UNIVERSITY OF NAIROBI

DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

WATER ALLOCATION ASSESSMENT: A STUDY OF HYDROLOGICAL SIMULATION ON MUKURUMUDZI RIVER BASIN

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F56/80192/2012

A thesis submitted in fulfillment for the degree of MSc. Environmental and Biosystems Engineering in the department of Environmental and Biosystems Engineering in the University of Nairobi

August, 2014

Declaration

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of information have been acknowledgement.

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Acknowledgement

I would like to thank Dr. Christian T. Omuto and Dr. John P. O. Obiero for supervising me through the thesis, their invaluable advice and guidance helped me to do this study with excellence. Particular thanks to the chairman's office of Environmental and Biosystems Engineering Department for the support, advice and encouragement.

I would like to express my sincere gratitude to Base Titanium for support, resources and approval to do this study. Special thanks to Dr. G. Jones for her inputs in problem identification, time, assistance, resources, suggestions, reference materials, advice, continuous support and encouragement. Particular thanks to Mike I. Lane, hydro-geologist with Aquasearch Ltd/Rural Focus Ltd, for his time inputs, assistance, advice, reviews, suggestions and support.

I would like to thank Rural Focus Ltd for the resources and time they gave me to write up this thesis. Special thanks to Eng. Mike K. Thomas for his guidance, patience, encouragement, valuable advice and comments to improve my report. I am also thankful to Eng. Thomas J. Traexler for his advice and encouragement.

I would also like to thank all my work colleagues at Rural Focus Ltd for their endless support and encouragement.

I would like to thank Prof. John Mwangi Gathenya for his support, advice and comments to improve my report.

Finally, I am forever grateful to my family-my mother, my sister, my cousins and my close friends for their boundless support and encouragement.

Abstract

The flow at RGS 3KD06 on 13/03/2013 was estimated at approximately 0.006 m^3/s ($\approx$520 m^3/d), which is 53% of the lowest recorded daily flow for March (0.011.28 m^3/s, $\approx$ 974 m^3/d). The concerns regarding the low flows on the Mkurumudzi River led to the need to quantify the available water resource, assessment and formulation of a water allocation framework for the catchment. An abstraction survey was conducted along the entire length of the Mkurumudzi River. Abstraction points were identified, mapped and abstraction volumes assessed. The assessment of the water resource was conducted using MIKE basin software and Danish Hydrologic Institute's (DHI) Nedbør-Afrstrømnings-Model (NAM). The rainfall runoff model was done using NAM and calibrated for a period of 30 years; the input time series comprised of observed flow data for RGS 3KD06, evapotranspiration data and precipitation data. The calculated Root Mean Square Error-observations standard deviation ratio (RSR) was 0.364 while Nash-Sutcliffe Efficiency (NSE) was 0.868. The NSE approached unity indicating that the predicted and the observed discharge values had a good correlation hence the model could fairly simulate the catchment response. The output time series was used in MIKE basin model.

The MIKE basin model was designed in ArcGIS 10.0, the water users and reservoirs were digitized and their time series of abstraction rates uploaded onto them. The model was run without the abstraction time series for the abstractors in the catchment to establish the environmental water requirements at the mouth of the river, the model was then run again with all existing current abstractions to establish a time series for the mouth of the river, and this time series was then used to compute the monthly reserve flow values which were compared to the environmental water requirements for the mouth of the river to assess the water balance and allocations. From the flow duration curve, the reserve flow at the estuary was calculated at 0.130 m^3/s (Q95), the normal flow at 0.190 m^3/s (Q80) and the flood flow at 0.520 m^3/s (Q50).

