	28.4	11.3	19.9	19
Oct-02	30.7	14.9	22.8	22
Nov-02	31	14.7	22.9	24
Dec-02	33	18.7	25.9	26
Jan-03	34.2	13.7	24.0	27
Feb-03	34.9	20.4	27.7	28
Mar-03	29.6	15.8	22.7	24
May-03	26.8	8.7	17.8	20
Jun-03	22.1	7.59	14.8	17
Jul-03	22.8	3.9	13.4	15
Aug-03	26.9	5.7	16.3	19
Oct-03	31.3	15.70645	23.5	24
Nov-03	32	17.7	24.9	26
Dec-03	32.3	18.2	25.3	25
Jan-04	32	19.5	25.8	24
Feb-04	31.1	18.8	25.0	23
Mar-04	26.9	18	22.5	23
Apr-04	27.5	15.1	21.3	23
Jun-04	23.7	5.9	14.8	16
Jul-04	24	5.2	14.6	15
Sep-04	29.5	10.5	20.0	21
Oct-04	31.4	14.9	23.2	24
Nov-04	34.7	17.4	26.1	26
Dec-04	32.4	19	25.7	26
Jan-05	33.4	19.3	26.4	25
Feb-05	33.9	18.2	26.1	24
Mar-05	31.7	16.9	24.3	23
Apr-05	30.2	14.4	22.3	23
May-05	29.4	8.8	19.1	18
Jun-05	27.8	7.8	17.8	16
Jul-05	24.7	4.8	14.8	14
Aug-05	30.2	10.5	20.4	21
Sep-05	32.4	12.2	22.3	22

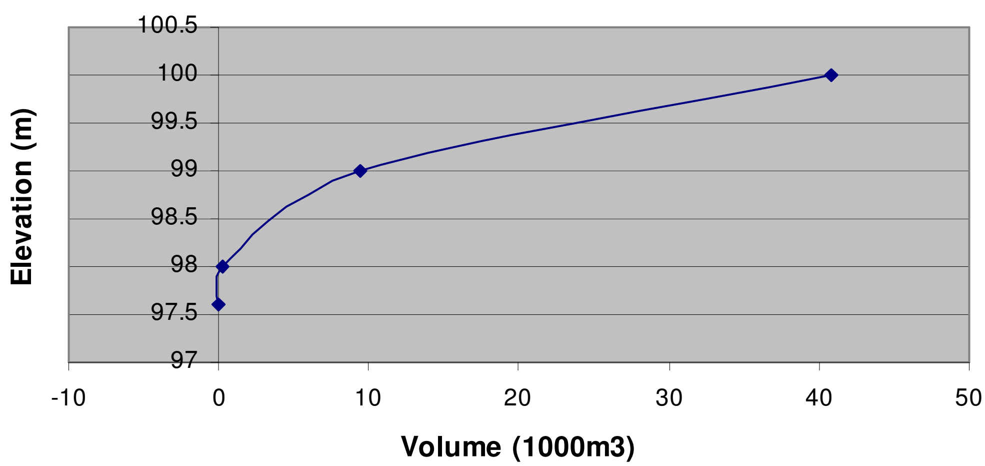
Appendix C **Rating curves for the studied reservoirs**



