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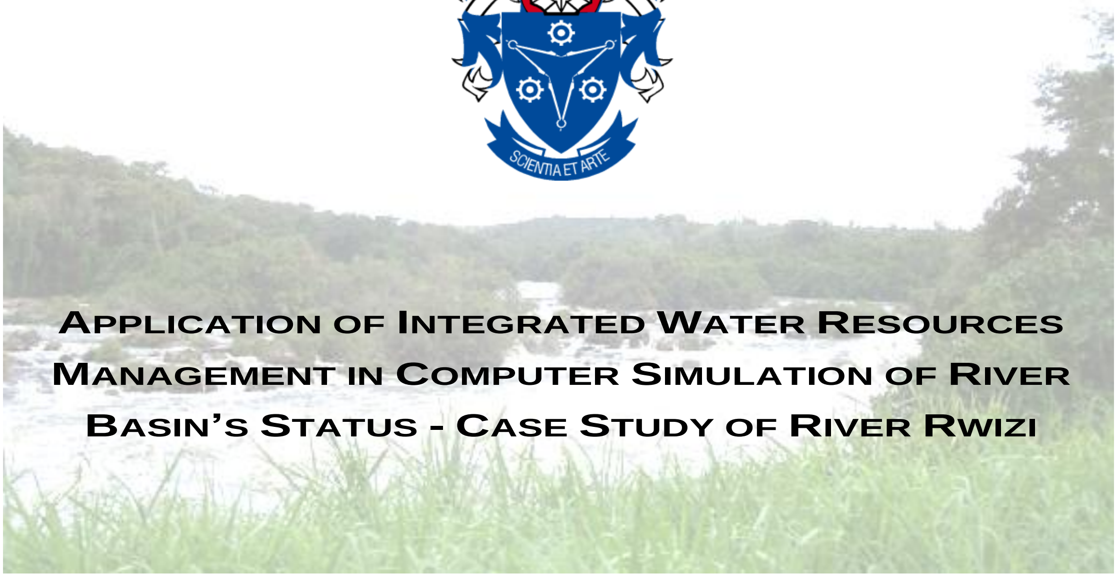

APPLICATION OF INTEGRATED WATER RESOURCES MANAGEMENT IN COMPUTER SIMULATION OF RIVER BASIN'S STATUS - CASE STUDY OF RIVER RWIZI

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DECLARATION

This work has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree in Vaal University of Technology or any other university.

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DEDICATION

To Richard and Josiah

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To my family: Thank you for being so supportive.

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ABSTRACT

During the last few years, concern has been growing among many stakeholders all over the world about declining levels of surface water bodies accompanied by reduced water availability predominantly due to ever increasing demand and misuse. Furthermore, overexploitation of environmental resources and haphazard dumping of waste has made the little water remaining to be so contaminated that a dedicated rehabilitation/remediation of the environment is the only proactive way forward. River Rwizi Catchment is an environment in the focus of this statement.

The overall objective of this research was to plan, restore and rationally allocate the water resources in any river basin with similar attributes to the study area. In this research, Integrated Water Resources Management (IWRM) methodology was applied through Watershed/Basin Simulation Models for general river basins. The model chosen and used after subjection to several criteria was DHI Model, MIKE BASIN 2009 Version. It was then appropriately developed through calibration on data from the study catchment, input data formatting and its adaptation to the catchment characteristics. The methodology involved using spatio-temporal demographic and hydrometeorological data.

It was established that the model can be used to predict the impact of projects on the already existing enviro-hydrological system while assigning priority to water users and usage as would be deemed necessary, which is a significant procedure in IWRM-based environmental rehabilitation/remediation. The setback was that the available records from the various offices visited had a lot of data gaps that would affect the degree of accuracy of the output. These gaps were appropriately infilled and gave an overall output that was adequate for inferences made therefrom.

Several scenarios tested included; use and abstraction for the present river situation, the effect of wet/dry seasons on the resultant water available for use, and proposed projects being constructed on and along the river. Results indicated that the river had insufficient flow to sustain both the current and proposed water users. It was concluded that irrespective of over exploitation, lack of adequate rainfall was not a reason for the low discharge but rather the loss of rainwater as evaporation, storage in swamps/wetlands, and a considerable amount of water recharging groundwater aquifers.

Thus, the proposed remedy is to increase the exploitation of the groundwater resource in the area and reduce the number of direct river water users, improve farming methods and conjunctive use of groundwater and surface water - the latter as a dam on River Rwizi. The advantage of the dam is that the water usage can be controlled as necessary in contrast to unregulated direct abstraction, thus reducing the risk of subsequent over-exploitation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS USED

DHI	Danish Hydraulic Institute
MB	MIKE BASIN Model
NAM	Nedbør-Afrstrømnings-Model
DWRM	Directorate of Water Resources Management
NWSC	National Water and Sewerage Corporation
DEM	Digital Elevation Model
GIS	Geographic Information System
IWRM	Integrated Water Resources Management Model
ICM	Integrated Catchment Management
TWM	Total Water Management
GWP	Global Water Partnership
EIA	Environmental Impact Assessment
UN	United Nations
MASL	Metres Above Sea Level

1.0 INTRODUCTION

1.1 Rationale for the Study

Water, like air, is a vital resource without substitute and its supply, allocation, and wastewater disposal present numerous challenges, all of which must be met to support the ever increasing population. The provision of potable water and sanitation in urban areas pose significant challenges for developing countries. Surface water and groundwater resources are increasingly over-exploited. Lack of wastewater treatment and insufficient control over other waste disposals also place water systems at risk of microbiological and chemical contamination. These come up as challenges that must be overcome in order to conserve our freshwater which is a finite resource.

The notion that freshwater is a finite resource arises as the hydrological cycle on average yields a fixed quantity of water per period. This overall quantity cannot yet be altered significantly by human actions, though it can be, and frequently is, depleted by man-made activities and abstractions. Freshwater resource is a natural asset that needs to be maintained to ensure that the desired services it provides are sustained. This maintenance can be done by everyone through Integrated Water Resources and Management (IWRM).

The Global Water Partnership (GWP 2009) considers IWRM as an approach that helps to manage and develop water resources in a sustainable and balanced way taking account of socio, economic and environmental interests.

The Food and Agricultural Organisation of United Nations (FAO 2005) defines IWRM as a process that promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

IWRM is a philosophy of managing the water resources of a catchment in an integrated manner. It relies on the recognition that components of the hydrological cycle are intimately linked, and each component is affected by changes in other components. It is inherent in the concept of Integrated Catchment Management (State of Environment South Africa Glossary 1999).

The need for IWRM has become more evident in recent years. According to the 1999 census, the world population had reached the 6 billion mark. As of April 2009, the earth's population was estimated to be about 6.77 billion – Wikipedia (United States Census Bureau). This population increase places the world's freshwater resources under increasing pressure due to increase in exploitation in order to meet the growing demand.

The following facts and figures further show the current situation of the water available for human consumption, the way these water resources are utilised and the challenges that have and will arise due to shortage of some of these resources - Cap-Net http://www.archive.cap-net.org/iwrm_tutorial/2_1.htm.

- Of the global water present; 97% is seawater, 3% is freshwater. Of the freshwater 87% is not accessible, only13% is accessible (which is 0.4% of the total).
- Today more than 2 billion people are affected by water shortages in over 40 countries.
- 263 river basins are shared by two or more nations.
- 2 million tones per day of human waste are deposited in water courses
- Half the population of the developing world is exposed to polluted sources of water that increase disease incidence.
- 90% of natural disasters in the 1990s were water related.
- The increase in world population from 6 billion to 9 billion will be the main driver of water resources management for the next 50 years.

The United Nations Water for Life Water for People Report (2003) listed 263 trans-boundary basins. These basins:

- Cover 45% of the land surface of the Earth;
- Affect 40% of the world's population;
- Account for approximately 80% of global river flow;
- Cross the political boundaries of 145 nations.

Although the "water crisis" tends to be viewed as a water quantity problem, water quality is increasingly recognized in many countries as a major factor (Ongley 1999). Historically, poor water quality has been principally associated with public health concerns about transmission of water-borne diseases that are still major problems in Africa and in many other parts of the developing world. In recent years, the contribution of degraded water to the water crisis is also measured in loss of beneficial use – that is, water that is lost for beneficial human, agricultural, and ecological uses through excessive pollution by pathogens, nutrients, heavy metals and acid mine drainage. In the same category are trace organic contaminants, localised high levels of oil and related pollutants such as salt, hydrocarbons, metals and other toxic wastes, and high levels of turbidity and sedimentation from excessive loadings of sediments.

Freshwater pollution is also a major contributor to coastal and marine contamination with negative impacts on coastal and pelagic species of fish, marine mammals, and sea birds. These impacts are recognized under the United Nations Global Programme of Action for Protection of the Marine Environment from Land-Based Activities (Washington Declaration on Protection of Marine Environment from Land-Based Activities 1995).

The largely silent killers in national economies are the multitude of economic costs/losses due to freshwater pollution. These losses include:

- Costs to expand water treatment facilities and to develop alternative potable water sources
- Loss of commercial fish species

- Degradation or loss of habitat and biodiversity and related loss in tourism revenues
- Direct and indirect costs of disease, including treatment costs and reduced economic productivity through mortality and morbidity
- Loss in agricultural production from increasingly salinity in irrigation water, or inability to use severely polluted water
- Loss, or increased cost, of industrial production due to impaired water quality
- Cost of social unrest and population migration associated with extremely degraded aquatic environments.

An integrated approach to management of water resources in order to resolve the above listed problems necessitates co-ordination of the range of human activities that create the demands for water, determine land uses and generate waterborne waste products. The Integrated Approach principle recognizes the catchment area or river basin as the logical unit for water resources management.

A river or lake basin/catchment is an area bounded by watersheds /hills /mountains in which streams and rivers flow towards the same outlet. In case of large rivers this is generally the sea, but may be an inland water body, such as a lake or swamp (Global Water Partnership 2009).

The rationale for undertaking water resources studies on a river basin scale instead of a project basis is the recognition that water and land resources of a basin form a unit, and hence must be treated as such if future conflicts over water utilisation are to be avoided. At river basin planning level, the broad objectives are (Petersen 1984):

- To utilize the natural resources of the basin wisely to avoid future shortages;
- To determine priorities for development and investment;

- To avoid implementation of irreversible plans that might limit future freedom of choice in vital areas;
- To facilitate future integrated development of water and related land resources.

River basins, administrative and political regions, and geographical areas all overlap. Of these, the river basin is widely acknowledged as the most appropriate unit for Water Resources Planning and Development (Petersen 1984). This is because it is naturally bounded as a unique hydrologic system, for which meteorological and hydrological inflows and outflows can be defined.

The Mar del Plata Action Plan (United Nations Mar del Plata Action Plan 1989) recommended the formulation of Master Plans for countries and river basins to provide a long-term perspective for planning of resource conservation and use. It recommended the use of such techniques as systems analysis and mathematical modelling as planning and management tools wherever appropriate.

The application of systems analysis to water resources management is growing rapidly because these applications enable the generation of alternative policies and plans that are optimal under specific assumptions and criteria. Furthermore, the use of the interactive software makes decisions more transparent and therefore easier to discern (Chaturvedi 1987). Similarly, mathematical models are gradually evolving into support frameworks for decision support systems. Of course mathematical models and systems engineering are tools, not a substitute for decision making process, they can be very valuable in generating outcomes under certain conditions and assumptions. Overall, models can be used in problem solving and crisis intervention (Gupta 2005). Models used in IWRM tend to incorporate the foregoing. Thus this research was carried out at a catchment that has had problems that could only be tackled through IWRM. The following paragraphs discuss the problem and River Rwizi catchment.

1.1.1 Case Study Catchment – River Rwizi

River Rwizi is one of the main rivers in South Western Uganda and is a source of water for thousands of local people and their livestock. The river passes through five districts in South Western Uganda namely Bushenyi, Mbarara, Ntungamo, Isingiro and Kirihura before joining Lake Mburo. This river is the major source of economic activities in these districts and also the source for water supply of Mbarara Municipality operated by the National Water and Sewerage Corporation – Mbarara.

Figure 1: A glimpse of the river taken in Kirihura District

River Rwizi was always a beautiful river that brought pride to the people in the area due to its sky blue waters and the purposes they served. Today, however, River Rwizi is back in news not for its great beauty but for being on the brink of "death". The activities that take place within and at the river banks of the resource are done without consideration of downstream users. As a result, the river has deteriorated both in quantity and quality and resulted in the drying up of wetland fringes of the river. Additionally, the poor farming methods in the region leave soils from unprotected hills and valleys dumped into the river every time it rains (Mugira 2008). Bifubyeka (2009) reported that the turbidity of River Rwizi increased from 30 units to 110 units in the dry spell further illustrating the severe level of the river's deterioration. Figure 1 gives a preview of the current state of the water quantity and quality in River Rwizi.

There is also increasing pressure on the already vulnerable water resource from factors such as rapid population growth averaging 2.4 per cent per annum (as per the 2002 Uganda census), increased industrial activities, environmental degradation, soil erosion, drainage of wetlands and pollution of the river. Furthermore, lack of wastewater treatment and insufficient control over waste disposal has also placed the water system at risk of microbiological and chemical contamination that increase disease incidence.

1.2 Statement of the Problem

In an increasing number of countries, water scarcity and deteriorating water quality have or will soon become critical factors limiting national economic development. Surface water and groundwater resources are increasingly over-exploited due to increasing demand driven by increase in population and subsequently water related activities. The recognition of the need to redress these weaknesses in their water governance structures has convinced many countries that a new water management framework is needed, hence the birth of IWRM. IWRM recognizes that there is a need to use available resources to satisfy competing and conflicting demands while ensuring sustainable water resources development. River Rwizi catchment is such a problem that needs IWRM for its solution. There hasn't been any in-depth study done to address the water shortage issues in River Rwizi catchment. Previous studies done were to address the existing policies within the area to fit into Integrated Water Resources Management framework.

1.3 Main Objective of the Research

This research aimed at modeling, using an Integrated Water Resources Management approach to assist in planning, restoration, and rational allocation of water resources in a river basin by recognizing priorities for development, related investment, and resource conservation.

1.3.1 Specific Objectives

The specific objectives of the study were:

a) To collect all current situational data/maps and information pertaining to the abstraction, recharge, and waste disposal into the river in order to determine the current conditions of the catchment in terms of available water for resources and their use.

b) To identify an appropriate computer simulation model that can represent the river network inputs (rainfall and other), abstractions, wastewater discharge, catchment hydrology, and various other water use activities

c) To carry out simulation analysis aimed at evaluating the impacts of the individual system elements on the performance of the system as a whole, thereby assessing compatibility of the elements in terms of water availability and setting limits for proposed additions to the existing system

d) To use the results generated from the adapted model to design improved water use and reuse strategies in order to meet quality, quantity, and rehabilitation demands (quality was not addressed directly).

1.3.2 Expected Output

The result of this Master's research would be recommendations using an IWRM approach to planning, restoration, and allocation of natural resources in all river basins of similar attributes to the case study area. These recommendations would be based on the results of the model adapted. The recommended activities will be done rationally by recognizing priorities for development, related investment, and for the present and future resource conservation.

All in all, proposals for innovative and improved water use and reuse strategies would be suggested.

1.4 Scope of the Research

The study was carried within River Rwizi Catchment which is located in South Western Uganda as a reference point. This study excluded ground water and irrigation components since there was no major groundwater abstraction or irrigation within the study area. A model was identified and subsequently calibrated based on the current situation in the catchment, which was the basis on which the applicability of the model was tested. The effect of the proposed developments on the system in terms of surface water abstractions, demands and deficits was then analysed.

2.0 LITERATURE REVIEW

2.1 Application of Integrated Water Resources Management

In recent decades, from the 1970s, the need for Integrated Water Resources Management (IWRM) has become more evident. This is mainly due to increasing pressure on the already vulnerable water resources from factors such as rapid population growth, increased industrial activities, environmental degradation, drainage of wetlands and pollution of surface water bodies. IWRM begins with the term "water resources management" itself, which uses structural and non-structural measures to “manage” natural and human-made water resources systems for beneficial use. Generating these measures often involves a lot of decision making at varying levels. The decisions and actions need to relate to situations such as river basin planning, planning of new capital facilities, controlling reservoir releases, regulating floodplains, and developing new laws and regulations (IWRM Tutorial, Cap-Net. 2009).

The decision-making process is often lengthy and involves many participants with varying viewpoints that have been described in a variety of ways. For example, Mitchell (1990) wrote that integrated water management considers three aspects: dimensions of water (surface water and groundwater, and quantity and quality); interactions with land and environment; and interrelationships with social and economic development.

IWRM can take different forms and is best examined in specific situations. In the water-supply sub-sector, the term "integrated resources planning" has come into use to express concepts of integration in supply development.

Many countries are facing ranges of water related challenges that are strongly inter-related and therefore need to be dealt with in an integrated way. Sustainable management of water is critical to economic and social development extending beyond provision of access to safe drinking water and sanitation to the presently unserviced settlements. It is the key to:

- meeting the challenges of rapidly growing urban water demands and wastewater discharges;
- securing water for increased food production; to reducing vulnerability to floods and droughts;
- reducing risk to human health and protection from diseases and hazards;
- Ensuring water for industry and other economic activities; and to protecting the resource base and vital ecosystems from negative impacts of these developments.

Meeting “water-demands” in an economically efficient, socially equitable and environmentally sustainable way is a daunting task that requires an IWRM approach. IWRM explicitly challenges conventional water development and management systems. It starts with the recognition that the traditional top-down, fragmented and supply led approach to water management is unsustainable and imposes high economic, social and ecological costs on human societies and the natural environment. The preparation of IWRM plans is thus fundamental to meeting the Millennium Development Goals; those related to social and economic development as well as those more directly related to domestic water and sanitation services (GWP 2003).

Public pressure caused by, for example, lack of safe and affordable drinking water and basic sanitation, pressure from national economic sectors due to lack of water for development all open opportunities and provide incentives for governments to initiate processes leading to improved management of water resources. Such improvements can be achieved through IWRM. Countries experience serious water resources issues. In an increasing number of countries water scarcity and deteriorating water quality have or will soon become critical factors limiting national economic development, expansion of food production and/or provision of basic health and hygiene services to the population. Recognition of the need to redress these weaknesses in their water governance structures has convinced many countries that a new water management framework is needed. Other common critical issues include (GWP 2003):

- Awareness and priority at political level of water issues is limited.

- Institutions are rooted in a centralised culture with supply driven management and fragmented and sub-sectoral approaches to water management. Few water managers view water holistically, but the integrated approach is required because of the biophysical reality where water movement through the catchment links livelihood and resource perspectives.

- Local governments lack capacity to manage pressures on water resources.

- Inappropriate pricing structures and hence limited cost recovery result in inefficient operation and maintenance of water systems, as well as in loss of water.

- Investments in the water sector are low, and do not get sufficient attention in the national budgeting procedures. Information and data to support sound management of water is generally lacking. There is often inadequate economic, social and environmental criteria for the approval of policies, plans and projects.

- IWRM relates to the macro-economy. Poor management of water resources causes health, environment and economic losses on a scale that impedes development and frustrates poverty reduction efforts.

- IWRM should be applied at catchment level. A catchment/basin is the smallest complete hydrological unit of analysis and management. Integrated Catchment/Basin Management (ICM/IBM), therefore, becomes the practical operating approach. Although this approach is obviously sound and finds wide acceptance, too narrow an interpretation should be avoided.

- It is important to integrate water and environmental management. This approach is widely and strongly supported. IWRM can be strengthened through the integration of Environmental Impact Assessments (EIA's), water resources modelling and land use planning. It should also be understood that a catchment or watershed approach implies that water should be managed alongside the management of co-dependent natural resources, namely soil, forests, air and biota.

- A true systems approach recognizes the individual components as well as the linkages between them and that a disturbance at one point in the system will be translated to other parts of the system. Sometimes the effect on another part of the system may be indirect, and may be damped out due to natural resilience and disturbance. Alternatively the effect will be direct, significant and may increase in degree as it moves through the system. While systems analysis is appropriate, analyses and models that are too complex to be translated into useful knowledge should be avoided.(UNEP – International Environment Technology Centre 2003)

- Full participation of all stakeholders, including workers and the community, involve new institutional arrangements. There must be a high level of autonomy/authority, but this must at the same time be associated with transparency and accountability for all decisions.

Many policy decisions affecting water management – within or between sectors (such as food, health, energy and so on) – can be taken only at the national level, not at the basin level and, within the "water sector," policy decisions for example, on cost recovery are necessarily taken at the national level. So the two are complementary, strongly interrelated, and both aim at wise water governance (Torkil 2004).

Most guidance on implementing IWRM considers the starting point as creation of an institutional framework for co-ordinated planning at the river basin level. It is said that in order to bring integrated river basin management into effect institutional arrangements are needed to enable (Jaspers 2003):

- The functioning of a platform for stakeholders involved in decision making,

- Water Resources Management on hydrological boundaries,

- An organisational set-up in river basin and sub-basin authorities with their respective by-laws to incorporate decision making at the lowest appropriate level,

- A planning system oriented towards production of integrated river basin plans. [Where planning can be defined as the orderly consideration of a project from the original statement of purpose through the evaluation of alternatives to the final decision on the course of action. It includes all the work associated with the design of a project except the detailed engineering of the structures. It is a basis for a decision to proceed or to abandon the proposed project and is the most important aspect of the engineering for the project. Planning for a river basin involves the evaluation of alternatives by principles of engineering economy (Ray et al. 1992)].

- Introduction of a system of water pricing and cost recovery.

According to a study done by International Water and Sanitation Centre (IRC) in Africa, Asia and South America it was established that (Visscher et al. 1999):

- Water catchment conservation is gaining recognition but requires further work. Necessary frameworks to ensure the required communication and cooperation between sectors and levels are still lacking.
- True stakeholder involvement in water allocation decision making remains limited. The reality of conflict between competing uses and users is often glossed over.
- Framework to allow management at the lowest appropriate level is often not available. Lack of clear legal frameworks enshrining rights and responsibilities within the decentralisation process often causes confusion. While community-based approaches are now accepted as the norm, the necessary underpinning capacity seldom exists in support agencies.
- Capacity building is promoted but not at all levels, and its effectiveness is not monitored. Proper monitoring of the effectiveness of capacity building programmes is essential to their success. While widely promoted, capacity

building programmes frequently pay insufficient attention to the lower and intermediate levels within decentralised support agencies - with the result that they are unable to fulfill their role in facilitating user decision making.

- Stakeholder involvement is growing, but is still too limited and too narrow in focus.
- Striking a gender balance is often taken as enhancing women's involvement. The case studies concentrated solely on the role of women within projects and agencies. In general women are insufficiently involved in both, but their absence is particularly striking within the staff of support agencies. A wider understanding of gender as encompassing other important aspects of community dynamics such as age, wealth, class, etc is missing.
- Efficient water use is gaining attention but requires much higher emphasis. Water use efficiency and demand management is gaining attention, however guidance is often lacking on how to integrate it into projects. Water is generally valued most highly where it is scarcest, or where tariff structures make waste expensive.

Perhaps the most comprehensive concept for water supply is "Total Water Management". According to a Report from the American Water Works Research Foundation (1996), Total Water Management is the exercise of stewardship of water resources for the greatest good of society and the environment. A basic principle of Total Water Management is that the supply is renewable, but limited, and should be managed on a sustainable-use basis. Taking into consideration local and regional variations, Total Water Management does the following, basically similar to IWRM:

- Encourages planning and management on a natural water systems basis through a dynamic process that adapts to changing conditions;
- Balances competing uses of water through efficient allocation that addresses social values, cost effectiveness, and environmental benefits and costs;

- Requires the participation of all units of government and stakeholders in decision-making through a process of coordination and conflict resolution;
- Promotes water conservation, reuse, source protection, and supply development to enhance water quality and quantity; and
- Fosters public health, safety, and community goodwill.

To carry out “total water management”, the most appropriate unit for its implementation should first be selected. The river basin is widely acknowledged to be the most appropriate unit for Water Resources planning and development (Petersen 1984). This is because it is a natural bounded area that acts as a distinct hydrologic system, for which meteorological and hydrological inflows and outflows can be defined.

2.2 River Basin Approach and the Need for a Model

According to Ray et al. (1992), a river basin is the area tributary to a given stream and is separated from adjacent basins by a divide, or a ridge, that can be traced on the topographic maps. All surface water originating in the area enclosed by the divide is discharged through the lowest point of the divide through which the main stream of the catchment passes. A river basin water resources system typically consists of several component sub-projects.

River basins are important from hydrological, economic and ecological points of view. They absorb and channel the run-off from snow-melt and rainfall which, when wisely managed, can provide fresh drinking water as well as access to food, hydropower, building materials (e.g. reeds for thatching), medicines and recreational opportunities. They also form a critical link between land and sea, providing transportation routes for people, and making it possible for fish to migrate between marine and freshwater systems. By acting as natural 'filters' and 'sponges', well-managed basins play a vital role in water purification, water retention and regulation of flood peaks. In many parts of the world, seasonal flooding remains the key to maintaining fertility for grazing and agriculture. Lastly yet significantly, these often very large-scale ecosystems combine both terrestrial (e.g. forest and grassland) and aquatic (e.g. river, lake and marsh) components, thereby providing a wide diversity of habitats for plants and animals.

Any activity that takes place in a river basin like disposal of waste water has impacts downstream. According to the International Commission for the protection of the Danube River (2010), the best way to protect and manage water is by close international co-operation between all the countries within the river basin – bringing together all interests upstream and downstream. Basin management is anchored in the principle of decentralization of decision making to the lowest appropriate level. While it seems to be comparatively easy to translate this concept into laws and regulations, its actual application often encounters obstacles due to the varying interests of different stakeholder groups, including those that would have to promote the decentralization.

Sound basin management requires attention to basin-wide water use efficiency and water quality management. In some circumstances, field efficiency is important because return flows degrade land and water resources. What is required is improved, customized understanding of water balances and water quality in specific basins, so that the benefits from often costly interventions to reduce losses are assessed in terms of the contribution to overall basin water use efficiency and water quality. Such understanding includes determining how much water can be consumptively used on a sustainable basis while still meeting environmental and other in-stream flow requirements without overexploitation of groundwater (World Bank 2010).

Integrated River Basin Management rests on the principle that naturally functioning river basin ecosystems, including accompanying wetland and groundwater systems, are the source of freshwater. The seven key elements to a successful Integrated River Basin Management initiative are (GWP 2000):

- A long-term vision for the river basin, agreed to by all the major stakeholders.

- Integration of policies, decisions and costs across sectoral interests such as industry, agriculture, urban development, navigation, fisheries management and conservation, including thorough poverty reduction strategies.
- Effective timing, taking advantage of opportunities as they arise while working within a strategic framework.
- Active participation by all relevant stakeholders in well-informed and transparent planning and decision-making.
- Adequate investment by governments, the private sector, and civil society organisations in capacity for river basin planning and participation processes.
- A solid foundation of knowledge of the river basin and the natural and socio-economic forces that influence it.
- Strategic decision-making at the river basin scale, which guides actions at sub-basin or local levels.

The application of systems analysis (in tackling problems in) to Water Resources Management is growing rapidly.The Mar del Plata Action Plan (UN Plata Action Plan, 1989) recommended the use of such techniques as systems analysis and mathematical modelling as planning and management tools.

This study involved the application of a simulation model to an entire river system to analyse and propose solutions to some of the water allocation, use and problems in the river basin. Models are used as decision support systems and they make it easy to predict feasibility of projects. For example Kizito and Ngirane-Katashaya (2006) used a model to predict the availability of water for ongoing and anticipated projects in the River Malaba catchment in Eastern Uganda.

By establishing a simulation model of the entire river system, the performance of the system as a whole, in response to changes in the individual components, can be evaluated through water balance studies of the entire system. Additionally, planned or proposed new developments can be tested for compatibility with existing projects, and their resource consumption levels limits set.

One important characteristic of water that was considered during the study is mobility. This implies that the several water uses taking place at different locations in the same river basin cannot be considered as being independent from each other (Kizito and Ngirane-Katashaya 2006). Secondly, some river systems are completely undeveloped whereas none is fully developed. Thus a typical planning problem is to fit additional elements optimally into a partly developed system. Thirdly, plans are based on assumptions regarding the future so that subsequent changes in technology, economic development, and public attitudes may differ significantly from those anticipated or predicted. Plans must, therefore, be amenable to revisions and modifications over time (Alan 2009). A model can predict all that very easily by simply varying the input scenarios as possible situations in the future.

2.3 Simulation Modelling

According to Leo (1961), a model in science is a physical, mathematical, or logical representation of a system of entities, phenomena, or processes. Basically a model is a simplified abstract view of the complex reality. A model can also be defined as a mathematical representation of a device or process used for analysis and planning (Farlex 2010).

Models are typically used when it is either impossible or impractical to create experimental conditions in which scientists can directly measure outcomes. Modelling techniques include statistical methods, computer simulation, system identification, and sensitivity analysis. None of these, however, is as important as the ability to understand the underlying dynamics of a complex system. These insights are needed to assess whether the assumptions of a model are correct and complete. The modeller must be able to recognize whether a model reflects reality, and to identify and deal with divergences between theory and data (Tahoe Integrated Information Management System 2009).

There are many specific techniques that modeller's use, which enables one to discover aspects of reality that may not be obvious to everyone. One of the essentials is the understanding of the role that assumptions play in the development of a model. The usual approach to model development is to characterize the system, make some assumptions about how it works and translate these into equations and a simulation program. Models should be able to explain past observations and predict future observations through simulations.

The Committee on Modelling and Simulation Enhancements for 21st Century Manufacturing and Defense Acquisition, National Research Council (2002) defined simulation as the implementation of a model over time. A simulation brings a model to life and shows how a particular object or phenomenon will behave. It is useful for testing, analysis or training where real-world systems or concepts can be represented by a model.
The following are steps taken during simulation using a model:

a) Model calibration: This stage involves testing or tuning of a model to a set of field data not used in the original model construction. Such tuning is to include a consistent rational set of theoretically defensible parameters and inputs. Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model that is calibrated to a set of conditions which are not representative of actual field conditions. This is mainly done to demonstrate that the model and its parameter values are reasonably representative of site conditions.

b) Model verification: This involves subsequent testing of a calibrated model to additional field data preferably under different external conditions to further examine model validity and verification is done to ensure that (Macal 2005):

- The model is programmed correctly

- The algorithms have been implemented properly
- The model does not contain errors, oversights, or bugs
- Verification tries to ensure that the specifications are complete and that mistakes have not been made in implementing the model

c) Model Sensitivity**:** This is important as it indicates how parameters /variables are sensitive to any changes in their values and will give a basis for limiting some values or reprogramming some parts of the model.

d) Optimisation: Typically an optimised design is around 10-40% less expensive to implement than alternative designs developed using traditional methods (Loucks et al. 2006). The new generation of computer programmes based on optimisation algorithms shortens the analysis process. The programme will try to satisfy a number of optimisation criteria set by the user. For example in this study, the model developed known as MIKE BASIN has an optimisation component, with a built-in nonlinear programme solver (based on a sequential quadratic programme algorithm). It can optimise with respect to any objective for example water quality (DHI 2008).

2.3.1 Computer Simulation and the Model Used in this Study

Computer simulations, as output indicators and part of mathematical modelling, have become so useful that many natural systems in physics (computational physics), chemistry and biology depend a lot on it to gain insight into the operation of those systems or to observe their behavior. Other areas where it is used is in human systems like economics, psychology, social science and in the process of engineering new technology. Traditionally, forming large models of systems has been via a mathematical model, which attempts to find analytical solutions to problems and thereby enable the prediction of the behaviour of the system from a set of parameters and initial/operational conditions.

While computer simulations might use some algorithms from purely mathematical models, computers can combine simulations with reality or actual events, such as generating input responses, to simulate test subjects who are no longer present. There are many computer simulation models available for management and planning in water resources and with set criteria and conditions.

The most important condition for choosing anything that needs to be used in reality is its availability. Once that is settled, all the available models can be subjected to the required criteria. The criteria used in this study was as follows:

- The data to be used was to be obtained from various sources and was already available in notepad and excel formats. The input data did not need external reprocessing;
- The data was available with no need to setup new stations;
- The model could be lumped and with the ability to process a lot of rainfall and evaporation data that would be spatially arranged;
- Ability to output several scenarios based on various inputs; and
- Visualisation of the output.

Several models like SWAT and WEAP models were considered and eventually MIKE BASIN 2009 Version developed by Danish Hydraulic Institute (DHI) was selected. It was available at Directorate of Water Resources Management (Entebbe, Uganda).

2.3.2 The MIKE BASIN Model

The current version of MIKE BASIN Model was developed by Danish Hydraulic Institute (DHI) in 2009. MIKE BASIN is a modelling tool for integrated river basin planning and management. It accommodates a basin-wide representation of water availability, sector water demands, multipurpose reservoir operation, transfer/diversion schemes, and possible environmental constraints. MIKE BASIN Model provides a mathematical representation of the river basin, encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major schemes, and their various demands of water (DHI 2008).

For addressing water allocation, conjunctive use, reservoir operation, or water quality issues, MIKE BASIN Model couples ArcGIS with hydrologic modelling to provide basin-scale solutions.

Regarding hydrologic simulations, the model works on a network model in which branches represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. The incorporated ArcGIS is an integrated collection of GIS software products that provides a standards-based platform for spatial analysis, data management, and mapping. Although MIKE BASIN Model is a quasi-steady-state mass balance model, it allows for routed river flows. The groundwater description uses the linear reservoir equation with a time constant CKBF which is used to calculate the baseflow from the ground water storage. MIKE BASIN Model has a GIS component that captures, stores, analyses, manages, and presents data that is linked to location, like rainfall data (DHI 2008).
Typical areas of application are:

- Water availability analysis in relation to conjunctive surface and groundwater use.

- Infrastructure planning as regards irrigation potential, reservoir performance, water supply capacity, waste water treatment requirements.

- Analysis of multi sectoral demands like domestic, industry, agriculture, hydropower, navigation, recreation, ecological, finding equitable trade-offs.

- Ecosystem studies involving water quality, minimum discharge requirements, sustainable yield, and effects of global change.

- Regulations like water rights, priorities and water quality compliance.

MIKE BASIN Model comes with MIKE 11's rainfall-runoff model Nedbør-Afrstrømnings-Model (NAM). Given rainfall and evaporation data, NAM calculates a runoff time series that is automatically assigned to MIKE BASIN for use in the river flow simulation. NAM is a lumped, conceptual rainfall-runoff model simulating overland flow, interflow and base flow as a function of the moisture content in Snow storage, Surface storage, Root zone storage and Groundwater storage.

Optimisation

MIKE BASIN Model has an optimisation component with a built-in nonlinear programme solver (based on a sequential quadratic programme algorithm) that can handle the inherently non-linear responses of, e.g., reactive water quality models or reservoir tail water elevation. The optimization user interface enables one to formulate both minimization, maximization, and goal attainment objectives, and any combination thereof.

The MIKE BASIN Model's concept for optimisation is its generality, as it can optimise with respect to any objective, for example water quality.

In order to carry out simulation runs with MIKE BASIN, there is need for preparation of simulation input data. The data requirements for this analysis are looked at in the following subsections.

2.4 Basin Recharge and Runoff

In order for a river basin model to be developed, an in-depth analysis and understanding of all processes that take place within a river basin and how these affect the water has to be done. This is so because simulation models are based on real life situations. One of these processes involves looking into the hydrologic cycle. Figure 2 illustrates the different components of the hydrologic cycle and the flow chart displays how each of these components feed into the model.

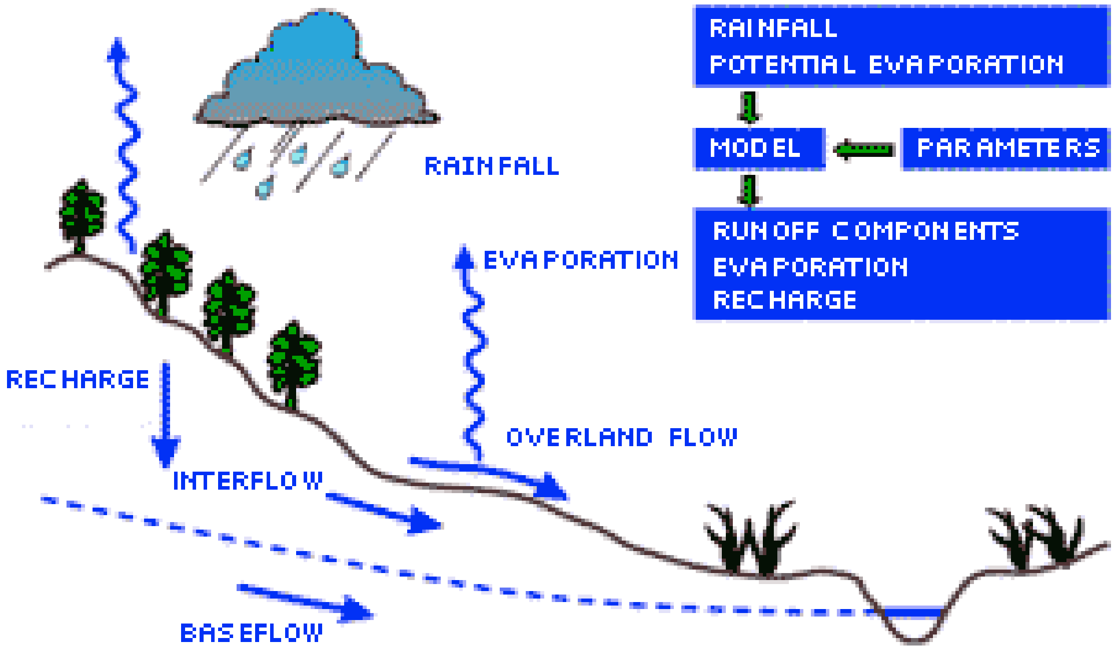

Figure 2: Diagrammatic representation of hydrologic cycle

Various components can be explained as follows:

- As rain falls towards the earth, a portion of it is intercepted by leaves and vegetation. Water so retained, together with depression storage and soil moisture, constitutes basin recharge, the portion of water that does not go into stream flow or groundwater. Depression storage includes the water retained as puddles in surface storage. Soil moisture is held as capillary water in small pore spaces of the soil or as hygroscopic water absorbed on the surface of soil particles.

- Rain water, exclusive of water withheld as basin recharge may follow three paths to the stream. A portion travels as overland flow (surface runoff) across the ground surface to the nearest channel. Still other water may infiltrate into the soil and flow laterally in the surface soil to a stream channel as interflow. A loose permeable soil will have a higher infiltration capacity than a tight clay soil. If much of the pore space is generally filled with water, infiltration rate is generally less than when the soil is relatively dry. A relatively impermeable stratum in the subsoil favours the occurrence of interflow. A third portion of the water may percolate downward through the soil until it reaches the groundwater. Vertical percolation of rain water results in groundwater accretion only if the soil is highly permeable or if the groundwater is near the surface. Low soil permeability encourages overland flow, while a thick soil mantle, even though permeable may retain so much water as soil moisture that little or none can reach the groundwater (Ray et al.1992).

- In order to carry out water balance studies for a catchment using any model, water supply into the catchment and the water demand from the catchment have to be established**.** Rainfall is looked at as the basic source of water for this particular catchment in this study. Other sources will include groundwater and inflows into the river from other surface water bodies. More often, available rainfall records do not clearly depict the actual rainfall distribution within a catchment. There is need to transfer the available data to the problem area with appropriate adjustments. Many techniques, some empirical and others rational have been devised to meet these problems of space and time adjustments (Ray et al. 1992).

There are several potential difficulties associated with analysis of spatial data; among these are boundary delineation, modifiable areal units, and the level of spatial aggregation or scale (Dickinson 1973). In each of these cases, the absolute descriptive statistics of an area - the mean, median, mode, standard deviation, and variation - are changed through the manipulation of these spatial problems.

2.4.1 Boundary Delineation

The location of a study area boundary and the positioning of internal boundaries affect various descriptive statistics. With respect to measures such as the mean or standard deviation, the study area size alone may have large implications. In this study, the catchment delineation was carried out using spatial analyst extension built in ArcGIS 9 software developed by ESRI in 2008.

2.4.2 Spatial Rainfall Distribution

Rainfall is a fundamental component of any water resource assessment strategy. Daily rainfall records are of paramount importance when performing hydrological investigations on a daily or monthly time scale. However, rainfall has one of the highest spatial-temporal variability, especially in mountain areas where there is scarcity of information. Furthermore, the limited number of weather stations to cover large heterogeneous areas has also a big impact in the process of interpolation (Guillermo et al. 2003). Many catchment authorities have implemented expensive and elaborate rainfall monitoring networks to capture spatial and temporal variability in rainfall. Due to financial constraints, rainfall monitoring networks are generally sparsely distributed within a catchment. To obtain information at a specific location in a catchment, either interpolation or extrapolation of the existing data is required. Currently, there are two methods of estimating precipitation spatially in an operational environment. The first, and older, is the use of observed precipitation measurements. These measurements are accepted as the most accurate. However, they are a point measurement and must be distributed spatially to be used in hydrologic forecasting. The distribution is accomplished by use of weighting techniques.

2.4.3 Computation of Average Precipitation

If one is attempting to reconstruct information on a watershed, there is interest in estimating average rainfall for the watershed. Areal-weighting is the most common form of quantitative aggregation. An areal-weighted average is useful when one wants an average value for the map unit but the data is stored by component. Simple averaging of the component values give erroneous results as the components can cover vastly different amounts of map units. The data values are multiplied by the percentage of the area that component covers and then divided by the total of the area percentages. With this method, one does not have to use the percentages of the area but any measure as long as it is consistent. Equation 1 is used to estimate the average precipitation as follows:

$$R_{Average} = \sum W_i R_i \Big/ \sum W_i \qquad \text{……………. (1)}$$

where W_i is the weighting factor for the area.

R_i is the i[th] rainfall amount

Three common methods for computing average watershed rainfall are the Thiessen, Arithmetic mean and Isohyetal methods all of which compute the average watershed rainfall as a weighted average of the nearby rain gauges. The Arithmetic mean is the easiest but the least accurate of these methods as it doesn’t take into account factors like the placement of the rain gauges. The Thiessen method is the second in the ease of application and accuracy. The Isohyetal method is the most accurate of the three methods but requires the most work (Ray et al. 1992).

In this study the Thiessen polygon method was used because the basis of the model is the geometry of the catchment thereby making implementation of Thiessen polygons in a GIS easy (Luk & Ball 1997). Thiessen polygons are probably the most common approach for modelling the spatial distribution of rainfall. As presented by Thiessen (1911), the approach is based on defining the area closer to a particular gauge rather than any other gauges and the assumption that the best estimate of rainfall on that area is represented by the point measurement at the gauge. An impact of the use of Thiessen polygon, however, is the development of discontinuous functions defining the rainfall depth over the catchment for example at the boundaries of the polygons where a discrete change in rainfall depth or intensity occurs.

In this approach, areas closest to a rain gauge adopt the rainfall recorded at that gauge. This results in constant rainfall regions with discontinuities between regions. In addition, there is no justification in assuming that point rainfall measurements provide reliable estimates of precipitation in the surrounding region (Anziam 2000). The weights are derived using Thiessen polygons and widely available Isohyetal information. The method is shown to eliminate long-term bias associated with the difference between the spatial distribution of precipitation implied by Thiessen polygons and the more accurate spatial distribution depicted by an Isohyetal map. However, it is not easy to use when modelling in GIS hence the reason for eliminating it as an option in this study.

Geographers often use Thiessen polygons to model or approximate the zones of influence around points. Immediately surrounding the Thiessen polygon enclosing a specific rain gauge are other Thiessen polygons, each which also encloses a single rain gauge. To achieve computational efficiency, elaborate sorting and searching algorithms need to be developed and this has led to use of the Thiessen polygon method of the ArcInfo system. The assumption that the polygons represent flat plans results in a very crude approximation of the surface (Davis 1986). It is assumed that a rain gauge station best represents the area that is closest to it. Equation 2 shows how the weighted precipitation in a Thiessen polygon is computed.

$$P = \sum_{i=1}^{i=n} W_i P_i \qquad \text{................. (2)}$$

where

P = average precipitation (mm)

P_i = gauge precipitation for polygon *i*

n = total number of polygons

W_i= weighted area = A_p / A

A_p = area of the polygon within

A = total area.

A Thiessen Network is constructed by connecting adjacent stations on a map by straight lines and erecting perpendicular bisectors to each connecting line. The polygon formed by perpendicular bisectors around a station encloses an area that is everywhere closer to that station than any other station. This area is assumed to be best represented by the precipitation at the enclosed station. This is often a reasonable assumption but may not always be correct (Ray et al. 1992).

2.5 Water Demand Within a Catchment

A river basin's water resources must be protected, used, developed, conserved, managed and controlled in ways that take into account, amongst others, the following factors (DHI 2008):

- meeting the basic human needs of present and future generations;
- promoting equitable access to water;
- redressing the results of past racial and gender discrimination;
- promoting the efficient, sustainable and beneficial use of water in the public interest;
- facilitating social and economic development;
- providing for growing demand for water use;
- protecting aquatic and associated ecosystems and their biological diversity;
- reducing and preventing pollution and degradation of water resources;
- meeting international obligations;
- promoting dam safety;
- managing floods and droughts.

2.5.1 Overall System Control

The overall system concept is related to the recognition that a catchment forms a unit and must be managed as a whole. The clear guiding principle in the management of a system is that upstream use has direct and indirect consequences on downstream users. There is also the need to recognise the physical constraints of a system whereby water flows in a downstream direction and it is expensive and in some cases unviable to reverse the flow by pumping or other mechanisms (DHI 2008).

It is for these reasons that water resource managers in water resources systems take an approach of emptying the system from bottom up. System managers should always attempt to reduce water levels in lower catchment units (dams) prior to getting water from dams higher up in the system. Users sourcing water from multiple units of the same type should also follow this priority structure where they would obtain water from the downstream units before using water from upstream dams/units. Thus their own priority should reflect this operating practice, which is the principle behind the Riparian Rights Doctrine (Steve 1997).

In other words, no upstream owner may materially lessen or increase the natural flow of the stream to the disadvantage of a downstream owner. On the other hand , Appropriative Rights provides for acquiring rights to use of water by diverting it and putting it to beneficial use in accordance with procedures set forth in the state statutes or acknowledged by the courts. Some systems have initiated permit systems in lieu of riparian systems. A permit confers a right to use a specified amount of water at a specific location and at specific times (Ray et al. 1992).

2.5.2 Controlled Versus Non-Controlled Activities

Certain water users can be controlled relatively easily in a system where they are dependent on a resource such as a major dam. The type of water use can also determine the amount of control one has over a particular activity. In many cases any person abstracting water from a particular water resource can be switched on and off. However there are activities which use water that cannot be easily turned on and off such as forestry.

Water users associated with a user association and dependent on a resource are thus considered easy to control and can easily be motivated or forced to stop using their water. However users not associated with a major dam resource are not easy to control and although they can have a major impact on a system to a large extent they are considered uncontrollable and thus are allowed to use their full allocation when modelling their water use. However in terms of an overall catchment perspective, such users should and need to be controlled in order to protect other users' water rights and optimise system efficiencies. It is thus recommended that such users also be subject to water use rules. The application of these rules could have profound impact on the system (DHI 2008).

Uncontrollable activities such as forestry and other dry land agricultural practices represent a tap which cannot be switched off although this varies in by country. In such a case these activities receive water as first priority as they form part of the natural system and are thus modelled as such. Their water use will take priority over all other users from a modelling perspective. These activities are often referred to as Stream Flow Reduction Activities.

2.6 Inferences from the Literature Review

The Literature Review has extensively covered the concepts of Integrated Water Resources Management as follows:

- Integrated Water Management considers three aspects: dimensions of water (surface and groundwater, quantity, and quality); interactions with land and environment; and interrelationships with social and economic development.
- Meeting water-demands in an economically efficient, socially equitable and environmentally sustainable way is a daunting task that requires an Integrated Water Resources Management approach where every user is responsible and IWRM should be applied at catchment level.
- The river basin is widely acknowledged to be the most appropriate unit for Water Resources Planning and Development because it is a natural bounded area that acts as a distinct hydrologic system, for which meteorological and hydrological inflows and outflows can be defined.

- A systems approach should be used as this recognizes the individual components as well as the linkages between them, and that a disturbance at one point in the system will be translated to other parts of the system.

- The use of such techniques as systems analysis and mathematical modelling as planning and management tools is recommended.

- By establishing a simulation model of the entire river system, the performance of the system as a whole in response to changes in the individual components can be evaluated.

- By understanding the complex system, one is able to assess whether the assumptions of a model are realistic and complete.