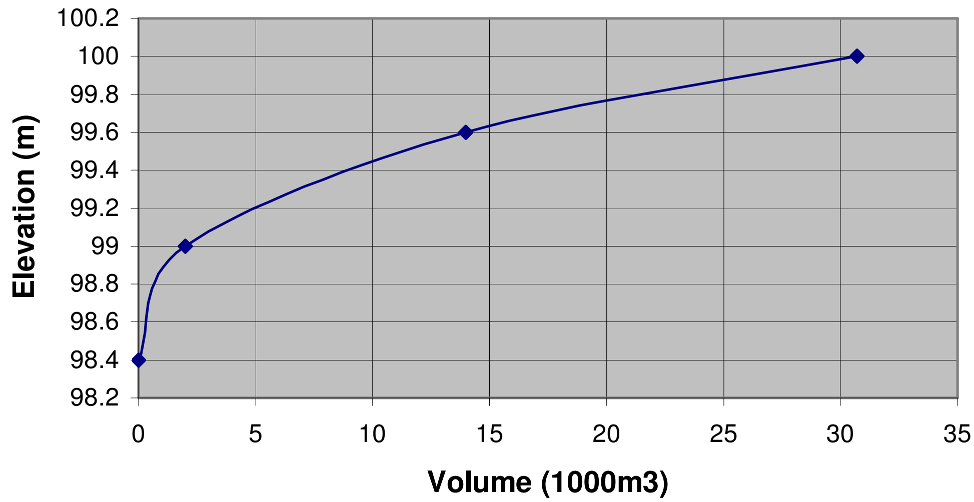
Sifinini dam rating curves



Majelimane dam rating curves



Avoca dam rating curves



Bhova dam rating curves

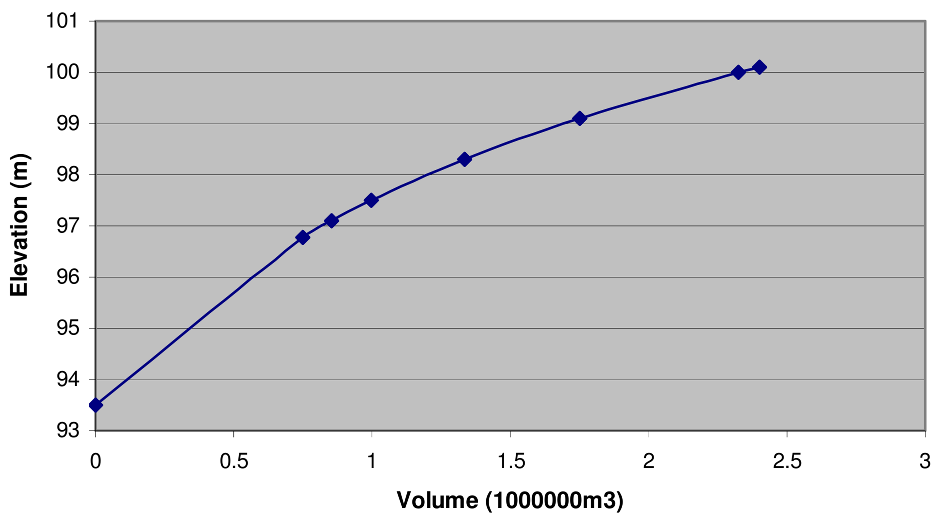


Figure 18: Siwaze dam rating curves

Source: Saunyama T. M.Sc. Thesis 2005

Appendix D The WEAP model

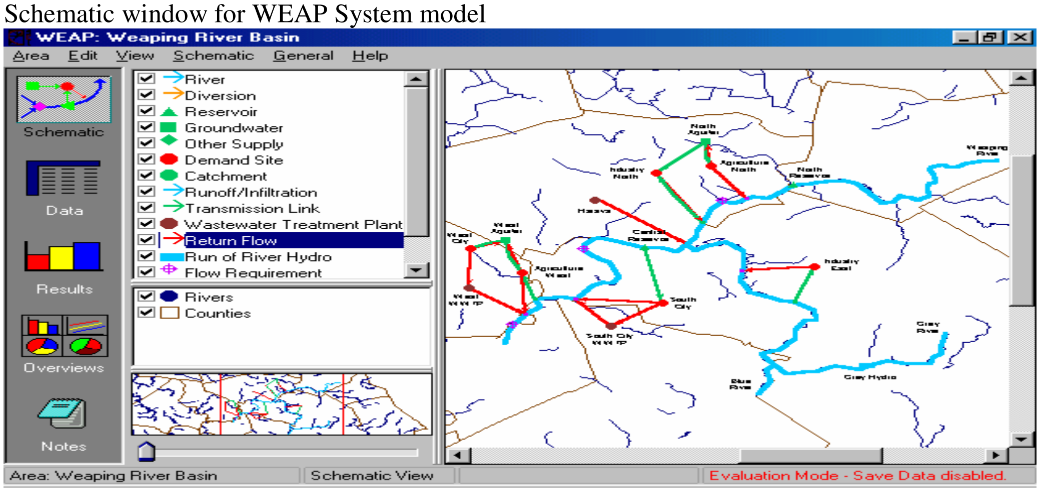
The WEAP system model
The Water Evaluation and Planning (WEAP) system model was developed by the Stockholm Environment Institute (SEI, 2005) (jsieber@tellus.org). The system operates on the basic principle of a Water Balance accounting and is applicable to both municipal and agricultural systems. WEAP can be used as either a database or as a forecasting tool or even as a policy formulation tool.

The system is represented in terms of supply (e.g. rivers, groundwater reservoirs), water transfers (abstractions, transmission) and of water demand (requirements).
Literature review was central to evaluating the water resource components in the sub-catchment (quantity, quality, availability, uses, demand, and sustainability,)
3.3.1 Model operating rules

Once WEAP is installed, start WEAP from the start/programs/WEAP menu.
WEAP will display a title screen, then the menu screen shown in Figure 1.
The main screen consists of 5 major "views", each of which lets you examine different aspects of the software. The **view bar** located on the left of the screen displays an icon for each view. You can switch between views by clicking on the bar or use the View menu to change views.

The **Schematic View** shows the water system depicted geographically.

Schematic window for WEAP System model



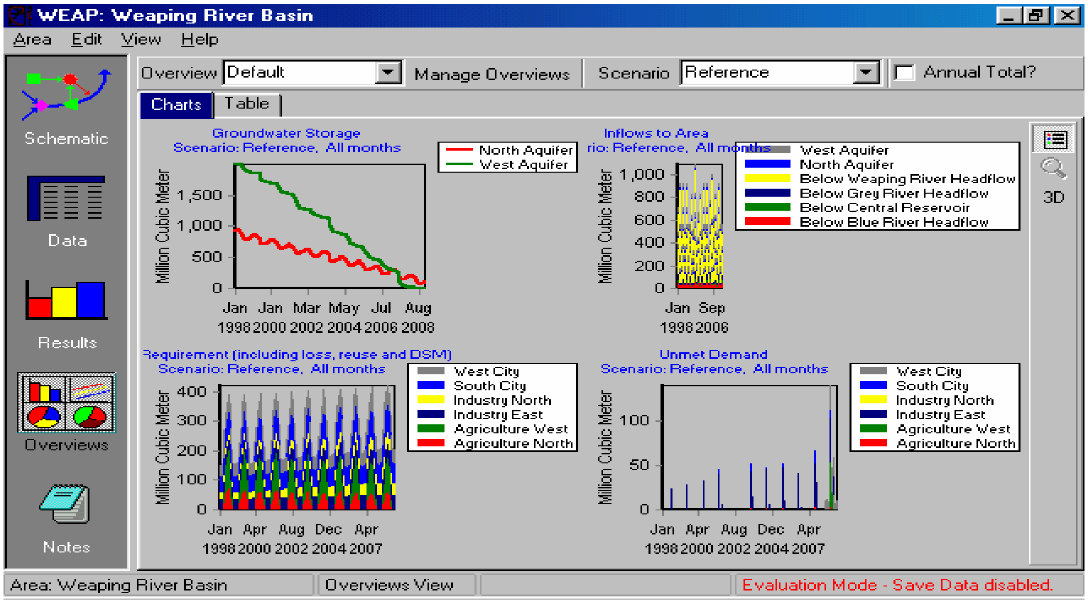
The **Data View** is where data is entered or edited to construct the model and scenarios.
The **Results View** displays the outcomes of the various scenarios in graphical or tabular form.

The **Overview View** gives a bird's eye perspective on key aspects of the modeled scheme

Finally the **Notes View** provides space for documentation of data sources and assumptions.

One of WEAP's advantages is giving the user tremendous flexibility in representing demands, supply and use of water resources depending on the availability of data, type of analysis and level of aggregation. WEAP is also user friendly being compatible with windows software and using integrated hydrological parameters.

Output windows for WEAP System model



3.8 Why WEAP?

Overview

WEAP is a microcomputer tool for integrated water resources planning that attempts to assist rather than substitute for the skilled planner. It provides a comprehensive, flexible and user-friendly framework for planning and policy analysis. A growing number of water professionals are finding WEAP to be a useful addition to their toolbox of models, databases, spreadsheets and other software. This introduction presents WEAP's purpose, approach, and structure; a detailed technical description of WEAP capabilities is available in a separate publication.

Background

Allocation of limited water resources, concerns regarding environmental quality, planning under climate variability and uncertainty, and the need to develop and implement sustainable water use strategies are increasingly pressing issues for water resource planners. Conventional supply-oriented simulation models are not always adequate for exploring the full range of management options.