- The simulation model chosen for this study is MIKE BASIN because of its ability to carry out in depth analysis of a river system and define new rules intended to maximize overall benefits and its availability.

- Overall, it was ascertained that systems modelling is still one of the best ways to analyse and manage the water availability in a water supply or utilisation system. The way forward in this research therefore is to embrace resource management modelling to solve the problem at hand.

- The subsequent Chapters detail the methodology employed, data collected details on the analysis done, discussion of results, the conclusions arrived at, and recommendations made.

3.0 METHODOLOGY OF THE STUDY

3.1 Study Area - River Rwizi Catchment

River Rwizi is one of the main Rivers in South Western Uganda, which is a source of water for thousands of local people and their livestock. The surface area of the river alone is approximately 2070 km^2. It is located at Coordinates: 36 E: 245300, N: 9931650. The river originates from Buhweju, a mountainous county of Bushenyi District and traverses five districts namely Bushenyi, Mbarara, Ntungamo, Isingiro and Kirihura before it pours joins River Kagera and hence into Lake Victoria. The river flows via several cattle grazing places in these districts mentioned and also goes through Lake Mburo National Park where it joins Lake Mburo. The average altitude of the river is 1800 meters above sea level.

Rwizi Catchment covers a total geographical area of approximately 8,346 km^2, subdivided as follows: Land Area 7821 km^2, wetlands 240 km^2, Forests 207 km^2 and open water area 85 km^2 (Mukwaya 2008). The lowland areas are occupied by wetland systems.

Some of the major water driven activities that take place within Rwizi study area are farming and cattle rearing, tourism, water abstraction to supply the commercial, industrial and domestic households by National Water and Sewerage Corporation (NWSC) Mbarara which treats about 4500 m^3 per day.

Some of the prospective developments on the river include:

- A plan to install a mini-hydro power station that will produce 0.49 MW, a probable annual energy generation of 1.8 GWh that will be located in Birere Sub-county in Mbarara District (Investment Opportunities under Small Hydropower Projects in Uganda profile, 2005).
- Additionally, there are plans by NWSC–Uganda to make River Rwizi a Reservoir (United Nations Environment Programme News July 2006). But the details of this are not yet finalized.

However, from the information obtained from the Directorate of Water Resources Management Water Permits Office, the two companies that currently had authorized permits within the catchment were NWSC - Mbarara that supplies water to Mbarara Municipality and GBK which is a milk processing company.

3.1.1 Physiography

Topography

The landscape is generally hilly especially in the South and Northwest and consists of rolling hills intercepted by wide and narrow long valleys. The major land form in the study area includes the hills of Ibanda and Ntungamo. The land rises slightly below 1267 Metres Above Sea Level (MASL) in Kiruhura along River Rwizi to about 2168 MASL in the northern areas of Ibanda. Rwizi River is the major perennial river in the area and its tributaries drain the Ibanda, Bushenyi and Ntungamo hills. The study area is characterized by savannah grasslands with mostly gentle terrain sloping towards River Rwizi, broken by occasional hills and seasonal rivers. The landscape is as shown in Figure 3.

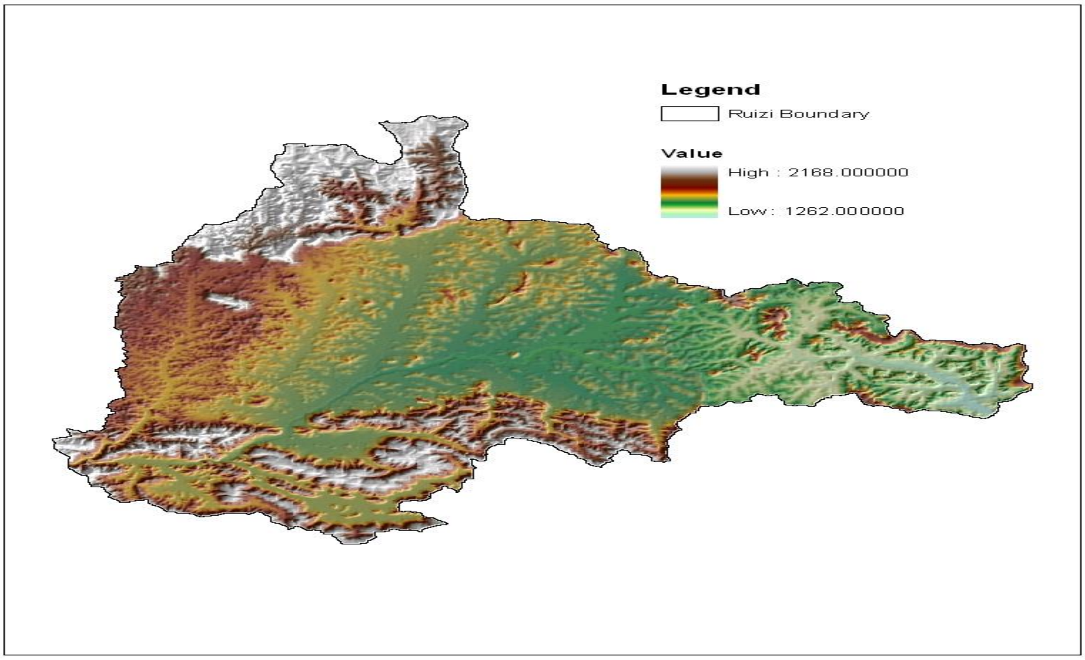

Figure 3: Landscape of Rwizi Catchment area (Source: DWRM Uganda 2007)

3.1.2 Soils

The catchment is predominantly occupied by brown gravelly loams and yellowish red gravelly loams. These soils generally have low water retention capacity and moderately rapid to rapid permeability (United States Department of Agriculture USDA 2004).

3.1.3 Vegetation

The distribution of vegetation in the area is controlled by a number of complex interrelated factors such as, climate, geological formation, soil type and the presence or absence of groundwater. The parts of Isingiro , Kiruhura and northern part of Mbarara districts within the catchment are typically semi-arid rangelands dominated by shrubby habitat (Figure 4). Natural vegetation is mainly an open formation of shrubs and small trees, utilized for grazing and fuel wood collection. Percentage of vegetation cover is very poor, ranging from 5 to 30% (DWRM Uganda Report 2007). The Rwizi flood plains in the middle of the catchment area are predominantly covered by wetlands. Parts of the Districts of Bushenyi and southern Mbarara within the catchment are significantly covered with cultivation.

3.1.4 Climate

The climate of this region is typically semi-arid and the area represents many other zones with similar conditions throughout the cattle corridor. The average annual rainfall, evaporation and temperature are in the order of 1000mm, 909mm, and 24^{o} C respectively. Rainfall is bimodal with high rain from March to May and low rains from November or December to early January. Short rains are more reliable in time than long rains and therefore most important. Figure 5 illustrates this pattern.

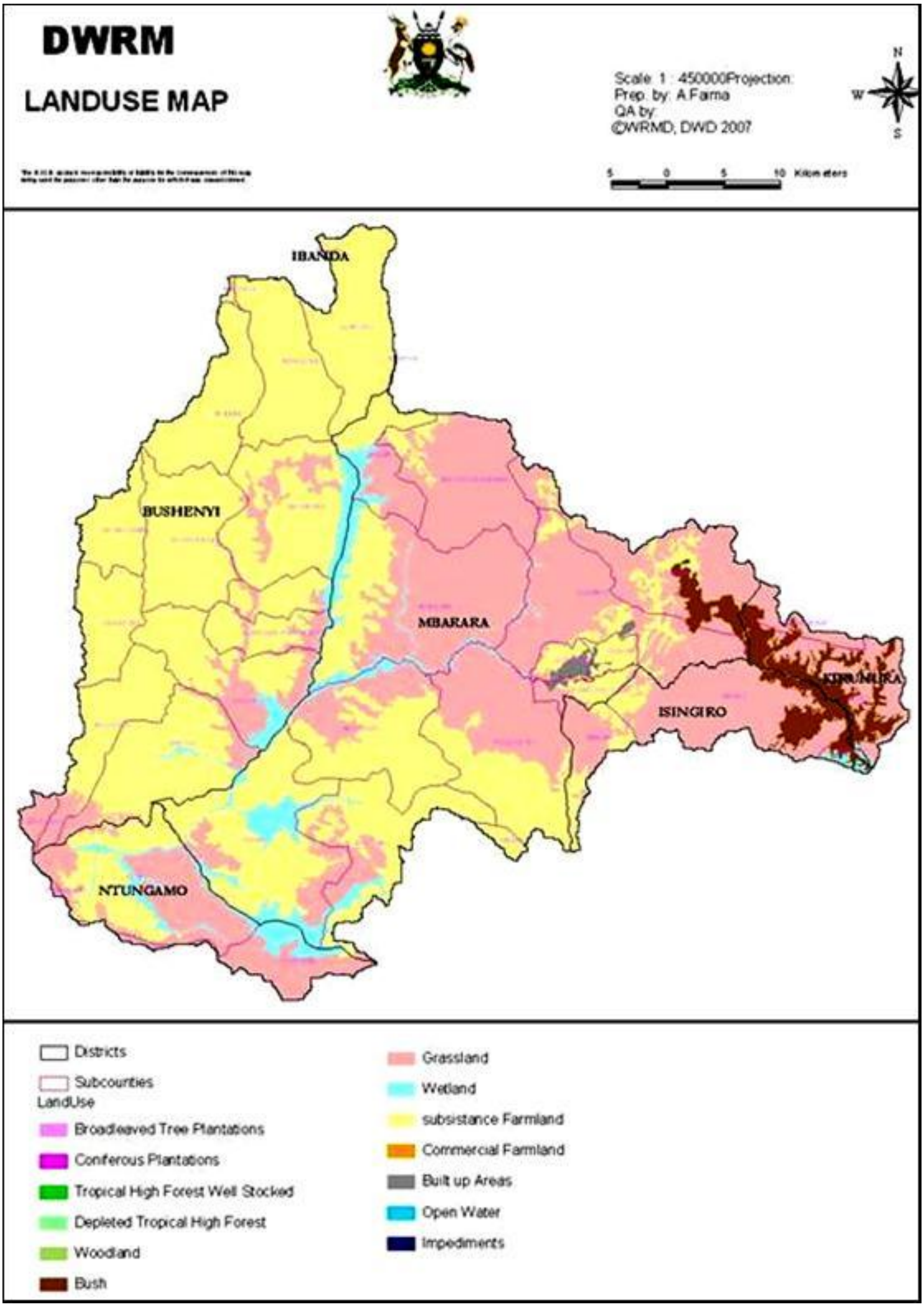

Figure 4: Land Use Map of Catchment (Source: DWRM Uganda)

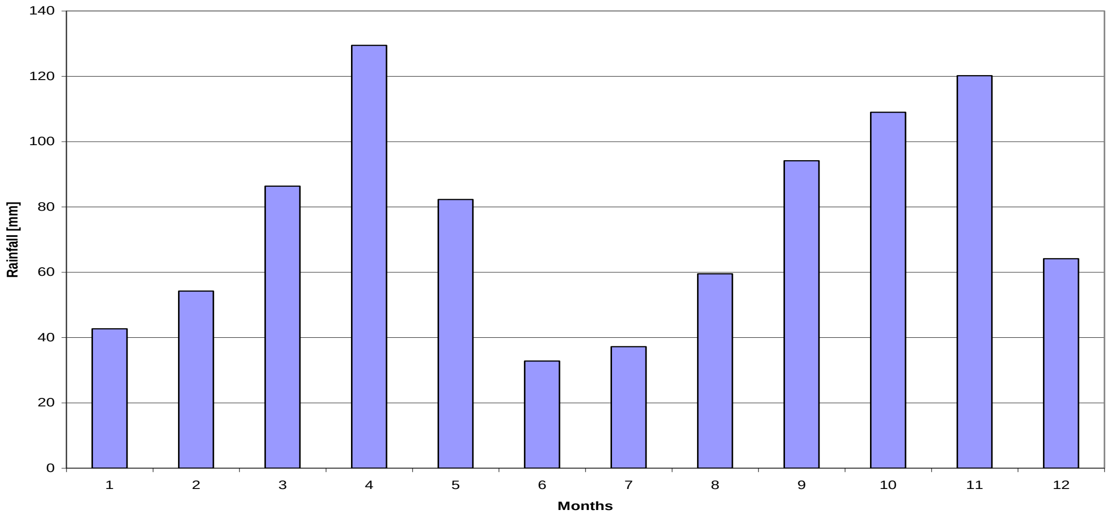

Figure 5: Average monthly rainfall pattern at Mbarara Weather Station

Although temperature varies with altitude, the area is generally hot. The area experiences average maximum temperatures of 28^{o}C, average minimum temperatures of 16^{o}C, dew-point temperatures of 19^{o}C and average temperatures of 24^{o}C. January to March are the hottest months of the year.

There is a lot of variability in rainfall amounts both in time and space and its reliability is low. Figure 6 gives a general overview of the temperature range within the study area during the different months of the year. It can be seen from this graph that the temperature range is 17 – 30 ^{0} C throughout the year.

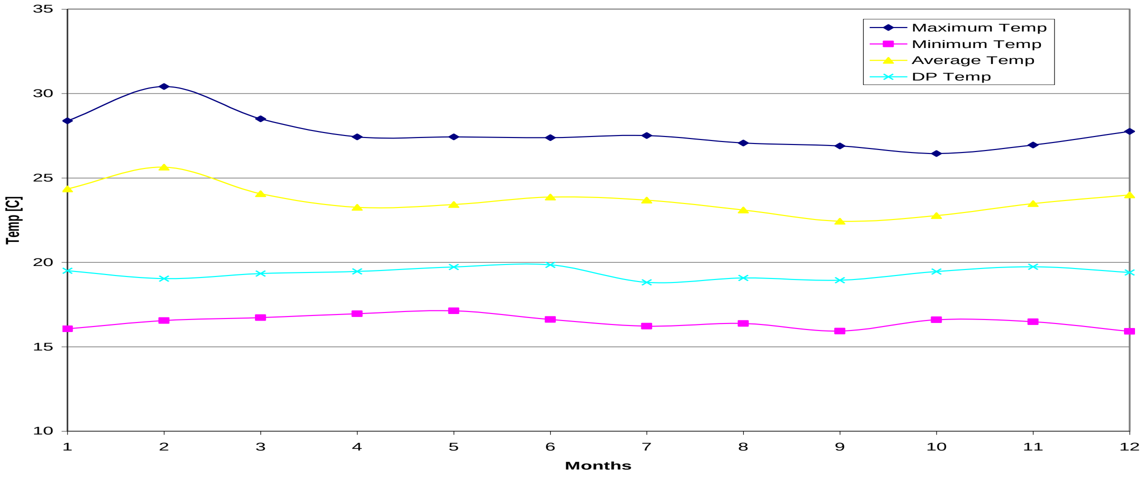

Figure 6: Average monthly temperatures from Meteorological station 89310330 in Mbarara

3.1.6 Geology

The geology of the catchment is composed of metamorphic rocks overlain by alluvial deposits in some places. The eastern, northwestern and southwestern parts of the catchment are composed of Buganda-toro system (Argillites, arenites with some basal metacalcareous rocks). The lower central part and northeastern part of the catchment is comprised of the Karagwe series (phyllites and schists, basal quartizites and amphibolites). The upper central part and some parts in the eastern region consist of undifferentiated gneises. Intrusive granites and highly granitized rocks are also present in the catchment as pockets. Highly mineralized rocks occur in some parts of the Buganda-Toro system. The phyllites in the catchment are associated with high iron content which makes the groundwater unpalatable (DWRM Uganda Report 2007). This is illustrated in Figure 7.

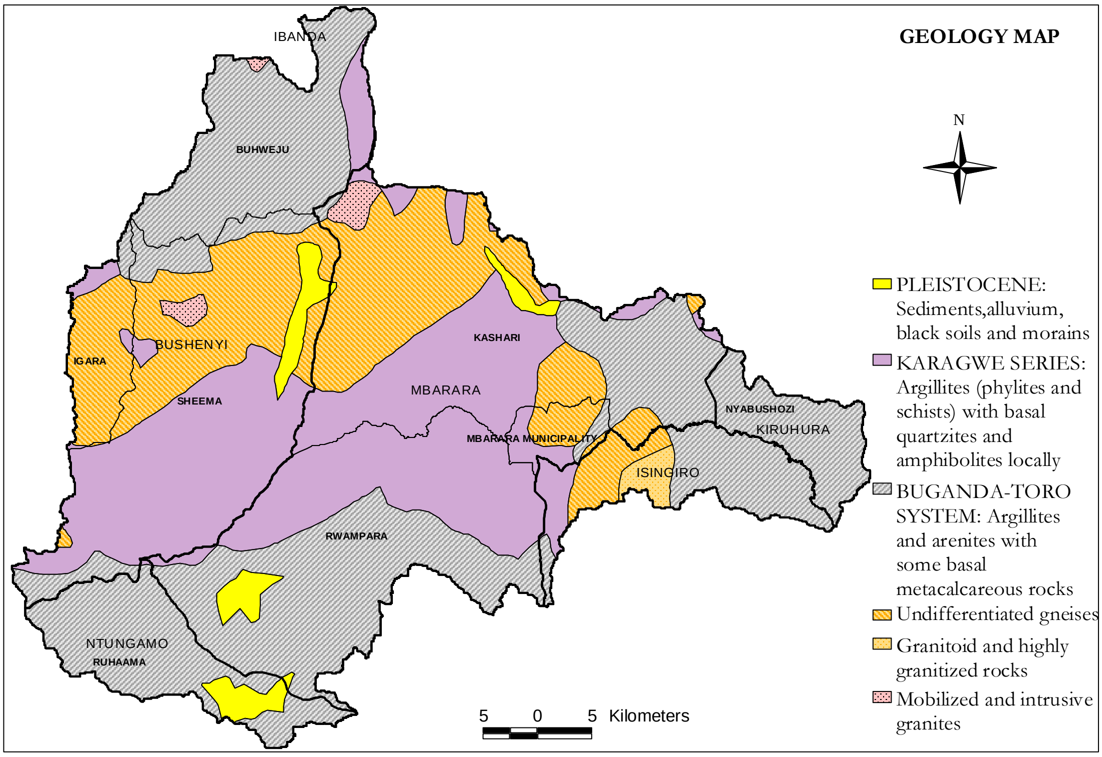

Figure 7: Map showing Geology of study area (Source: DWRM Uganda)

3.1.7 Hydrogeology

The hydrogeology of the Rwizi Catchment comprises of two types of aquifers;

fractured bedrock and Regolith aquifers, the former being the dominant aquifer type.

3.1.71 Fractured bedrock aquifers

These aquifers are from variably fractured fresh bedrock and the sap rock or weathered bedrock. The sap rock-fresh bedrock junction is generally transitional or even fluctuating in banded sequences. Fractured systems are related either to decompression or to tectonic forces.

Fissures permeability is assumed to correlate to some degree with frequency of fractured occurrence, with a further assumption that both parameters will decrease with depth. The rocks are typically of low productivity and development is mainly from point sources utilizing hand pumps. The aquifers are generally phreatic in character but may respond to localized abstraction in semi-confined fashion if the rest water level occurs in a low permeability horizon such as clay regolith. Although the aquifers have a regional occurrence they respond to abstraction in discontinuous fashion due to discontinuities or barrier boundaries within the fracture system being tapped or the constraints of the low permeability regolith. These features are reflected in a significant borehole failure rate and a wide range of yields, despite the apparent regional uniformity of the basic controls of climate, morphology and geology (Wright & Burgess 1992).

3.1.72 Regolith

The regolith consists of the collapsed zone and saprolite. Since weathering is most effective in the vadose zone and the zone of the water table fluctuations, there is a tendency to develop subdivisions into an upper and lower saprolite relative to current (or previous) water levels.

Regolith thickness and lithology, along with corresponding aquifer hydraulic parameters depend on the complex combination of controls including bedrock characteristics, climate and relief.

3.1.8 Hydrology

This is detailed as follows:

3.1.81 Water Resources

River Rwizi passes through the middle of the catchment and it is the main river of the catchment. This river is dominated by wetlands throughout the year, which contribute significantly to the loss of water in the catchment. The river has an average discharge of 86 million cubic meters of water (MCM) per year with considerable high flows up to 386 MCM per year during the wet years and a minimum recorded annual flow of 19 MCM. During the dry seasons, water exists as storage in the swamps and other depressions within the valley. River Rwizi is supplied by nine major tributaries some of which are seasonal. There are several ground water abstraction points in the area. This is illustrated in Figure 8.

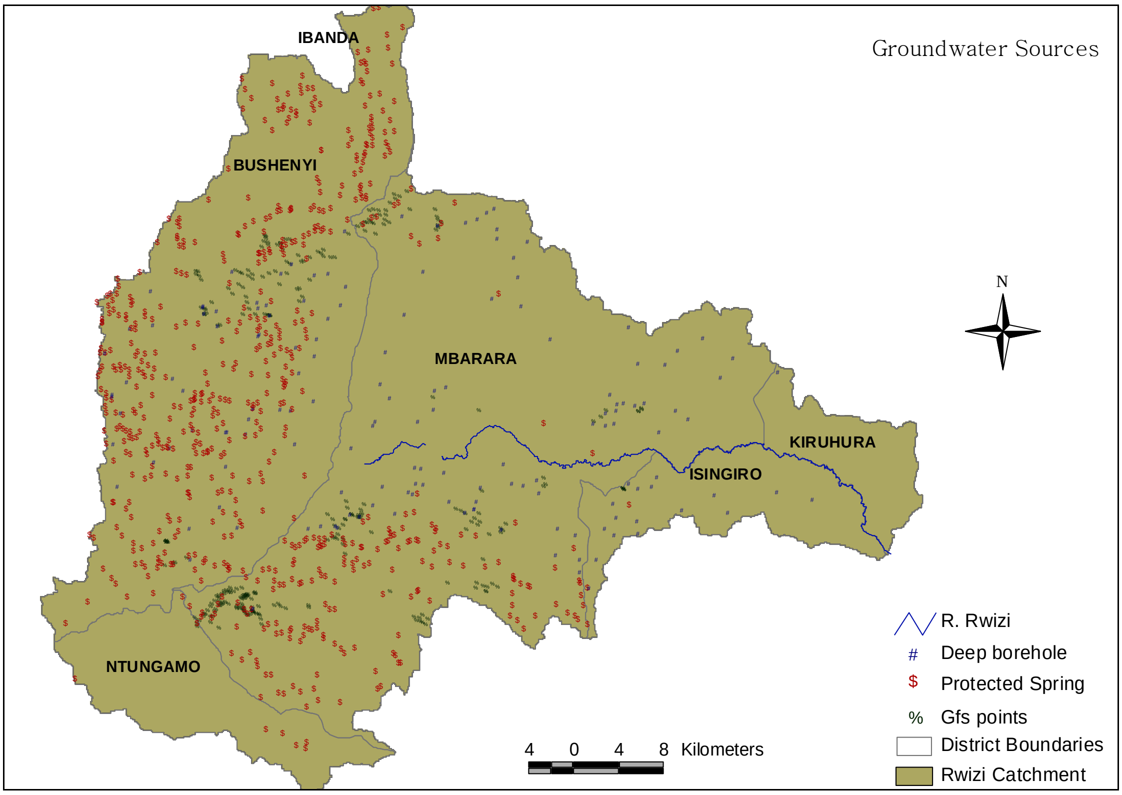

Figure 8: Map of Rwizi showing groundwater resources (Source: DWRM Uganda)

The months of December to March have the highest water stress because there is little rain during this period and the temperatures are relatively high. High temperatures result in very high evaporation and therefore most of the recorded rainfall re-evaporates back into the atmosphere. Even in a typical normal year where rainfall is of the expected amount, the area experiences seven months of rainfall/water stress. During these months, the available flows are not even adequate to supply Mbarara Municipality and in most cases all the water in the river has to be appropriated for the Water works of Mbarara thus leaving the downstream users in the areas of Isingiro and Kiruhura in a critical water stress situation.

The small valley tanks are not large enough to store water for the two periods of about four months with water deficit in the area. During these periods water availability is usually in the depressions within the swamps and most of the time inaccessible due to the following reasons:

- These water deposits are too deep in the wetlands and cannot be easily accessed or
- They are situated in private land and the owners of the land may not allow access to the water either to preserve it for themselves or for fear of disrupting their farms.
- The distances that have to be travelled to access this water are prohibitive.

In the years with below normal rains, even these depressions dry out making the water shortage a severe problem.

The rural population in the area is supplied mainly by groundwater. There are 153 boreholes whose yields range between 0.5 and 3 cubic meters per day and 624 protected springs with 284 gravity flow springs. The western part of the catchment is predominantly covered by springs and gravity flow schemes while the eastern part is covered by boreholes. This is attributed to the hydrogeological conditions described in the previous section.

3.1.82 Groundwater variation with respect to Seasons

The hydrograph shown in Figure 9 illustrates the trends of water level and rainfall changes in relation to time from Surface water Station 81272 .

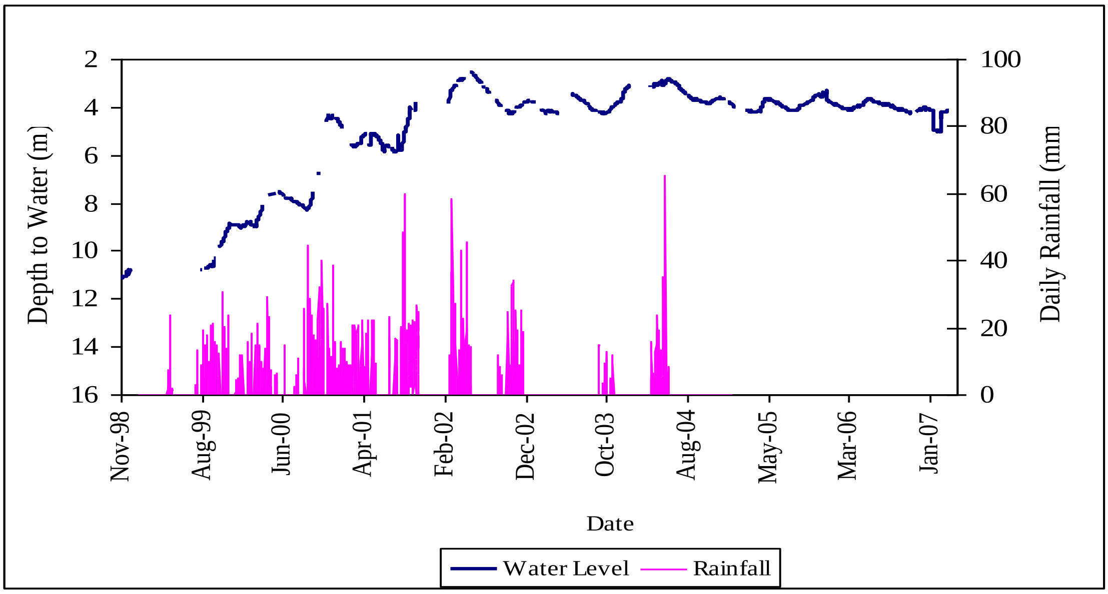

Figure 9: Graph showing water levels and rainfall changes with respect to time. Rainfall station is 81272 (Source: DWRM Uganda).

The hydrograph shows a gradual increase in water levels by 9m between 1998 and 2002. Thereafter, water levels have remained constant despite prevailing drought conditions. Further investigations are required before the phenomena can be fully explained.

.

3.2 Methodology

In this section, it is indicated how the previously stated Specific Objectives were achieved. It details the needed data and information, how it was obtained, the analysis done, and the tools used (MIKE BASIN Watershed Model) for analysis and the arrival at logical and sustainable solutions. Chapters 4 and 5 will present and discuss the analysis of results respectively.

3.2.1 Catchment Delineation by the Mike Basin Model

Catchment delineation is one of the essential steps for watershed modelling. A watershed (drainage basin) is a spatial unit where integrated water management can be accomplished (Singh 1995). Due to spatial and temporal variations of characteristics of a watershed, it is often necessary to delineate a watershed into smaller size modelled areas where variables can be considered homogeneous. In this study, the size of the modelled area was based on the information available. The watershed delineation was carried out using Geographic Information Systems (GIS) tools. Following the same procedures, the large watershed was delineated into several sub-watersheds. Figure 10 shows a DEM of South Western Uganda stretching into Lake Victoria that was imported into the model. This DEM was added as a background image to the map file created in Mike Basin and then it was processed.

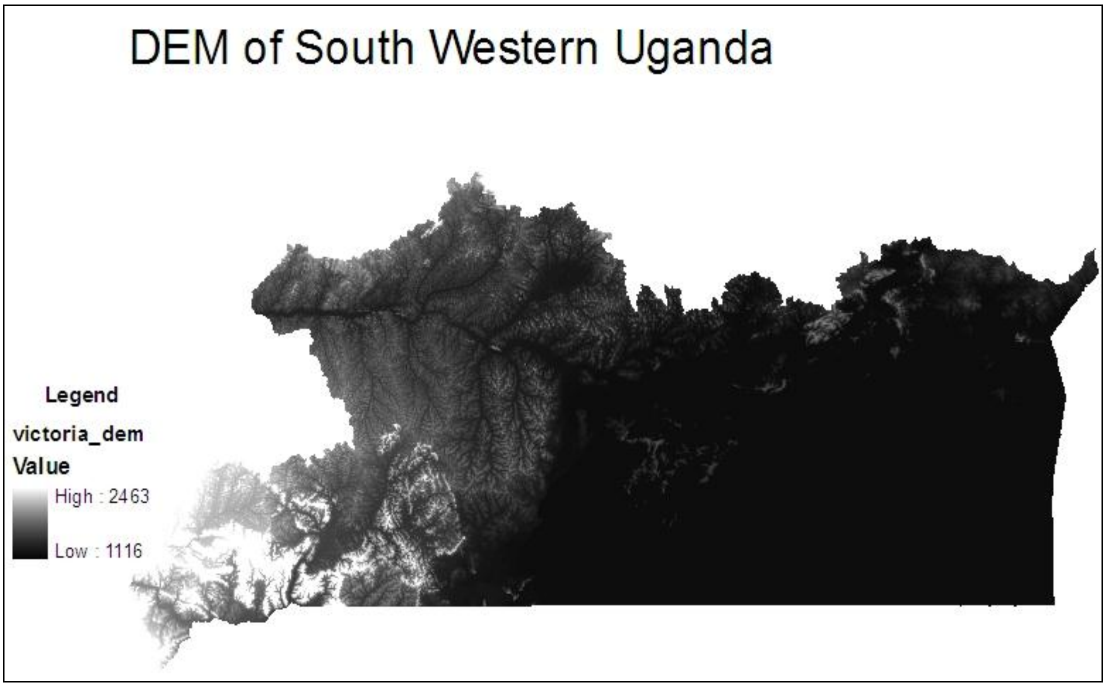

Figure 10: DEM of South Western Uganda

The delineation was based on the topography of the surface to determine the concentrated channel flow directions. Figure 11 shows the DEM after the concentrated flow directions were established.

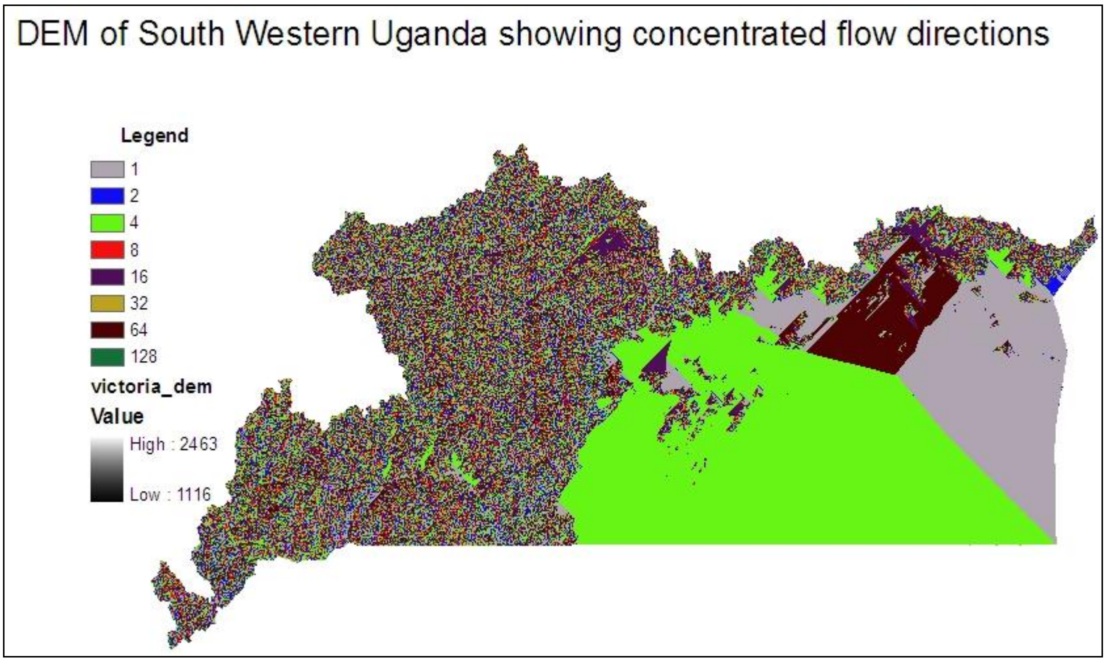

Figure 11: DEM of South Western Uganda showing concentrated flow directions

After the flow directions were generated, River Rwizi was then digitized using background images from maps and the flow direction was automatically created from the concentrated flow directions that were earlier derived from the DEM. Thereafter, the catchment boundary was defined based on the digitised river and overall catchment area was as shown in Figure 12

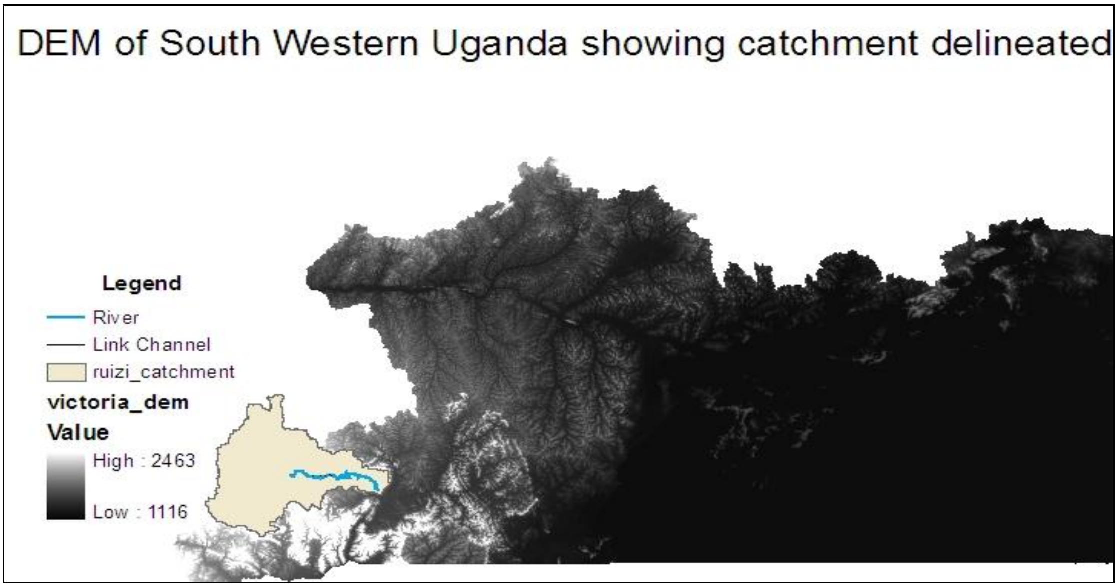

Figure 12: DEM showing catchment and river

Based on the DEM, and the Rwizi Tributaries, this catchment was further subdivided into several sub-catchments using the same procedure described earlier. The result was as shown in Figure 13.

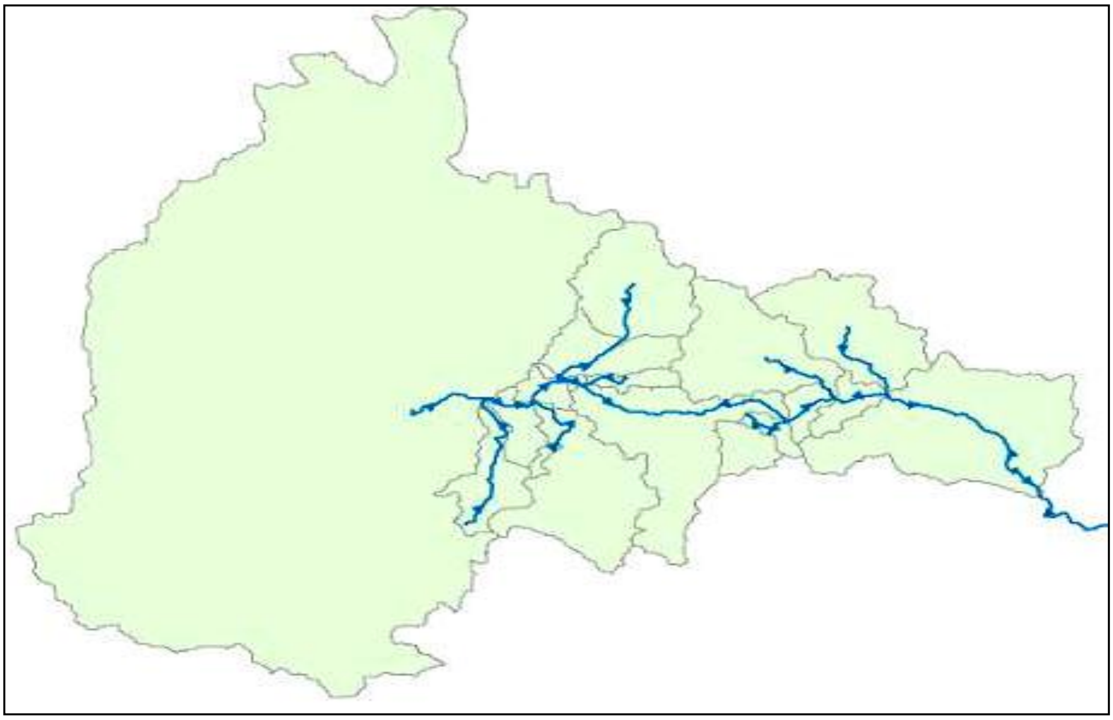

Figure 13: Rwizi Sub-catchments

At this point specific runoff to each catchment could be added to get the model to run. However, in this study, Rwizi was considered as one catchment as the data available was not detailed enough to capture all these sub-catchments but River Rwizi as a whole. Gauging stations were on the main river and not on the tributaries hence it was not possible to look at the sub-catchments for each tributary individually.

3.2.2 Steps taken in model calibration

A. The NAM Model

DHI's Nedbør-Afstrømnings-Model (NAM) is a lumped conceptual model for simulating streamflow based on precipitation at a catchment scale. The model was used to develop input time series for MIKE BASIN catchment nodes as follows:

Basic data requirements during this study for the NAM model included catchment area, initial conditions, and concurrent time series of precipitation, potential evapotranspiration (ET), and stream discharge. The calibration of the NAM model involved adjusting the coefficients for the exchange of water between storage units and the storage unit depth so that simulated and observed discharges matched as best as possible. A minimum of 3 years including periods of above-average precipitation was used for calibration as is recommended (Ray et al. 1992).

3.2.21 Time Series Data

Time series data that was used for the NAM model during this study included concurrent precipitation and evapotranspiration (ET) data. Available flow data on the catchments was used to calibrate the models. Due to the mountainous nature of the basin, precipitation measurements around the basin varied greatly. Precipitation data was available from sites located in the basin. There were seven gauges available namely 9300130, 9300210, 9300250, 9300060, 9300030, 9300190, 90300270. In addition to meteorological station data, spatially modelled continuous monthly and daily precipitation were obtained. In order to obtain a precipitation distribution for the NAM model, the Thiessen Polygon method was used to determine the portions of each zone that correspond to each gauge. The various sets of Thiessen Polygon datasets were then merged to produce a series of polygons with each polygon being associated with one of the 7 precipitation gauge sites.

The spatial variation of ET throughout the basin was much less significant than the variation in precipitation; thus a single ET gauge was assigned to the model catchment and this gauge was located in Mbarara and was the only ET gauge Eto Mbarara within the catchment.

Figure 14 shows the location of the metrological and hydrological stations in the catchment.

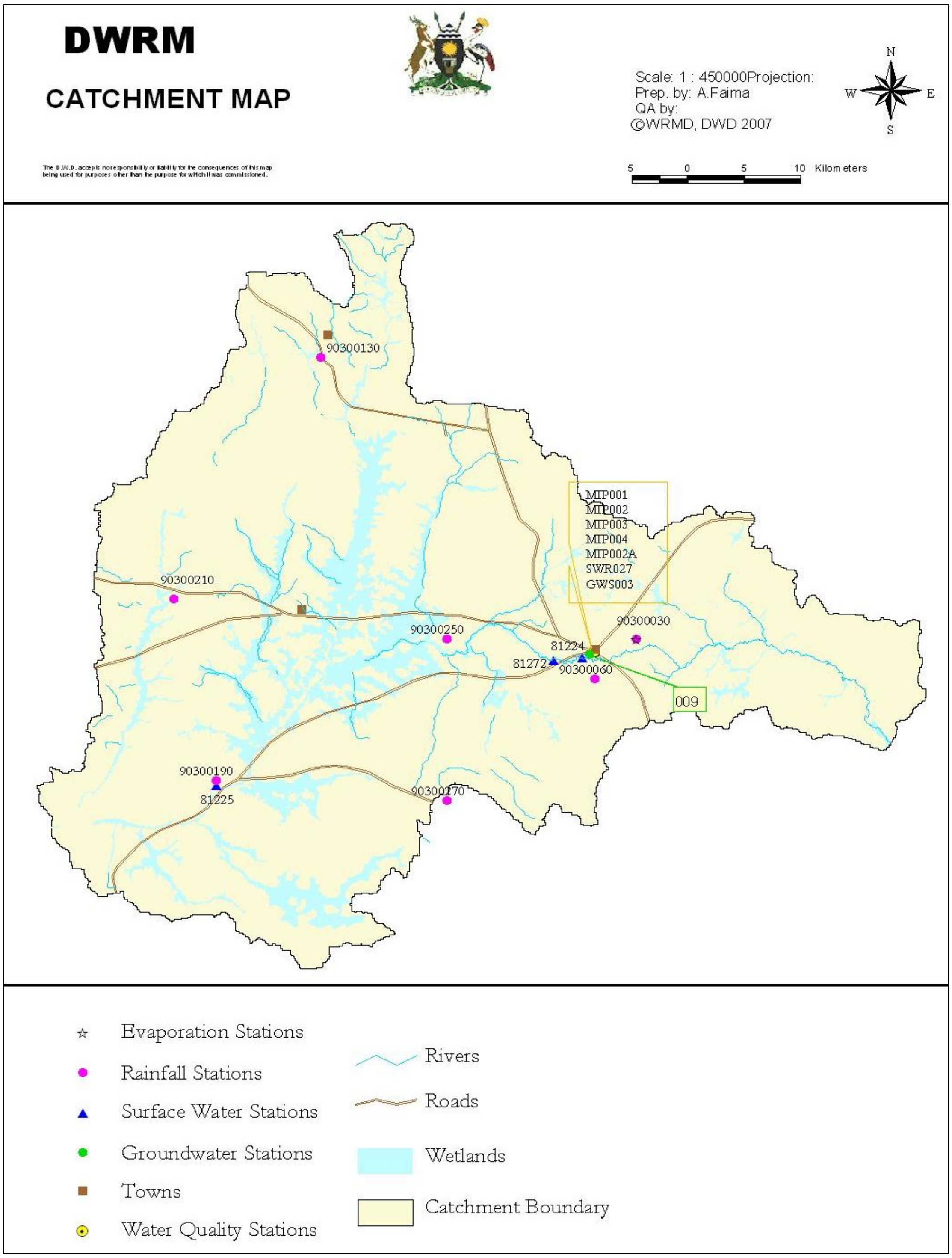

Figure 14: Location of meteorological stations in catchment (Source: DWRM Uganda)

B. MIKE BASIN Model

MIKE BASIN is an integrated water resource management and planning computer model that integrates a Geographic Information System (GIS) with water resource modelling (DHI 2006). In general terms, MIKE BASIN is a mathematical representation of the river basin, including the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, and existing as well as potential major water use schemes and their various demands for water.

In this study, the river system was represented in the model by a digitized river network that was generated in ArcMap 9.3 (a GIS software package). All information regarding the configuration of the flow simulation network, location of water users, reservoirs and intakes, and outlets of return flow were also defined by on-screen editing. Catchment inflows were simulated using the rainfall-runoff model, NAM. Basic model inputs were time series data for catchment run-off, diversion, and allocation of water for the off-river nodes.

The main sources of demand include abstractions by various water users. During this study, the existing water demand together with the laws that govern this abstraction were analysed in order to propose solutions where there were shortfalls. This analysis developed the ability to choose a number of different water source or supply options and prioritised them in order of importance, which is vital for modelling. It also entailed looking into the allocations and developing ways through which the abstraction could be controlled.

Once water usage was defined, the model simulated the performance of the overall system by applying a water mass balance method at every node. The simulation took into account the water allocation to multiple usages from individual extraction points throughout the system. Results from the model were viewed as time series or in graphic or tabular form. MIKE BASIN was also used to simulate hydropower water users and apply priorities to water distribution.

3.3 Channel Network

The river network for River Rwizi and its tributaries included in the MIKE BASIN model was developed by using ArcHydro geodatabase encompassing the watershed. In general, the planar course of the rivers was copied directly from the maps obtained from DWRM, and the flow direction was generated by the system based on the DEM.

3.4 Catchments

Catchment runoff nodes represent locations in the model where water is introduced directly to the stream network system. In this study, the catchment inflows were divided into three categories: simulated inflows from NAM, stream gauge inflows, and reach gain/loss. The catchment was simulated with the rainfall-runoff model, NAM. The available flow data was used for data infilling in cases where there was missing data by interpolation.

3.5 Water Users

An estimate of consumptive water use was included in this study. Data on water rights from the DWRM permits office were obtained and analyzed in order to estimate water demand by each of the water users that possess an abstraction permit. The annual/ monthly/ daily demand was converted to hourly demand. It is from this demand that an abstraction time series was developed. The resulting hourly time series datasets were then assigned to the appropriate water user represented in the model. The two water users as per the DWRM permits office are GBK dairy and National Water and Sewerage Corporation – Mbarara. The other water users were the livestock and Lake Mburo National Game park. At this point, the different water user properties were then specified.

3.6 Irrigation and Groundwater

Water use associated with irrigation or groundwater pumping is also accounted for in NAM. The result is a continuous time series of the runoff from the catchment throughout the modelling period. However, no major irrigation schemes and groundwater extraction is done in the catchment area as per the information given from the water permits office and the district offices.

3.7 Calibration and Results

In order to calibrate the model, a two-step process was followed. First NAM rainfall-runoff model was calibrated. The model calibration process involved assigning suitable values to the parameters relating to the four storages modelled by NAM, and adjusting the values of these parameters in an iterative, trial and error procedure until a close fit was obtained between simulated and observed discharge hydrographs. The automatic calibration routine wasn't available in this version of MIKE 11.

The results from the NAM model were then imported into the MIKE BASIN model. The second and final phase of the calibration was accomplished by comparing the simulated and observed hydrographs at the main-stem River gauges and computing reach gains/losses. For calibration purposes all observed discharge time series files were included in the database and associated to the appropriate node for comparison with the simulated time series after MIKE BASIN was run.

It is after the Mike Basin with the various scenarios was run that the research question was answered. The implication of the results obtained in relation to IWRM concepts are discussed in Chapter 5.

4.0 DATA COLLECTION AND ANALYSIS

4.1 Data Collection

This step involved collection of all current situational data and information, and data on potential developments. This data and information included hydro-metrological data and data pertaining to the abstraction, recharge and waste disposal into the river. All water related activities within the catchment were obtained during the same period of data collection.

The data collection was accomplished by:

- Visits to the Directorate of Water Resources Management (DWRM) offices in Entebbe, Uganda.
- Visits to the Water Permits office under DWRM Uganda.
- Review of all available literature and records on the catchment in the DWRM office.
- One on one interviews conducted during the field trips.
- Field visits made to the river and surrounding catchment, water user offices in the catchment as well as Local Government offices.

The Data from the respective offices and the river catchment collected included:

- Meteorological and hydrological data,
- Data on waste water discharge,
- Digital Elevation Model (DEM) of the area – a digital representation of the ground surface topography or terrain.
- Maps available on physiography, land use, hydrogeology
- Main activities that affect water abstraction and recharge, wetland conservation and the environment

- Any immediate and future developments that were anticipated.