Over the last decade, an integrated approach to water development has emerged which places water supply projects in the context of demand-side management, and water quality and ecosystem preservation and protection. WEAP incorporates these values into a practical tool for water resources planning and policy analysis. WEAP places demand-side issues such as water use patterns, equipment efficiencies, re-use strategies, costs, and water allocation schemes on an equal footing with supply-side topics such as stream flow, groundwater resources, reservoirs, and water transfers. WEAP is also distinguished by its integrated approach to simulating both the natural (e.g., evapotranspirative demands, runoff, baseflow) and engineered components (e.g., reservoirs, groundwater pumping) of water systems, allowing the planner access to a more comprehensive view of the broad range of factors that must be considered in managing water resources for present and future use. The result is an effective tool for examining alternative water development and management options.

WEAP operates in many capacities:

Water balance database: WEAP provides a system for maintaining water demand and supply information.

Scenario generation tool: WEAP simulates water demand, supply, runoff, streamflows, storage, pollution generation, treatment and discharge and instream water quality.

Policy analysis tool: WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.

The WEAP Approach

WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. Moreover, WEAP can simulate a broad range of natural and engineered components of these systems, including rainfall runoff,

baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. A financial analysis module also allows the user to investigate cost-benefit comparisons for projects.

The analyst represents the system in terms of its various supply sources (e.g., rivers, creeks, groundwater, reservoirs, and desalination plants); withdrawal, transmission and wastewater treatment facilities; water demands; pollution generation; and ecosystem requirements. The data structure and level of detail can be easily customized to meet the requirements and data availability for a particular system and analysis.

WEAP applications generally include several steps.

Study definition: The time frame, spatial boundaries, system components, and configuration of the problem are established.

Current accounts: A snapshot of actual water demand, pollution loads, resources and supplies for the system are developed. This can be viewed as a calibration step in the development of an application.

Scenarios: A set of alternative assumptions about future impacts of policies, costs, and climate, for example, on water demand, supply, hydrology, and pollution can be explored. (Possible scenario opportunities are presented in the next section.)

Evaluation: The scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

Examples of WEAP Scenario Analyses

Scenario analysis is central to WEAP. Scenarios are used to explore the model with an enormous range of "what if" questions, such as:

What if population growth and economic development patterns change?
What if reservoir operating rules are altered?
What if groundwater is more fully exploited?
What if water conservation is introduced?
What if ecosystem requirements are tightened?
What if a conjunctive use program is established to store excess surface water in underground aquifers?
What if a water recycling program is implemented?
What if a more efficient irrigation technique is implemented?
What if the mix of agricultural crops changes?
What if climate change alters demand and supplies?
How does pollution upstream affect downstream water quality?
How will land use changes affect runoff?

Appendix E Selected Calculation Algorithms (Source WEAP User Guide)

Demand

A demand site's (*DS*) demand for water is calculated as the sum of the demands for all the demand site's bottom-level branches (*Br*). A bottom-level branch is one that has no branches below it.

Supply

The monthly demand represents the amount of water needed each month by the demand site for its use, while the **supply requirement** is the actual amount needed from the supply sources. The supply requirement takes the demand and adjusts it to account for internal reuse, demand side management strategies for reducing demand, and internal losses. These three adjustment fractions are entered as data--see Demand\Loss and Reuse and Demand\Demand Side Management.

$$MonthlySupplyRequirement_{DS,m} = (MonthlyDemand_{DS,m} \times (1 - ReuseRate_{DS}) \times (1 - DSMSavings_{DS})) / (1 - LossRate_{DS})$$

Runoff

There is a choice among three methods to simulate catchment processes such as evapotranspiration, runoff, infiltration and irrigation demands. These methods include (1) the Rainfall Runoff and (2) Irrigation Demands Only versions of the FAO Crop Requirements Approach, and (3) the Soil Moisture Method. Your choice of method depends on the level of complexity desired for representing the catchment processes and data availability.

Of these three methods, the Irrigation Demands Only method is the simplest. It uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfill that portion of the evapotranspiration requirement that rainfall can not meet. It does not simulate runoff or infiltration processes.