Information/Data collected was used as input in time series for demand and recharge into the catchment. This information was a good representation on how the river was being utilised, how any new developments would affect it, and how the challenges could be addressed hence meeting the overall objective of the study. The data that was collected is attached in Appendix B.

The data collected was used to develop the model through calibration in NAM, adaptation of the model to the catchment parameters/characteristics, input data formatting and use of current situational data to verify the model reliability. A model simulates what is reasonably closest to actuality on the ground and hence the need for the current situational data and data on any future/planned developments. The use of current situational data tested the model and the reliability of the results displayed. It was from running different "what if" scenarios that a probable solution to the challenges were obtained. After inputting into the model the catchment information and observed data collected, the results displayed showed what was happening in the catchment.

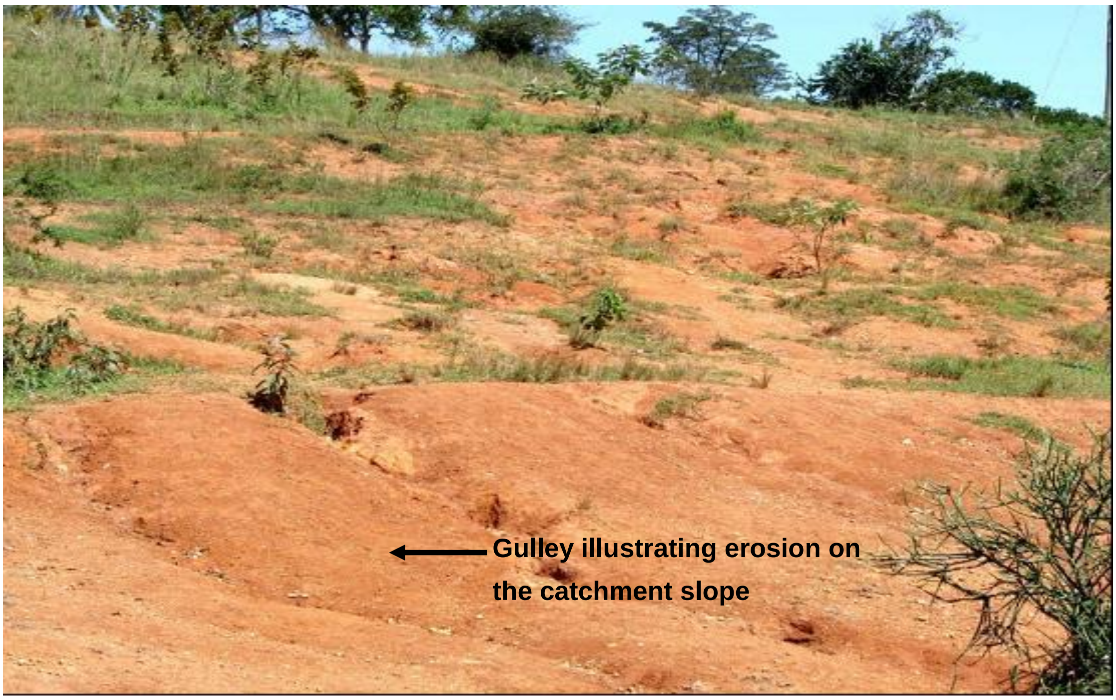

Figure 15: Erosion on the catchment slopes, hilly nature of the catchment.

Figure 16: Soil in Rwizi River

Figure 17: Poor farming methods lead to erosion in Rwizi

The pictures in Figures 15 – 17 show the catchment features namely the hilly nature of the catchment, the poor farming methods that lead to erosion and eventually all the soil ending up in the river, thereby affecting its quality.

In order to ensure accurate and consistent data collection during one-on-one interviews, the template in Figure 18 was used at the various offices visited. The data collected as a result of these interviews was also used in the model.

QUESTIONNAIRE TEMPLATE FOR ONE-ON-ONE INTERVIEWS	
Research Title: Development of an IWRM model for a river catchment - River Rwizi	
DEPARTMENT/AUTHORITY	**ANSWERS**
NWSC MBARARA	
Have you had any problems with water abstraction because of reduction in water levels	Yes
How often does this happen	Almost all year round, additionally the water quality is sometimes very poor
DIRECTORATE OF WATER RESOURCES MANAGEMENT	
Which users in Rwizi Catchment have permits for abstraction and /or waste discharge into River Rwizi	NWSC & GBK
Are there any maps to show water related activities, topography, hydrogeology of the catchment	Yes
Is there information on daily discharge/ water levels of River Rwizi for a period of at least 30 years	Yes
Do you have a Digital Elevation Model for the catchment	Yes
DEPARTMENT/AUTHORITY	**ANSWERS**
LOCAL GOVERNMENT MBARARA	
Aside from National Water and GBK Diary, what are the other water related activities in the area	Lake Mburo Game Reserve, Cattle rearing
Approximately how many cattle are there in the Ankole cattle corridor	0.5 million
What future plans are there in the pipeline for Rwizi?	Hydro power station
METEOROLOGICAL DEPARTMENT OF UGANDA	
Is there data available for daily precipitation and Evaporation for River Rwizi for a period of at least 30 years	Yes but only 25 years for evaporation
What technique is used to measure Evaporation	Penman’s equation

Figure 18: Template for one on one interview

Figures 15 – 17 show some photos that were taken during field visits, and other photos that were obtained from other socio economic studies that were done in the catchment in an attempt to raise awareness of the problem at hand. These photos can in themselves aid in establishing the reliability of the results (output) of the model. Since the surface runoff , interflow and base flow depend on surface slope, soils and vegetation cover, the photos which display some of these features can help verify the reliability of the result.

4.2 Data Analysis

The main methodology of analysis used during this research was simulation modelling. This was done by inputting catchment information and data into the model programme that had already been prepared for the purpose, adjusting the model parameters to suite the catchment and then running the programme. Prior to carrying out this process, the data quality was tested, its adequacy examined, and the need for infilling the existing gaps satisfied/identified.

4.2.1 Quality of Data

The quality of data can be viewed as the state of its completeness, validity, consistency, timeliness and accuracy that would make it appropriate for a specific purpose. In assessing its quality the following was done:

4.2.11 Initial data analysis (assessment of data adequacy)

During the initial data analysis, data quality was considered especially in terms of possible options for its improvement. This mainly covered analysis of missing records. The data considered included precipitation, water levels, discharge, and evaporation. Table 1 shows a summary of the data that was available and what was missing and therefore needed infilling.

Table 1: Summary of Hydro meteorological data available for Rwizi

Station Name	Type of Data	Start date (dd/mm/yy)	End date (dd/mm/yy)	Complete data
81225/81272	Discharge	1/1/1954	31/12/2009	55
81224/81272	Water Levels	1/1/1954	31/12/2009	55
Eto Mbarara	Evaporation	1/1/1975	31/12/2009	34
90300130_Nsika	Precipitation	1/1/1950	31/12/2006	18
90300190_Ndeizha	Precipitation	1/1/1950	31/12/2006	27
90300250_Mbarara	Precipitation	1/1/1950	31/12/2006	26
90300060_Mbarara	Precipitation	1/1/1950	31/12/2006	20
90300270_Bugamba	Precipitation	1/1/1950	31/12/2006	36
90300030_Mbarara	Precipitation	1/1/1950	31/12/2006	45
90300210_Rubare	Precipitation	1/1/1950	31/12/2006	43

- **Precipitation**

As a result of a study done by Bisher (2010), it was concluded that data quality problems and lack of consistent precipitation data impeded hydrometeorological analysis. Considering the data that was collected, it was observed that the rainfall data available was characterized with gaps. Among the seven stations, only six stations had data that exceeded 30 years. Considering daily precipitation data for all seven stations ranging from 1st January 1950 to December 31st 2006, 64 524 out of 145 726 values were missing giving 44.27% of the daily precipitation data being absent.

The fact that a lot of information was missing was the basis on which a decision was made to carry out Coefficient of correlation analysis for the seven stations each being compared against one of the other stations. The result from this analysis was to be used as a basis for missing data infilling and therefore making the data more representative of actual conditions. This would in turn give a more reliable model output.

Correlation coefficients calculated from the available data for the seven stations were all relatively low as shown in Table 3. The highest possible correlation between two stations was used as a basis for using the data from one station to infill the gaps in the other.

Table 2: Correlation analysis of stations

Stations	Correlation	No. Mths	Weight	weighted Correlation	Average Weighted Correlation
Stations 130 and 190					
Jan 1951 -May 1954	0.173172503	5	0.03649635	0.006320164	0.179560801
July 1954 - July 1958	0.166244729	48	0.350364964	0.058246328	
Sep 1958 - Oct 60	0.157659021	25	0.182481752	0.028769894	
Jan 61 - Sept 64	0.197441499	44	0.321167883	0.063411868	
Mar 73 - Jul 74	0.208354578	15	0.109489051	0.022812545	
Sub Total		137	1	0.179560801	
Stations 130 and 250					
Feb 57 - Nov 60	0.205331936	46	0.380165289	0.078060075	0.201703948
Jan 61 - Sep 64	0.225496686	44	0.363636364	0.081998795	
Mar 73 - Nov 74	0.156597448	20	0.165289256	0.025883876	
Aug 75 - Jul 76	0.173373225	11	0.090909091	0.015761202	
Sub Total		121	1	0.201703948	
Stations 130 and 270					
Feb 68 - Nov 71	0.216098312	45	0.6	0.129658987	0.222827024
Mar 73 - Nov 74	0.255755086	20	0.266666667	0.068201356	
Jan 75- June 75	0.17920432	5	0.066666667	0.011946955	
Jan 76- June 76	0.195295893	5	0.066666667	0.013019726	
Sub Total		75	1	0.222827024	
Stations 130 and 160					
Feb 50 - Sep 51	0.237737847	21	0.112903226	0.02684137	0.159038495
Nov 51 - Mar 54	0.126674547	36	0.193548387	0.024517654	
June 54 - Dec 61	0.148791564	90	0.483870968	0.071995918	
Jan 59 - Dec 61	0.121802076	24	0.129032258	0.015716397	
Mar 73 - jul 74	0.247592734	15	0.080645161	0.019967156	
Sub Total		186	1	0.159038495	
Stations 130 and 30					
Feb 50 - Nov 57	0.106972923	93	0.481865285	0.051546538	0.129531404
Jan 58 - Sept 64	0.165793729	80	0.414507772	0.068722789	

Mar 73 - Nov 74	0.089379041	20	0.103626943	0.009262077	
Sub Total		193	1	0.129531404	
Stations 130 and 210					
Jul 51 - Sep 58	0.158770062	86	0.551282051	0.087527086	0.207559893
Stations	**Correlation**	**No. Mths**	**Weight**	**weighted Correlation**	**Average Weighted Correlation**
Nov 58 - Sep 64	0.267501684	70	0.448717949	0.120032807	
Sub Total		156	1	0.207559893	
Stations 130 and 190					
Nov 50 - May 54	0.173172503	42	0.365217391	0.06324561	0.166908414
Jul 54 - Jul 58	0.166244729	48	0.417391304	0.069389104	
Sep 58 - Oct 60	0.157659021	25	0.217391304	0.0342737	
Sub Total		115	1	0.166908414	
Stations 190 and 210					
Jul 51 - May 54	0.209106999	34	0.127340824	0.026627858	0.242789072
Jul 54 - Jul 58	0.271174557	48	0.179775281	0.048750482	
Nov 58 - Oct 60	0.173131005	23	0.086142322	0.014913907	
Jan 61 - Jul 74	0.25133736	162	0.606741573	0.152496825	
Sub Total		267	1	0.242789072	
Stations 190 and 30					
Nov 50 - May 54	0.097685125	42	0.154411765	0.015083733	0.166844274
Jul 54 - Nov 57	0.069382959	43	0.158088235	0.01096863	
Sep 58 - Oct 60	0.271750923	25	0.091911765	0.024977107	
Jan 61 - Jul 74	0.194454488	162	0.595588235	0.115814805	
Sub Total		272	1	0.166844274	
Stations 190 and 60					
Nov 51 - Mar 54	0.214266598	32	0.201257862	0.043122837	0.14841747
Jul 54 - Dec 57	0.224902177	41	0.257861635	0.057993643	
Jan 59 - Oct 60	0.088441236	21	0.132075472	0.011680918	
Feb 65 - Jul 70	0.087132175	65	0.408805031	0.035620072	
Sub Total		159	1	0.14841747	
Stations 190 and 270					
Feb 58 - Jul 58	0.131322846	5	0.034013605	0.004466763	0.152958904
Sep 58 - Oct 60	0.156421001	25	0.170068027	0.026602211	
Jan 62 - Oct 71	0.153143758	117	0.795918367	0.12188993	
Sub Total		147	1	0.152958904	
Stations 190 and 250					
Feb 57 - Jul 58	0.087529495	17	0.098837209	0.008651171	0.185327006
Aug 58 - Oct 60	0.103238291	26	0.151162791	0.015605788	
Jan 61 - Jul 74	0.214760062	129	0.75	0.161070047	
Sub Total		172	1	0.185327006	
Stations 250&270					
Feb 58 - Nov 60	0.471168542	33	0.204968944	0.096574919	0.369399492
Jan 61 - Nov 61	0.343160721	10	0.062111801	0.02131433	

Jan 62 - Oct 71	0.34316228	118	0.732919255	0.251510242	
Sub Total		161	1	0.369399492	
Stations 250 &60					
Feb 57 - Dec 57	0.158669006	8	0.064	0.010154816	0.24776608
Mar 58 - May 58	0.125829046	2	0.016	0.002013265	
Stations	**Correlation**	**No. Mths**	**Weight**	**weighted Correlation**	**Average Weighted Correlation**
Jan 59 - Nov 60	0.573816364	21	0.168	0.096401149	
Jan 61 - Dec 61	0.230813904	11	0.088	0.020311624	
feb 65 - jul 70	0.160874042	65	0.52	0.083654502	
Jan 73 - jul 74	0.244657809	18	0.144	0.035230724	
Sub Total		125	1	0.24776608	
Stations 250 and 30					
feb 57 - Sep 58	0.218070413	21	0.088607595	0.019322695	0.243598108
Nov 58 - Nov 60	0.282093667	24	0.101265823	0.028566447	
Jan 61 - Jan 77	0.241578255	192	0.810126582	0.195708966	
Sub Total		237	1	0.243598108	
Stations 210 and 30					
Jul 51-Nov 57	0.152654578	76	0.337777778	0.051563324	0.158108048
Nov 58 - Feb 71	0.160889684	149	0.662222222	0.106544724	
Sub Total		225	1	0.158108048	
Stations 210 and 60					
Nov 51 - Mar 54	0.348784586	26	0.179310345	0.062540684	0.238758128
Jun 54 - Dec 57	0.350202553	30	0.206896552	0.072455701	
Jan 59 - Dec 61	0.273956087	24	0.165517241	0.045344456	
Feb 65 - Jul 70	0.130315487	65	0.448275862	0.058417287	
Sub Total		145	1	0.238758128	
Stations 210 and 270					
Nov 58 - Nov 61	0.260954541	24	0.186046512	0.048549682	0.262918882
Jan 62 - Oct 71	0.263367874	105	0.813953488	0.2143692	
Sub Total		129	1	0.262918882	
Stations 270 and 60					
Jan 59 - Dec 61	0.308527025	24	0.242424242	0.07479443	0.220215567
Feb 62 - Oct 62	0.369143333	10	0.101010101	0.037287205	
Feb 65 - Jul 70	0.164696296	65	0.656565657	0.108133932	
Sub Total		99	1	0.220215567	
Stations 270 and 30					
Feb 58 - Nov 61	0.159279766	45	0.326086957	0.051939054	0.172947163
Jan 62 - Oct 71	0.17956042	93	0.673913043	0.121008109	
Sub Total		138	1	0.172947163	
Stations 60 and 30					
Feb 50 - Sep 51	0.149189749	21	0.142857143	0.021312821	0.159359126
May 54 - Nov 57	0.177559064	42	0.285714286	0.050731161	
Jan 59 - Dec 61	0.265760959	24	0.163265306	0.043389544	
Feb 65 - Jul 70	0.107617717	60	0.408163265	0.043925599	

Sub Total		147	1	0.159359126	

- **Water Levels**

The available data on water levels was from 1st January 1954 to 31st December 2009. The percentage of available data was 93.5%, leaving only 6.5 % as missing data. This implied that the error generated due to missing data during analysis would be minimal.

- **Discharge**

The available data on discharge obtained was from 1st January 1954 to 31st December 2009. The percentage of available records was 93.3%, leaving only 6.7 % as missing data. This displayed the fact that the results derived from analysis using this data would contain minimal errors.

- **Evaporation**

Evaporation data that was available started from 1975 as compared to the discharge and rainfall that start from 1954. The evaporation data available was from 1975 to 2009. The percentage of available data was 100%. Although all the evaporation data was available for the mentioned period, the discharge and rainfall data for the period starting from 1970 had very many gaps. The difference in the time frame of available data hindered the time period over which the study was done. This was because the availability of concurrent data for all parameters, which was necessary for the model was for a limited time frame.

4.2.12 Main Data Analysis

The model used for the calibration was Mike 11's NAM. The concurrent data available for rainfall, discharge and evaporation was limited. However, a good calibration period for computer simulation can be obtained for a three to five year period (Ray et al. 1992). Since the rainfall, evaporation and discharge data available were not concurrent, a three year period was chosen based on the availability of best represented concurrent data. For example there was no data for the period before 1975 for evaporation and the data available was only monthly totals. Regarding rainfall, the data given was characterized by gaps and only one out of seven stations had data beyond 1996. This lack of data gave results which were not ideal. However, the missing values were estimated by use of the highest correlation from the other rainfall stations in the case of rainfall and by interpolation for the case of the discharge. The daily evaporation was computed by dividing the monthly value by the number of days in the respective month.

Consequently, the calibration period chosen was from 1975 to 1977. The average flow during this period was established as being 1.97m^3/s compared to 2.12m^3/s and 1.7m^3/s for the periods 1954 – 1974 and 1978 – 2002 respectively. This showed that the period chosen represented a normal flow period since the average flow during this period wasn't higher or lower than the rest of flow periods. This gave a good picture of the average catchment conditions.

The calibration was done by comparing the simulated and observed discharge hydrographs. Input data used to calibrate the NAM parameters included daily accumulated precipitation, daily stream discharge and monthly evapotranspiration and catchment area. Calibration of the model involved adjusting the coefficients for the exchange of water between storage units and the storage unit depth so that simulated and observed discharges fitted as best as possible. Table 4 shows the result of this calibration for each parameter.

Table 3: Rwizi best fit parameters

Parameter	Parameter Description	Final Value	Lower bound	Upper bound
U_{max}	Denotes the upper limit of the amount of water in the surface storage.	10	10	20
L_{max}	Denotes the upper limit of the amount of water in the root zone	300	50	300
CQOF	Determines the division of excess rainfall between overland flow and infiltration	0	0	1
CKIF	Determines the amount of interflow	500	500	1000
CK1,2	Determines the shape of hydrograph peaks	3	3	48

TIF	Determines the relative value of the moisture content in the root zone (L/Lmax) above which interflow is generated.	0	0	0.99
TG	Root zone threshold value for groundwater recharge	0	0	0.99
CKBF	base flow *BF* from the groundwater storage is calculated as the outflow from a linear reservoir with time constant CK_{BF}	2000	100	4000

The parameters that gave the best fit indicated certain properties of the catchment. Such inferences are discussed in Subsection 4.3.

Figure 19 shows the resultant hydrographs generated for the observed and simulated discharge. This hydrograph is one in which the parameters used gave the best fit between observed and simulated hydrographs. The hydrographs that were generated during the calibration process are attached in Appendix A.

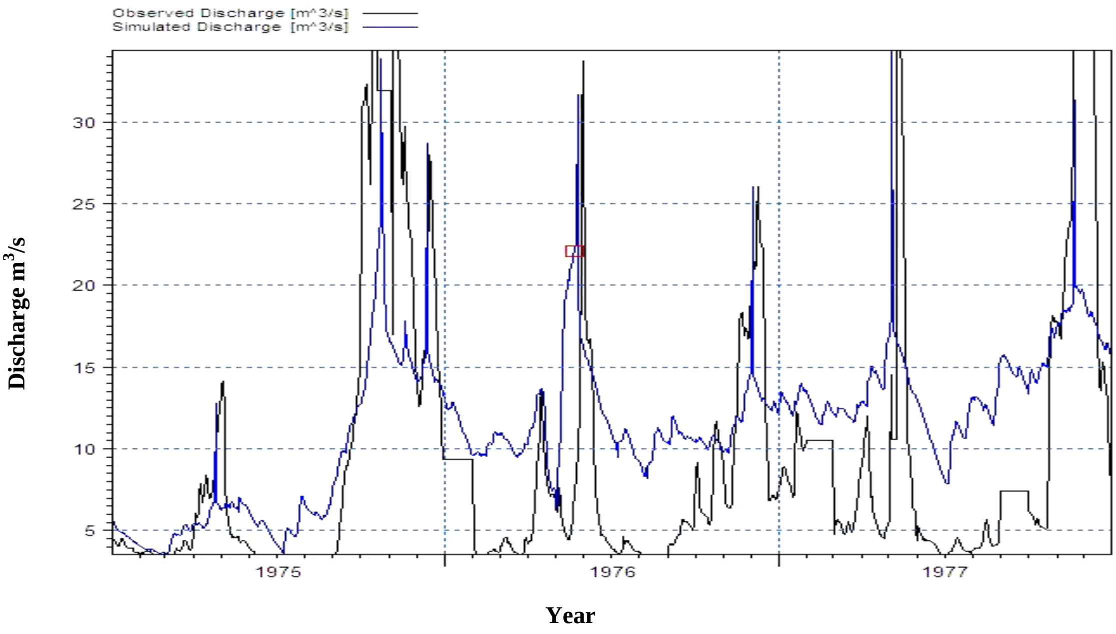

Figure 19: Calibration of River Rwizi resultant hydrograph

The resultant hydrographs showed that there was some variation between simulated and observed discharge even after the parameters were adjusted to obtain the best fit curve. The overall average simulated discharge volume varied from the observed volume by 16% with the average simulated flow being greater than the observed flow. This implied that inspite of the variation; the simulated flow of River Rwizi for the time frame used was a good representation of the actual flow in the river during this period. This showed that the results from subsequent analysis using the simulated flow were reliable. The hydrographs displayed also showed that the simulated flow tended to under predict large flows although it did an excellent job at predicting the timing of peak flows and overall shape of the observed discharge hydrograph. The statistics showing the discharge of the observed and simulated hydrographs were as shown in Table 5:

Table 4: River Rwizi discharge statistics generated from observed and simulated hydrographs.

Hydrograph name	Minimum	Time weighted mean value	Arithmetic mean of values	Maximum	Std. Dev
Observed	2.836	9.671406	9.668294	50.423	9.34237
Simulated	3.541	11.23768	11.23714	42.2	9.93851

In spite of these variations, the resultant model gave a relatively good picture of the observed discharge hydrograph.

4.3 Implication of the Calibrated Mike Basin Model Parameters on the Catchment Characteristics and Output

Considering the calibration of the model the following was concluded about the characteristics of the catchment in question:

a) The final value of the U_{max} that gave the simulated hydrograph the best fit to the observed hydrograph was 10mm. U_{max} represents the cumulative total water content of (DHI 2008):

   i. The interception storage (on vegetation),

   ii. Surface depression storage and

   iii. Storage in the uppermost layers of the soil.

   It was derived from the result that the amount of water from rainfall that was taken up by the uppermost, cultivated part of the ground (surface storage) of the catchment before runoff occurred is the least compared to the limits (Table 4). Since soil moisture is held as capillary water in small pore spaces of the soil or hygroscopic water absorbed on the surface of the soil particles, the result showed that:

i. The uppermost layers of the soil would not retain a lot of water therefore the pore spaces are not small.

ii. The soil type in the catchment was established as being brown and yellowish red gravelly loam soils (from Chapter 3) which has moderately rapid to rapid permeability (United States Department of Agriculture USDA 2004) and therefore low available water capacity thus justifying the result observed from the model.

iii. This result also suggested that the vegetation cover in the catchment was poor. This was established as being 5 to 30% (Chapter 3) during data collection further depicting the reliability of the results.

b) The final value of L_{max} that gave the simulated hydrograph the best fit to the observed hydrograph is 300mm which was relatively high (Table 4). L_{max} denotes the upper limit of the amount of water in a soil layer below the surface from which the vegetation can draw water for transpiration and controls the amount of water that enters the groundwater storage as recharge and the interflow component (DHI 2008). It was concluded that a considerable amount of rainfall was maintained within this zone and was therefore available for consumption by vegetation. The vegetation cover within the catchment was found as being 5 to 30% (Chapter 3). Since the vegetation cover was low, more water was available for groundwater recharge as the moisture content in this zone controls the amount of water that enters the groundwater storage as recharge.

c) The Overland flow runoff coefficient (CQOF) value that gave the simulated hydrograph the best fit to the observed hydrograph was 0 which is the least possible value compared to the given range (Table 4). This value indicated that the amount of rainfall that went as overland flow is negligable since this coefficient determines the division of excess rainfall between overland flow and infiltration. This result further illustrated that all rainfall goes into the ground as infiltration and not as runoff. This demonstrated the reliability of the model results as the final value of CQOF showed the rapid permeability properties of the soil in the catchment, which had already been verified as being gravelly loam during data collection (Chapter 3). Figure 20 shows the quantity of overland flow that was generated after rainfall events. The curve shows a reduction in overland flow to nearly zero over the first few months of the study period which shows low overland flow.

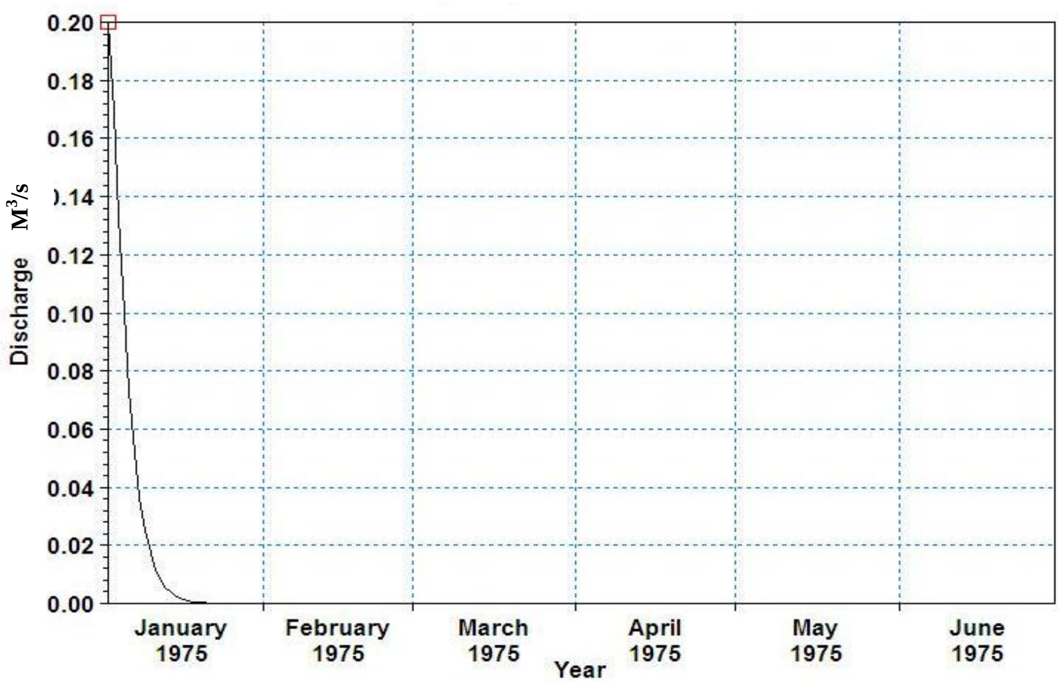

Figure 20: Showing overland flow versus time

d) The CK1_2 value that gave the hydrograph the best fit is 3. CK1_2 determines the shape of hydrograph peaks. Values in the range of 3 - 48 hrs are common (DHI 2008). Since high, sharp peaks are simulated with small time constants, whereas low peaks are simulated with large values of these parameters, this result showed that that in spite of the minimum value assigned in order to generate sharp peaks that would match the observed discharge hydrograph, there was still some error generated probably by missing data infilling.

e) CKIF determined the amount of interflow, which decreased with larger time constants. The value that gave the hydrograph the best fit was 500hrs. Typical values of CKIF are 500-1000hrs (DHI 2008). Since the result was relatively low, it showed that there was a considerable amount of interflow within the catchment. Interflow involves lateral movement of water in the soil to stream channels or any other depressions that could retain water in the catchment. Some of this water could also end up in the springs and shallow wells. This observation was backed up by the fact that there were already some existing protected springs within the catchment. This result also implied that the subsoil was more closely packed than the uppermost layers since it could favour lateral movement.

f) Root zone threshold value for interflow (TIF) determines the relative value of the moisture content in the root zone ($L/_{Lmax}$) above which interflow is generated (DHI 2008). The value that gave the hydrograph best fit was 0 which implied that little moisture is required before interflow is generated. This further demonstrated the fact that the soil particles within the subsoil are more closely packed than in the top soil. Figure 21 shows the flow distribution in the interflow and base flow components as per the parameters that gave the hydrograph of best fit.

Figure 21: Interflow and base flow in Rwizi Catchment

The baseflow hydrograph shows an upward trend towards 1977 which insinuated that more of the precipitation went into the baseflow component. This could be attributed to change in land use activities that favour this trend.

g) TG is the root zone threshold value for groundwater recharge and varies as 0 < TG <1 (DHI 2008). The value that gave the hydrograph best fit was 0 which showed that the threshold value required to recharge the groundwater was low which implied that even with small amounts of rainfall, there was some groundwater recharge.

It can be concluded that from the calibration hydrographs in Figure 19 and from Table 5 summarizing the simulated and observed discharge hydrograph statistics, there was some variation between the simulated and observed discharges. Additionally, there was only one station for evaporation in the catchment and this could also affected the accuracy of the information as there wasn't proper representation of what was actually happening in the catchment. In spite of these short comings, the resultant model gave a relatively good picture of the actual situation.

After calibration, the resultant best fit hydrograph was automatically assigned for use in Mike Basin as was indicated during the calibration run. Consequently, the Mike Basin model would have time series for runoff but would then need time series for demand, which was generated from each of the water users.

The Mike Basin model was run for the catchment as one unit and not as smaller units which would entail each of the tributaries. This was so because the flow data available was only for the main stream of the river as no gauging stations were located along the tributaries. This inhibited the level of study detail that could have been done within the catchment.

The demand time series were generated as follows for each of the water users in the catchment:

- Regarding National Water and Sewerage Corporation Mbarara, the daily water abstracted, treated and supplied Mbarara town was used to generate what was named "NWSC water demand time series". The source document was NWSC Annual Reports 2000 - 2002. It was established that the average water consumption is 352m^3/day given the average statistics from July 2000 to June 2001 as per the NWSC reports.

- The daily water consumption time series for Lake Mburo National Park and the cattle in the Ankole cattle corridor was established from reference documents and one on one interviews. It was ascertained that the estimated number of cattle in the Ankole corridor is 0.5 million. It was estimated that an average cow takes about 16 litres of water per day (Ground Water Survey Kenya Ltd 2006). Therefore the estimated average consumption is 0.0868m^3/s. This is the same estimate that was used as water demand in the game park area.

- Looking at GBK Dairy, the average water consumption used was 9,000,000 litres per annum. This was the basis for the generation of what was later called "GBK water demand time series".

Each of these water users was then digitised and assigned to a water abstraction node on the river. However, there was need to prioritise the water going to each of the users in order to find out what effect this would have on the available water and in order to set abstraction limits to eliminate over exploitation.

The prioritization rule used in this study was "call by priority rule". In this rule, water is extracted from the upstream nodes to satisfy the demand in order of priority beginning with the nodes that had the lowest priority number. The impact of this prioritization on the overall model and how this affects the catchment will be further discussed in Chapter 5.

4.3.1 Scenarios simulated

After assignment of runoff and demand time series, the Mike Basin model was run. The simulation was done for two scenarios. The first scenario considered the existing water users and the effect they had on the resulting water available for use. The second scenario considered a situation whereby both the existing and proposed water users are in place. The effect of this on the river was then examined. The two additional water users simulated were a dam and hydropower station.

The dam and Hydropower station were designed and a time series for water use and return flows were generated from these designs. The results of the first scenario are shown in Figure 22. The red infilled circles along the river show the water that was available to each user at the respective draw-off points. The results show that the water available for use was 0-0.36m^3/s. This indicated water deficits to each of the water users. The impact of each of these scenarios on the catchment is discussed in detail Chapter 5.

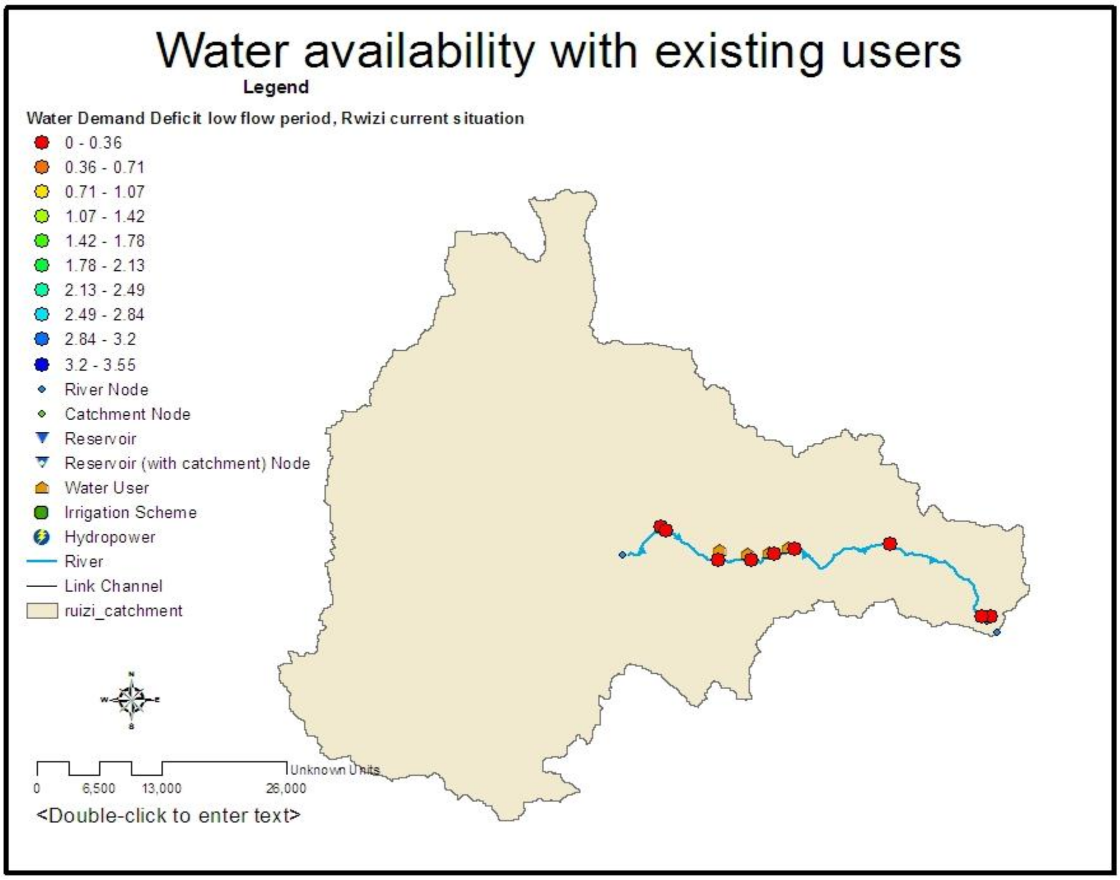

Figure 22: Mike Basin results with existing users

4.3.2 Secondary scenarios simulated

To establish whether the amount of rainfall available in the catchment affected the resultant water available, analysis was also done with consideration being given to period of high discharge and low rainfall. This scenario was termed as secondary scenario analysis. The results of dry and high rainfall seasons analysis are as shown in Figures 23 and 24 respectively. The red infilled circles represent the amount of flow in the river at each of the water user draw-off points. The available water was still in the range of 0 – 0.36 m^3/s irrespective of the season. The details of the implication of these results in relation to IWRM are discussed in Chapter 5.

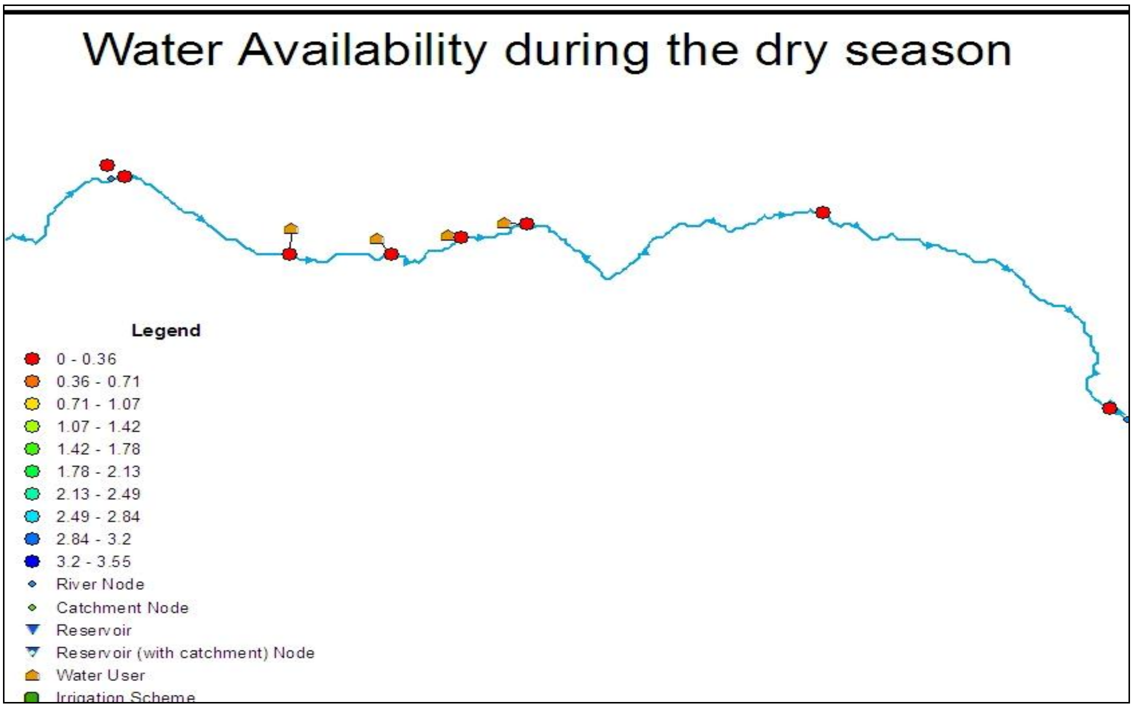

Figure 23: Mike basin current scenario - Graphical representation of low flow scenario

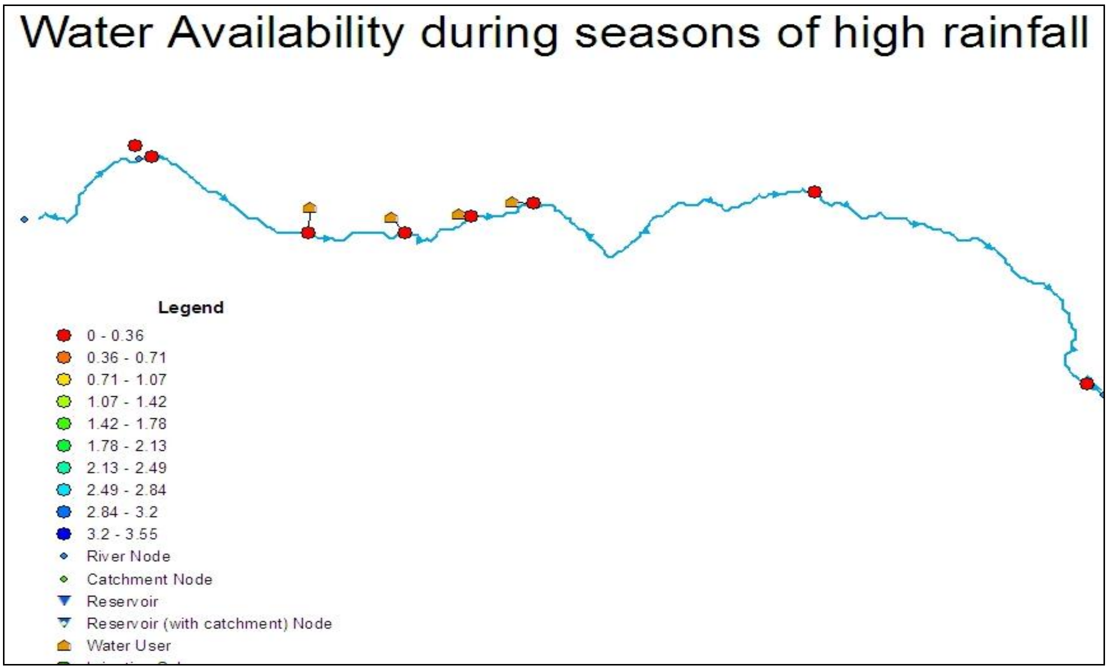

Figure 24: Graphical representation of high flow periods

It was observed that the available water for use in the river within the catchment in considering both wet and dry seasons is very low ranging from 0 - 0.36m^3/s. This observation was indeed backed up by field findings and complaints which was that little water was available for use by the various consumers. This also showed that the model gave reliable results.

The model developed was then used to test the impact of the proposed plans which were construction of the dam and hydro power station on the overall discharge in the river. The dam designed was a multipurpose dam for both provision of head to the hydro power station and storage of water for use. The ET and ground water infiltration that were used in the dam design were considered as being 0.5 and 0mm/day respectively. This was because there was no daily ET data available and the ET estimate had to be derived by dividing the monthly ET by the number of days to get an average daily ET. The ground water infiltration was first assumed as being negligible. If it was deemed feasible then more scenarios with some ground water infiltration would be tested to ascertain the threshold for which this design would be practical. The reservoir and hydropower stations are all located upstream of the existing water users. The parameters in Table 6 were used for the hydropower station design:

Table 5: Parameters used in proposed Hydro power

Parameter	Value	comment
Target power [MW]	0.49	
Installed Capacity [MW]	0	There is no power station at present on the river
Minimum head for operation operation [m]	6	

Regarding the design of the proposed reservoir, Figures 25 illustrates how the volume of water that would be stored varied with the reservoir level area.

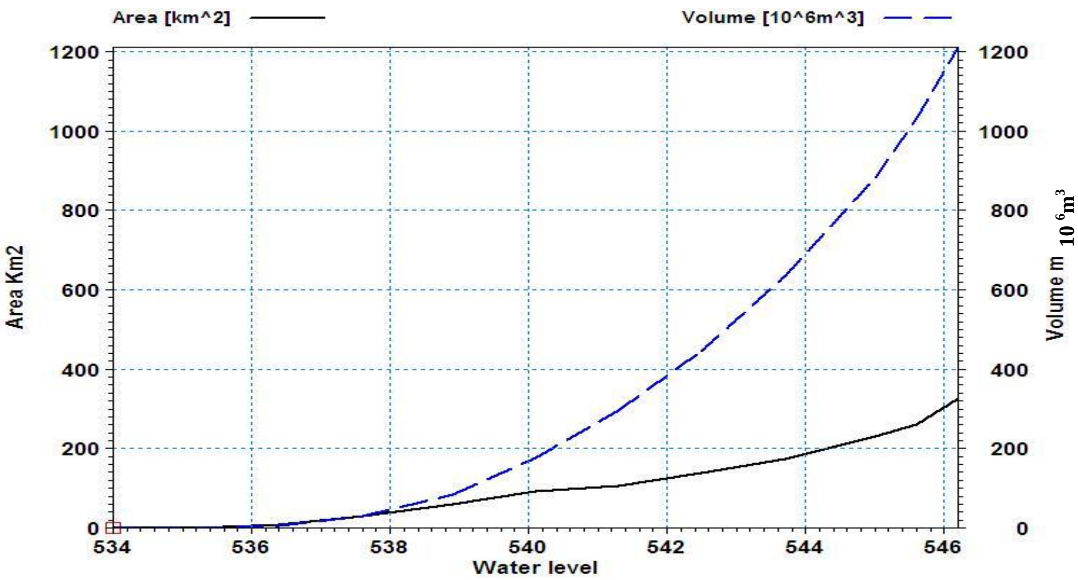

Figure 25: Variation in Volume of water stored with the level area of the reservoir

Figure 26 shows the losses and gains that were assumed to be occurring on a daily basis for the proposed reservoir over the simulation time period. It can be observed that the average precipitation that was assumed for the proposed reservoir was 2mm/day and this was assumed to be constant. The potential evaporation was assumed as constantly being 0.5mm/day and was computed by dividing the monthly ET data gathered during data collection by the number of days in a month and the bottom infiltration as being negligible. These assumptions were based on averages from the data collected:

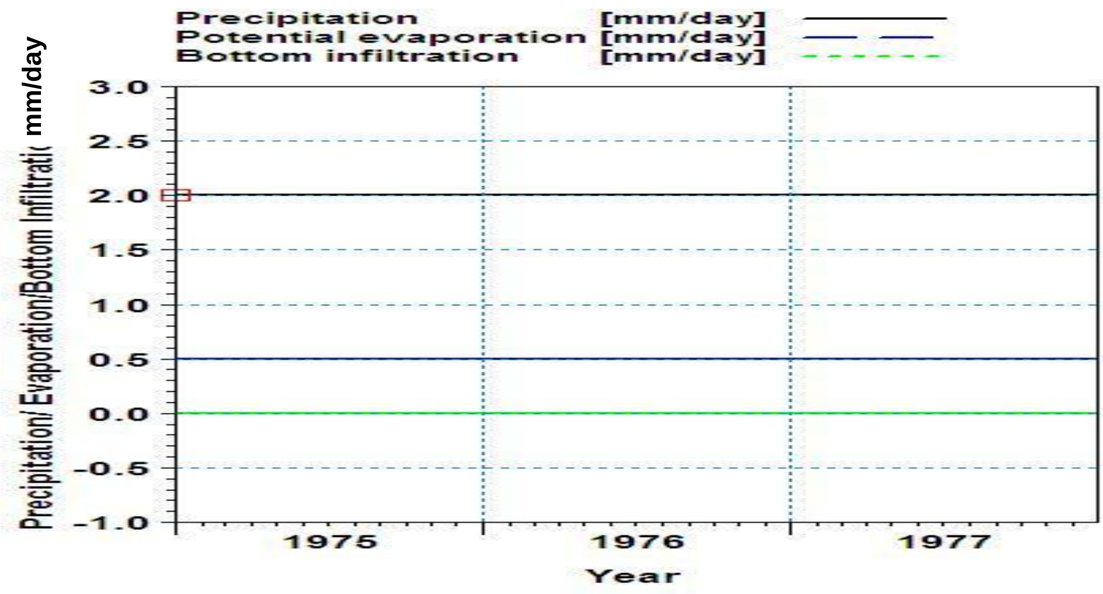

Figure 26: Proposed reservoir gains and losses time series

The Mike Basin model that had now been tested and seen to be giving reliable results was then run with the two additional water users. The proposed reservoir was placed upstream of the existing water user nodes to ensure that the quantity of stored water is adequate for its intended use.

Table 7 shows the resultant numerical estimate of water that would be available to each of the existing water users irrespective of rainfall season. It can be concluded from this table that the water that was available for use was minimal as has already been verified by the outcry of the water users in the catchment. A detailed discussion of these results is done in Chapter 5.