The Rainfall Runoff method also determines evapotranspiration for irrigated and rainfed crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

The Soil Moisture Method is the most complex of the three methods; it represents the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. Baseflow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes. One can also link groundwater nodes to catchments simulated with the Soil Moisture Method. In this case, the lower soil layer is ignored and precipitation that passes through the upper soil layer is routed to the groundwater node rather than baseflow and increases in soil moisture in this lower layer.

River reservoir flows

A reservoir's (*Res*) storage in the first month (*m*) of the simulation is specified as data (see Supply and Resources\River\Reservoir\Storage).

$$BeginMonthStorage_{Res,m} = InitialStorage_{Res} \text{ for } m = 1$$

Thereafter, it begins each month with the storage from the end of the previous month.

$$BeginMonthStorage_{Res,m} = EndMonthStorage_{Res,m-1} \text{ for } m > 1$$

This beginning storage level is adjusted for evaporation. Since the evaporation rate is specified as a change in elevation (see Supply and Resources\River\Reservoir\Physical\Net Evaporation), the storage level must be converted from a volume to an elevation. This is done using the volume-elevation curve (specified as data--see Supply and Resources\River\Reservoir\Physical\Volume Elevation Curve).

$$BeginMonthElevation_{Res} = VolumeToElevation(BeginMonthStorage_{Res})$$

The elevation is reduced by the evaporation rate.

$$AdjustedBeginMonthElevation_{Res} = BeginMonthElevation_{Res} – EvaporationRat$$

Then the adjusted elevation is converted back to a volume.

$$AdjustedBeginMonthStorage_{Res} = ElevationToVolume(AdjustedBeginMonthElevation_{Res})$$

A reservoir's operating rules determine how much water is available in a given month for release, to satisfy demand and instream flow requirements, and for flood control. These rules operate on the available resource for the month. This "storage level for operation" is the adjusted amount at the beginning of the month, plus inflow from upstream and return flows from demand sites (*DS*) and treatment plants (*TP*).

$$StorageForOperation_{Res} = AdjustedBeginMonthStorage_{Res} + UpstreamInflow_{Res} + DSReturnFlow_{DS,Res} + TPReturnFlow_{TP,Res}$$

The amount available to be released from the reservoir is the full amount in the conservation and flood control zones and a fraction (the buffer coefficient fraction is entered as data--see Supply and Resources\River\Reservoir\Operation) of the amount in the buffer zone. Each of these zones is given in terms of volume (i.e. not elevation). The water in the inactive zone is not available for release.

$$StorageAvailableForRelease_{Res} = FloodControlAndConservationZoneStorage_{Res} +$$

$$BufferCoefficient_{Res} \text{ x } BufferZoneStorage_{Res}$$

All of the water in the flood control and conservation zones is available for release, and equals the amount above Top Of Buffer (TOB and other reservoir zones levels are entered as data--see Supply and Resources\River\Reservoir\Operation),

$$FloodControlAndConservationZoneStorage_{Res} = StorageForOperation_{Res} - TopOfBuffer_{Res}$$

or zero if the level is below Top Of Buffer.

$$FloodControlAndConservationZoneStorage_{Res} = 0$$

Buffer zone storage equals the total volume of the buffer zone if the level is above Top Of Buffer,

$$BufferZoneStorage_{Res} = TopOfBufferZone_{Res} - TopOfInactiveZone_{Res}$$

or the amount above Top Of Inactive if the level is below Top of Buffer,

$$BufferZoneStorage_{Res} = StorageForOperation_{Res} - TopOfInactiveZone_{Res}$$

or zero if the level is below Top Of Inactive.

$$BufferZoneStorage_{Res} = 0$$

For example, the conservation zone in a downstream reservoir will not be drained while an upstream reservoir remains full. Instead, each reservoir's conservation zone would be drained halfway.)

$$Outflow_{Res} = DownstreamOutflow_{Res} + TransLinkInflow_{Res,DS}$$

where

$$Outflow_{Res} \; StorageAvailableForRelease_{Res}$$

The storage at the end of the month is the storage for operation minus the outflow.

$$EndMonthStorage_{Res} = StorageForOperation_{Res} - Outflow_{Res}$$

The change in storage is the difference between the storage at the beginning and the end of the month. This is an increase if the ending storage is larger than the beginning, a decrease if the reverse is true.

$$IncreaseInStorage_{Res} = EndMonthStorage_{Res} - BeginMonthStorage_{Res}$$