Table 6: Summary of water demand and deficits

User	Actual demand	Range of volume of water available
NWSC Mbarara	0.1	0-0.36m^3
GBK dairy	0.09	0-0.36m^3
Cattle	0.047	0-0.36m^3
National Park	0.04	0-0.36m^3

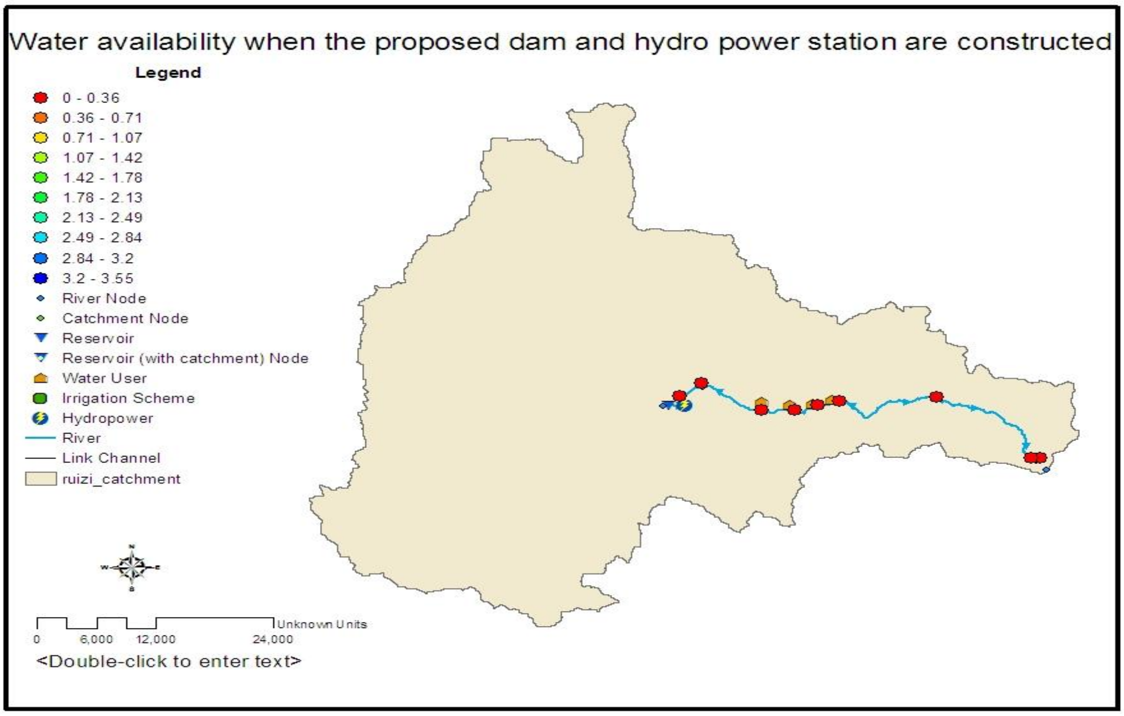

Figure 27: Rwizi with proposed projects

After considering a scenario in which the two additional water users namely the power station and reservoir were added to the system, Figure 27 shows the diagrammatic representation of the amount of discharge that was available in the river reach. The red infilled circles indicated that low flows (0-0.36 m^3) would result.

This therefore showed that with the dam and the hydro electric power stations constructed, the flow would be insufficient to cater for all the other water users downstream and that the project was not feasible considering the low flows that resulted.

Considering the dam that had now been proposed to help the situation, Figure 28 shows how the volume of water stored in the reservoir would vary with time. The results showed that it was not practical to construct the dam even with no water infiltrating into the ground. The constant daily precipitation evaporation and groundwater infiltration gave a straight line variation in storage of the resulting reservoir. Figure 28 also shows that it would take approximately two years for the reservoir to reach its storage capacity of 265million cubics that is in the year 1977. The impact of this water stored in the dam and the results from this scenario are discussed in Chapter 5.

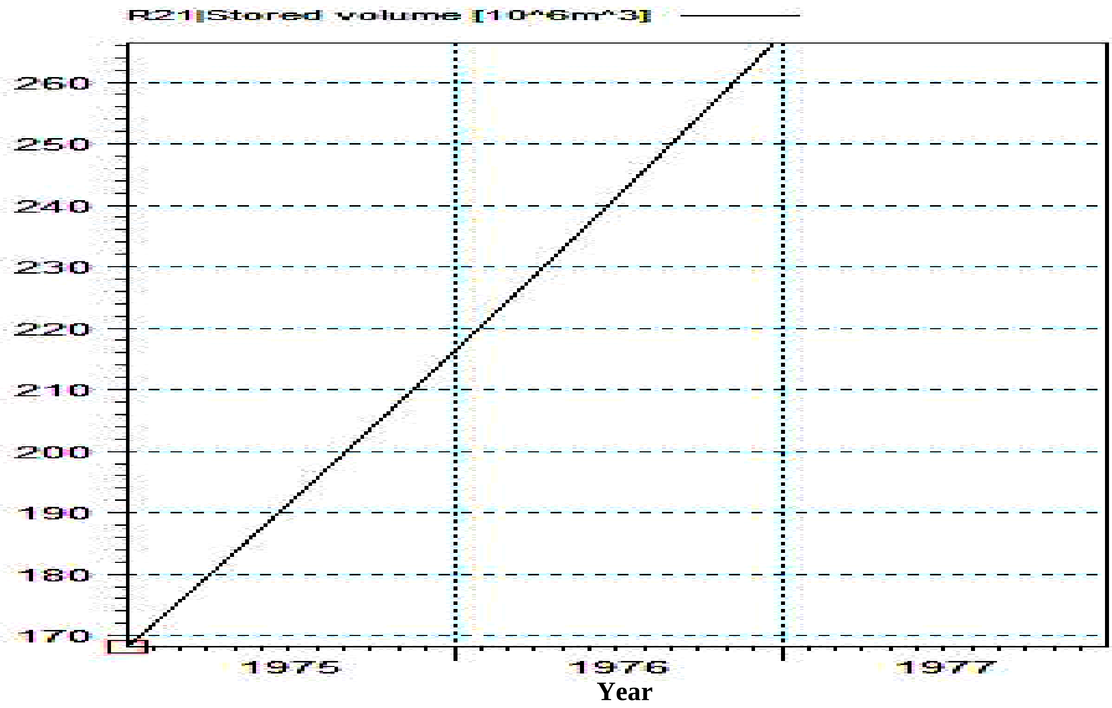

Figure 28: Volume of water in proposed reservoir over time

5.0 DISCUSSION OF RESULTS

5.1 The Concept of Integrated Water Resources Management

Integrated Water Resources Management begins with the term "water resources management" itself, which uses structural and nonstructural measures to “manage” natural and human-made water resources systems for beneficial uses. (IWRM Tutorial; Cap-Net. 2009)

Mitchell (1990) wrote that integrated water management considers three aspects: dimensions of water (surface water and groundwater, and quantity and quality); interactions with land and environment; and interrelationships with social and economic development. With this background, the details of what the model results imply are discussed in the next subsection and how they relate to the concept of Integrated Water Resources Management.

5.2 Addressing IWRM Concept through MIKE BASIN Simulation Results

a) In order to plan or manage any water resource, the users should know how much water is available to them at the present time and how much will be available to each user after any future developments. Aside from testing the viability of the model, this was the reason for running the different scenarios.

b) Still in line with Integrated Water Resources Management concept, solutions in case of water scarcity have to be generated in order for one to make good decisions.

c) Considering the demand versus supply analysis in Mike Basin, the scenario representing the current situation in the catchment for the whole study period 1975 to 1977 showed that the amount of water available to each of the users was in the range of 0 to 0.36m^3/s which was the least possible according to the model. This was shown by the red filled circled at each of the user nodes (Figure 22). The result displayed was indeed backed up by field observations and indicated that model output was reliable and could be used for further analysis. The results from this analysis also showed that there was need to address the water scarcity in the area in order to restore the river. But before this was done, there was need to ascertain the cause of the water shortage. The first exercise that was done was to establish if the cause of water scarcity was low rainfall. This was done by carrying out what was referred to as secondary scenario analysis. In this analysis, the effect of the wet or dry seasons on the resultant amount of water available to the users was determined. It was established that for both wet and dry seasons, there was no difference in the water available for use (Figures 23 and 24). The resultant available water at each user node was still the least possible that was 0 to $0.36m^3/s$.

This secondary scenario analysis eliminated insufficient rainfall as a major cause of water shortage with subsequent deterioration of River Rwizi and its catchment. This scenario also illustrated that there was a considerable amount of water not reaching the river but being stored up in swamps and other depressions in the catchment. Some of this water was lost as evaporation and the rest would percolate into groundwater as recharge. This scenario also illustrated the possibility that some of this water ends up in shallow wells and the fact that there were already existing small scale ground water users further verified this observation.

d) The results of the secondary scenarios formed a strong basis for decision making regarding the course of possible action - which is a tenet of Integrated Water Resources Management. The model was then used to analyse the effect of the two proposed additional water users on the river. The results showed that the hydropower and a reservoir projects were not feasible (Figure 27). It was also revealed that the dam would store water over a period of time, but there would be little water available to the downstream users. This would not solve the problem of water scarcity in the area nor revive the already degraded river, as indicated in red colour in Figure 27. The dam would also increase the water lost by evaporation and therefore would not in itself alleviate the problem.

e) All these findings were a strong basis for decision making and as they were also indicators to tentative solutions to the water scarcity in the Rwizi catchment and a guiding principle to the management of the Water resource.

A possible solution derived from the usage of this model was the option of further exploring the use of groundwater more and diverting some of the water users to the groundwater sources depending on their yield. This would reduce the demand on River Rwizi hence giving it an opportunity to be restored. Figure 29 shows the trend in the rainfall (in mm) and the base flow (in m^3/s) which recharges the groundwater. It was observed that a considerable amount of water goes into groundwater recharge which justified advocating for use of groundwater as one of the solutions to the problem in the catchment.

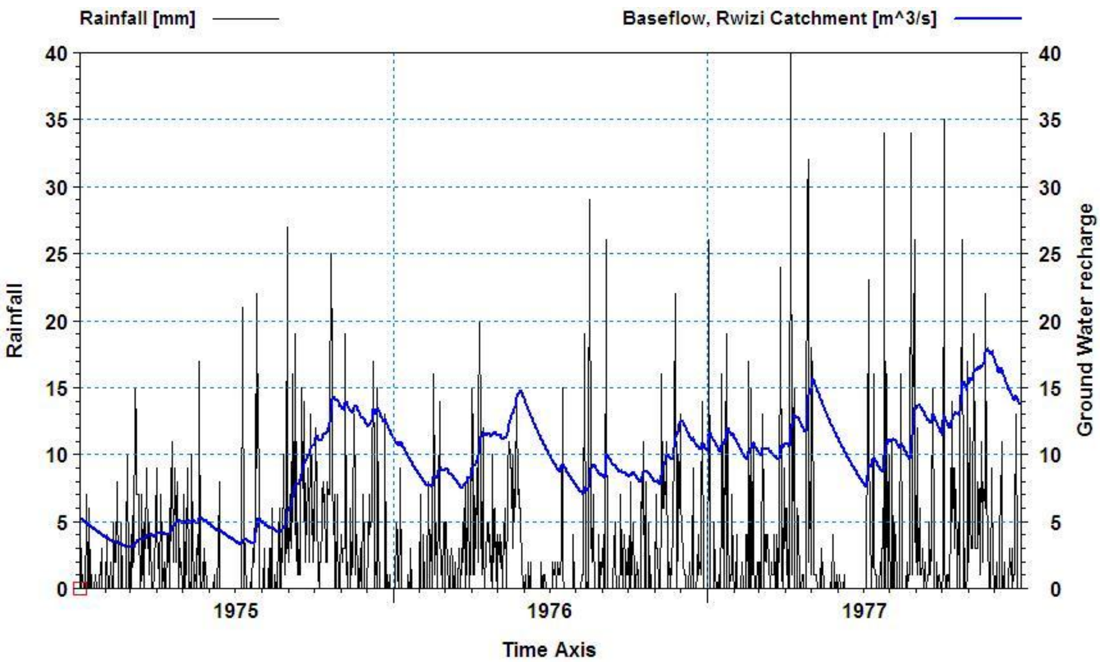

Figure 29: Rainfall versus Groundwater recharge

The combined use of both the dam and the groundwater was another possible solution that was realised. The advantage with the dam was that the water usage could be controlled compared to direct abstraction from the source. This is because with a dam, there would be contructed points of abstraction, which can be monitored and in the event of water scarcity, rationing of water supply could be done. This eliminates the possibility of all available water being taken up by only some water users. The dam also stores water for use thereby reducing on the water scarcity during the dry season. This therefore also fulfils one of the main principles of Integrated Water Resources Management which is considering all the water users and developing a planning system oriented at the production of integrated river basin plans.

The overall result of these simulations showed that the model now developed could be used to test any intended developments in any catchment with similar attributes. The model developed could also be used to prevent and come up with intervention measures for a deteriorated river as well as set parameter limits as to how many users and how much water each can draw. This already fulfilled part of the Integrated Water Resources Management principles.

Even if the proposed intervention measures were put in place, the current careless attitude towards land use has to be addressed. There is, therefore, need for more vigilant sensitization on land use and the prevailing attitude towards waste disposal. This brings forward the idea of involving all stake holders in their different capacities in order to manage and sustain intervention measures that have been put in place.

With the results from this study, the fact that the proposed projects were not feasible has saved what would be wasted time and resources thereby indicating the economic aspect of this methodology of appropriate managing water resources.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

All current situational data/maps and information pertaining to the abstraction, recharge, and waste disposal into the river were collected and used appropriately. This data was then tested for reliability and consistency.

The MIKE BASIN Model developed by the Danish Hydraulic Institute (DHI) was selected for this research because it would best model the catchment situation and assist in reaching IWRM decisions. Thus data was analysed using MIKE BASIN Model.

The results obtained indicated that there wasn't sufficient surface water in River Rwizi to support both the current or any other additional users and that the lack of water wasn't due to insufficient rain. However, it was discovered that most of the water was available as groundwater.

The proposed solutions for River Rwizi and its Catchment's restoration are:

- A proposal for a study to be undertaken to find out how much ground water is available and whether the ground water recharge is replenishing the abstractions adequately. This is to ascertain the feasibility of the option of exploring the possibility of using groundwater resources and diverting some of the current surface water users to these groundwater sources. This would reduce the demand on River Rwizi hence giving it an opportunity to revive.

- Based on the results drawn from the above study, another option can be combined use of a groundwater and a dam through which abstraction can be controlled and hence reduce any further over exploitation.

- Despite these interventions, there is need to change the prevailing careless attitude towards land use through proactive sensitisation.

A model was developed that can be used to plan for sustainable use of water in a catchment, give alerts for an impeding over exploitation, and prioritise water usage in times of stress.

Thus, these form the requirements for rehabilitation/remediation of a catchment such as that of River Ruizi, which has satisfied the research objectives.

6.2 Recommendations

I. This research approach and methodology can be extended to other catchments to address any challenges such as assessing water availability and sustainable use or other similar challenges that may exist.

II. There is need to address the water quality issues in River Rwizi Catchment. This research therefore can also be extended to tackle the water quality aspects including further pollution of the river by haphazard disposal of wastewater into it.

III. A detailed study of the shallow and deep groundwater resources within Rwizi catchment needs to be carried out in order to ascertain the most feasible yet economical water source alternative.

IV. More effort should be placed on collecting and proper data storage as this saves time and aids any studies that are done within any field.

V. The use of models in decision making can also be extended into the socio-economic aspects of IWRM.

VI. There is need to raise awareness to the current worldwide water situation because even with the best remedies to the current water crisis, the peoples' attitude should be directed towards individuals/groups taking care of their water and land resources.

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APPENDIX A

Fitting Simulated Data to Observed Curves

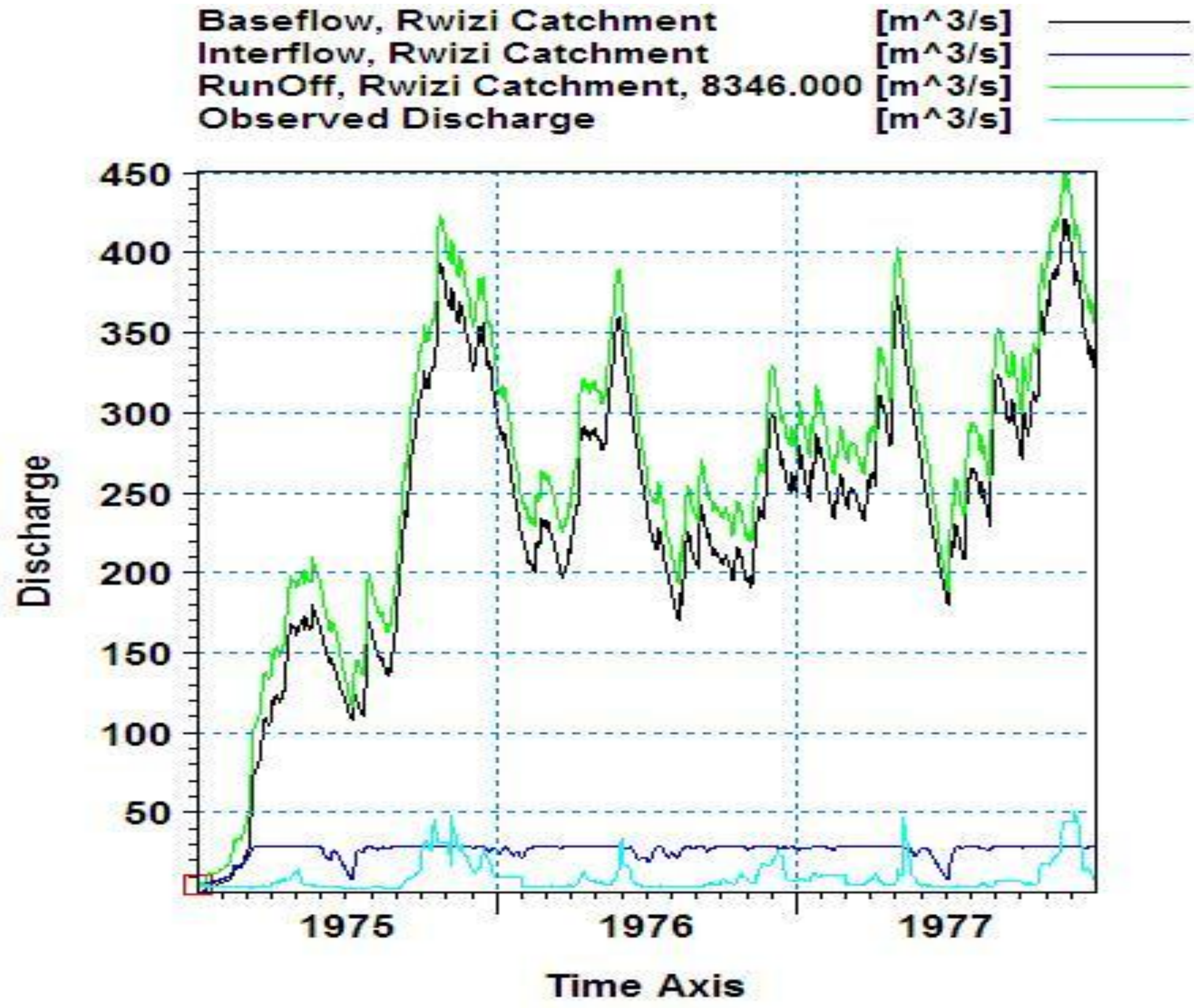

Figure 30: Calibration first trial

All parameters used in this trial that gave the results as is shown in Figure 30 were estimated from reports on similar studies done in other catchments in Uganda and around the world. Subsequent adjustments were done with these parameters as a starting point.

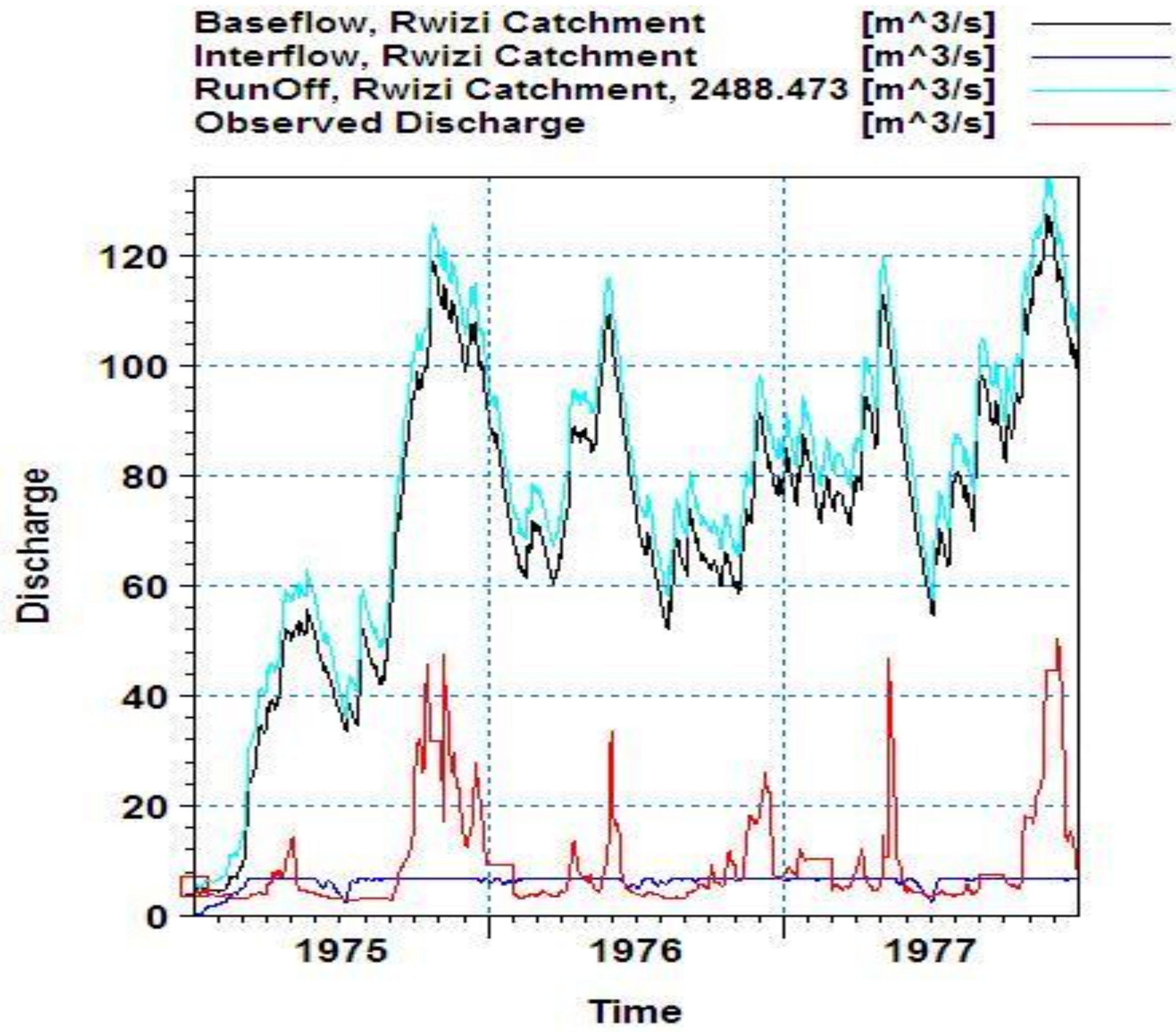

Figure 31: Calibration second trial

Figure 31 shows the resultant hydrographs after changing surface root coefficient.

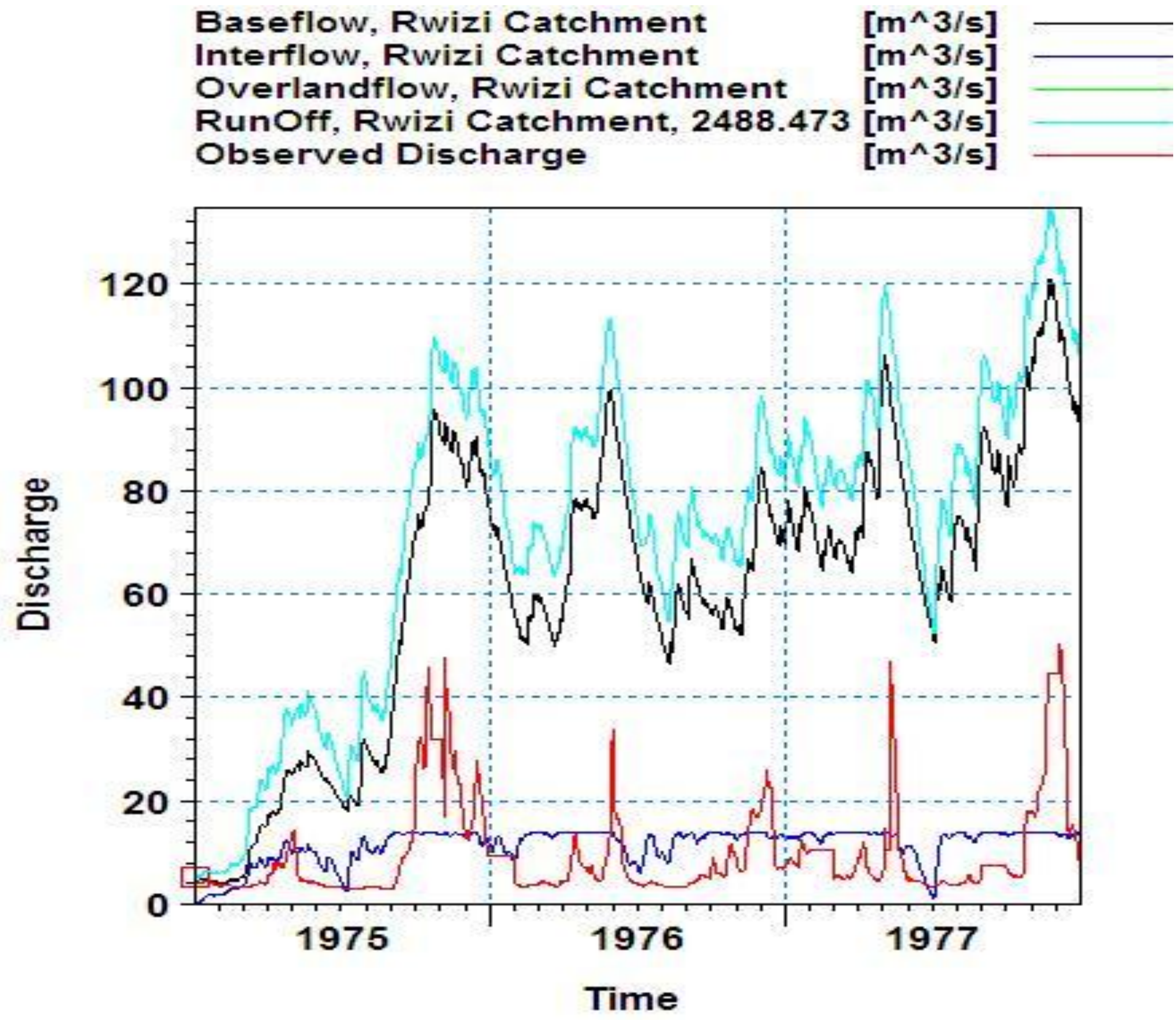

Figure 32: Calibration Third trial

Following the change in groundwater parameters, the hydrographs also change as is shown in Figure 32.

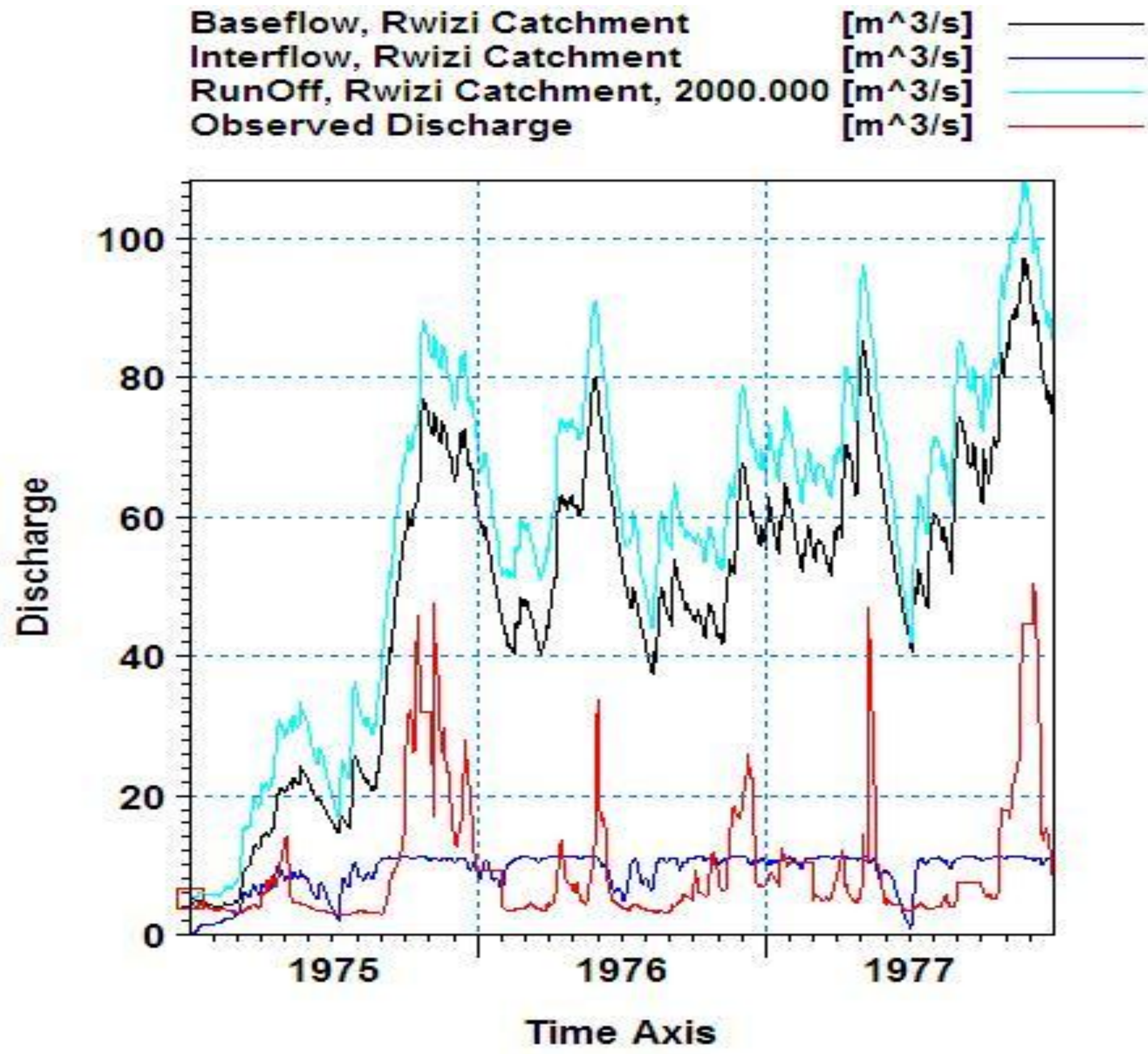

Figure 33: Calibration fourth trial

As a result of adjusting root surface storage parameters, the hydrograph was as shown in Figure 33.

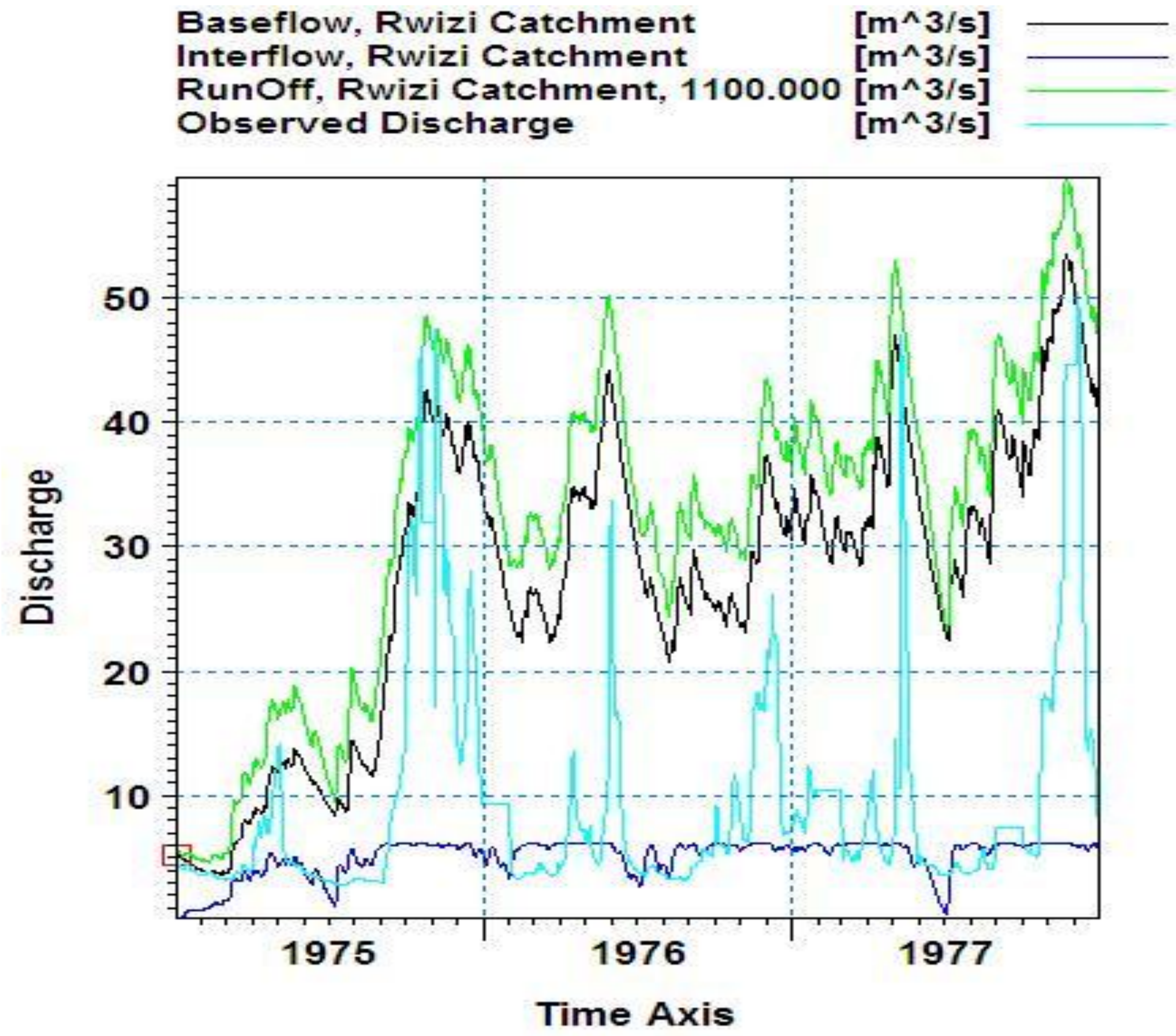

Figure 34: Calibration fifth trial

The hydrographs displayed in Figure 34 were as a result of change in assigned catchment area.

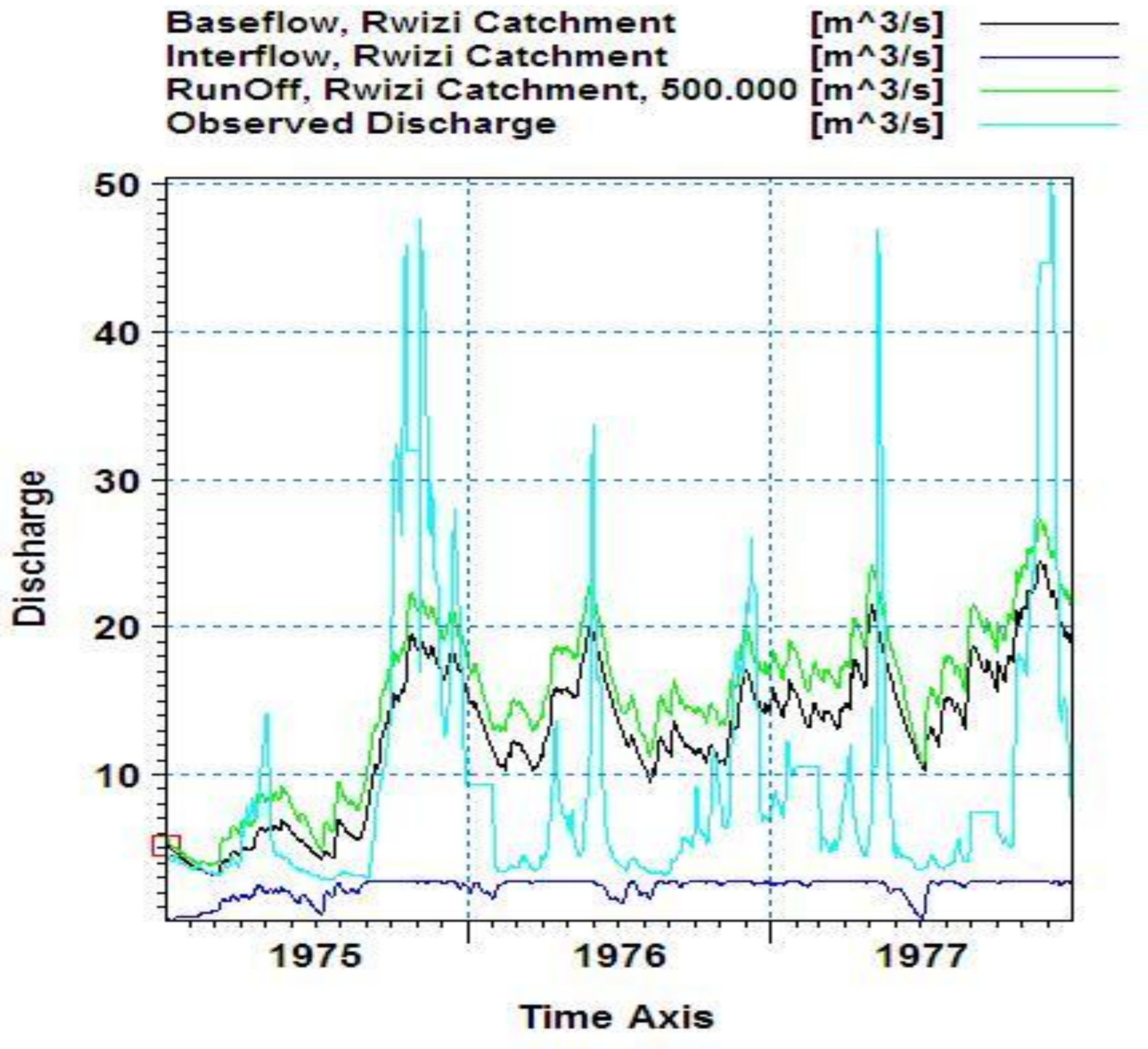

Figure 35: Calibration sixth trial

The hydrograph changed as is displayed in Figure 35 still as a result of change in assigned catchment area.

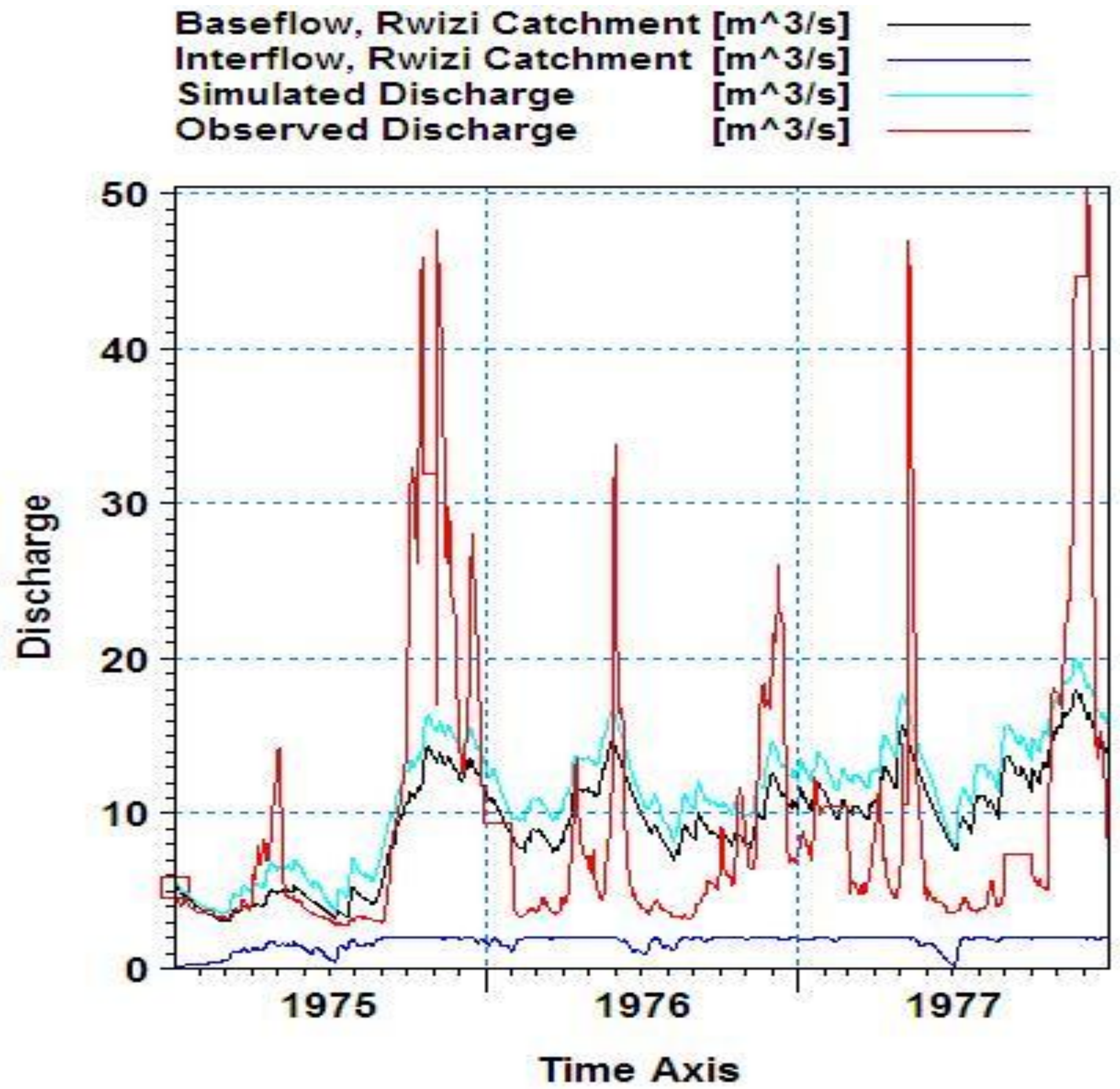

Figure 36: Calibration seventh trial

Further adjustment in catchment area led to the hydrographs displayed in Figure 36.

APPENDIX B

Evaporation and River Flow Data

EVAPORATION DATA

	Eto	mbarara										
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	5.2	5.3	5.3	5	4.7	4.5	4.5	4.7	4.8	4.9	4.8	5
1976	4	4.6	5	3.8	3.8	3.9	3.5	3.8	3.9	4.2	3.9	4
1977	3.7	3.7	4	3.8	3.8	3.8	3.8	3.9	3.9	3.9	4.3	4.4
1978	4	4.1	4.1	3.7	3.9	3.6	3.8	4.2	4.1	4	4.5	4.3
1979	4.3	3.7	3.9	4.8	4.5	4.3	4.3	3.7	4.1	4.8	4.6	4.6
1980	4.4	4.1	4.2	3.8	4	3.7	4	4.2	4.1	3.9	3.9	4.2
1981	5	5.4	4.8	4.7	4.7	4.8	4.7	4.7	4.9	4.8	4.8	5
1982	4.9	5.7	5.5	4.4	4.4	4.4	4.4	4.7	4.8	4.9	4.6	4.8
1983	4.9	5.4	5.2	4.7	4.6	4.5	4.4	4.7	5	4.7	4.7	4.6
1984	5	5.6	5.1	4.7	4.7	4.8	4.7	4.8	5.1	4.7	4.5	4.5
1985	4.9	5.2	5.1	4.7	4.5	4.5	4.6	4.7	4.9	4.7	4.5	4.6
1986	4.9	5.2	5.1	4.7	4.5	4.5	4.6	4.7	4.9	4.8	4.5	4.6
1987	4.9	5.2	5.1	4.7	4.5	4.5	4.6	4.8	5	4.8	4.6	4.7
1988	4.9	5.2	5.1	4.7	4.5	4.5	4.6	4.8	5	4.8	4.6	4.7
1989	5	5.2	5.1	4.7	4.5	4.5	4.6	4.8	5	4.8	4.6	4.7
1990	5.1	4.6	4.8	4.6	4.4	4.2	4.5	4.7	4.6	4.6	4.7	5
1991	5.1	4.7	4.7	4.9	4.6	4.3	4.5	4.6	4.7	4.6	4.8	5
1992	5.2	4.8	4.9	4.7	4.5	3.5	4.6	5	5.5	4.6	4.6	4.5
1993	2.9	4	4.1	4	4.3	3.6	5	4.8	4.5	3.7	3.7	3.7
1994	3.6	3.7	4.7	4.5	4.3	3.7	3.8	3.8	3.9	3.6	3.6	4.3
1995	4.2	4	5	3.7	3.7	3.8	3.9		4	3.7		4.5
1996	4.6	3.7	3.9	3.8	3.9	3.2	3.9	4.1	4.2	3.9	3.4	3.8
1997	4.1	4.6	4	3.6	3.9	4	3.8	4.1	4.4	3.7	3.5	3.4
1998	4.3	4.8	4.2	4.2	3.8	3.9	3.9	3.9	4.1	3.9	3.7	4.5
1999	3.9	4.8	3.7	4.1	3.9	4.1	4.2	3.6	4	3.8	3.5	3.6
2000	4.9	5	4.9	4.5	4.4	4.5	4.8	4.9	5	4.4	4.1	3.7
2001	3.7	4.3	3.8	3.8	3.6	3.8	3.8	4.1	3.8	3.6	4.4	4.5
2002	4.6	5.4	4.7	4.4	4.3	4.6	5	5	5.2	4.6	4.2	4.3
2003	4.2	5	4.1	3.7	3.7	4.3	4.5	4	3.9	3.8	3.7	4
2004	4.7	5.2	4.9	4.5	4.5	4.9	4.8	4.9	5.2	4.6	4.5	
2005										4.8	4.6	5.1
2006	4.8	5.3	4.8	4.5	4.3	4.7	4.6	4.8	4.9	4.6	4	4
2007	4.3	4.6	4.6	4.3	3.9	3.8	4	4.2	4.2	4.2	4	4.2
2008	4.3	4.5	4.5	4.2	4	3.9	4.2	4.1	4.3	4	4.3	4.4
2009	4.2	4.5	4.7	4.2	4	4.4	4.3	4.5	4.5	4	3.9	3.8

A SAMPLE OF FLOW DATA COLLECTED

1-Jan-1954,,m,

2-Jan-1954,,m,

3-Jan-1954,,m,

4-Jan-1954,,m,

5-Jan-1954,,m,

6-Jan-1954,,m,

7-Jan-1954,,m,

8-Jan-1954,,m,

9-Jan-1954,,m,

10-Jan-1954,,m,

11-Jan-1954,,m,

12-Jan-1954,,m,

13-Jan-1954,,m,

14-Jan-1954,,m,

15-Jan-1954,,m,

16-Jan-1954,,m,

17-Jan-1954,,m,

18-Jan-1954,,m,

19-Jan-1954,,m,

20-Jan-1954,,m,

21-Jan-1954,,m,

22-Jan-1954,,m,

23-Jan-1954,,m,

24-Jan-1954,,m,

25-Jan-1954,,m,

26-Jan-1954,,m,

27-Jan-1954,,m,

28-Jan-1954,,m,

29-Jan-1954,,m,

30-Jan-1954,,m,

31-Jan-1954,,m,

1-Feb-1954,,m,

2-Feb-1954,,m,

3-Feb-1954,,m,

4-Feb-1954,,m,

5-Feb-1954,,m,

6-Feb-1954,,m,

7-Feb-1954,,m,

8-Feb-1954,,m,

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13-Feb-1954,2.702,,

14-Feb-1954,2.702,,

15-Feb-1954,2.702,,

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18-Feb-1954,2.665,,

19-Feb-1954,2.662,,

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21-Feb-1954,2.662,,

22-Feb-1954,2.665,,

23-Feb-1954,2.702,,

24-Feb-1954,2.743,,

25-Feb-1954,2.781,,

26-Feb-1954,2.785,,

27-Feb-1954,2.785,,

28-Feb-1954,2.785,,

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11-Mar-1954,3.130,,

12-Mar-1954,3.130,,

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14-Mar-1954,3.130,,

15-Mar-1954,3.130,,

16-Mar-1954,3.126,,

17-Mar-1954,3.089,,

18-Mar-1954,3.085,,

19-Mar-1954,3.085,,

20-Mar-1954,3.085,,

21-Mar-1954,3.085,,

22-Mar-1954,3.089,,

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12-Aug-1954,4.061,,

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9-Oct-1954,9.195,,

10-Oct-1954,9.009,,

11-Oct-1954,8.825,,

12-Oct-1954,8.644,,

13-Oct-1954,8.465,,

14-Oct-1954,8.289,,

15-Oct-1954,8.159,,

16-Oct-1954,8.073,,

17-Oct-1954,7.987,,

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25-Oct-1954,7.009,,

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27-Oct-1954,6.867,,

28-Oct-1954,6.925,,

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