This catchment had 18 abstraction points with a total abstraction of 506 m^3/day, at this time the mining and irrigation scheme had not started operations; The total authorised normal flow abstractions with valid documentation were 0.023 m^3/s; the total authorised flood flow abstractions with valid documentation was 1.20 m^3/s. The water balance and allocation analysis in MIKE basin showed a deficit of water for the environmental flow requirements in the months of July and August, 0.023 m^3/s and 0.010 m^3/s respectively. The water allocation framework sets out that any future demands to be allocated water should be based on normal flows of 0.02 m^3/s and flood flows of 0.13 m^3/s. This analysis did not take into account climate change variability. This thesis sets out the need to further conduct a comprehensive and holistic watershed modelling (hydrogeological) of Mukurumudzi basin and the reservoirs that takes into account the groundwater dynamics and water quality since these will have a general impact onto health, sanitation and living standards of the people that rely on the catchment's groundwater resource for domestic use.

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ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CC	Climate Change
DEM	Digital Terrain Model
DHI	Danish Hydrologic Institute
DWF	Dry Weather Flows
GSK	Groundwater Survey (K) Ltd
EWR	Environmental Water Requirements
FDC	Flow Duration Curve
H/Q	Height/Discharge
KARI	Kenya Agricultural Research Institute
KISCOL	Kwale International Sugar Company Limited
KMD	Kenya Meteorological Department
KMSP	Kwale Mineral Sands Project [Base Titanium]
MSP	Mineral Separation Plant
m^3/s	Meters cubic per second
m^3/d	Meters cubic per day
NAM	DHI's Nedbør-Afstrømnings-Model
Q_{95}	Discharge that is exceeded 95 percent of the time
Q_{80}	Discharge that is exceeded 80 percent of the time
Q_{50}	Discharge that is exceeded 50 percent of the time
SCMP	Sub-Catchment Management Plan
SML	Special Mining Lease
SRTM	shuttle Radar Topography Mission
SWAT	Soil Water Analysis Tool
WCP	Wet Concentrator Plant
WDC	Water Development Cycle
WGS	World Geodetic System
WRMA	Water Resources Management Authority
WRUA	Water Resource Users Association

1. INTRODUCTION

1.1 Background

The Mukurumudzi River basin (MRB) covers an area of 207 km^2 and is located in Kenya, approximately 50 km south of Mombasa (Kenya's principal port facility), and starts 30 km inland from the Indian Ocean. The Mukurumudzi River basin has the Mukurumudzi River, 40 km long, as the main river flowing from the Shimba Hills and draining into the Indian Ocean. The catchment has two major upcoming industries, a titanium mining company and an irrigation farm. The mining is being done by the Kwale Mineral Sands Project while the irrigation of 8,000 ha of sugarcane is being done by the Kwale International Sugar Company. Both the mining and irrigation companies have so far developed 3 dams on the Mukurumudzi River basin to meet their water demands

Kwale Mineral Sands Project plans to mine titanium-bearing mineral sand deposits in the Maumba and Nguluku areas of Msambweni District, Kwale County. Minerals will be extracted and separated from the Pliocene Magarini sands in a Wet Concentrator Plant (WCP). The heavy mineral concentrate will then be further refined into Ilmenite, Rutile and Zircon in a Mineral Separation Plant (MSP). The water demand for the WCP and MSP is approximately 22,000 m^3/d. Up to 82% of the water demand will be supplied from recovered water recycled to the front of the process, the remaining amount is expected to evaporate and seep into the soil matrix through lateral and vertical leakage or lost to entrapment within the slimes and sand tailings emanating from the mineral extraction process. Kwale Mineral Sands Project has constructed an 8.4 Mm^3 dam to supply water to the processing plant. It has also a well field to supplement the water from the dam (Kibson Consult, 2010). The irrigation scheme has over 26 boreholes and has constructed 2 dams, upper Koromojo dam and lower Koromojo dam with a total storage of 5.5 Mm^3 in the Mukurumudzi basin.

An abstraction survey was carried out in January 1999 by GSK on the Mkurumudzi River downstream of 3KD06. This study reported authorized abstractions of 126 m^3/d from normal flow and 714 m^3/d from flood flow and a cumulative measured abstraction downstream of 3KD06 for both legal and illegal abstractors of 110 m^3/d.

With the introduction of the dams, the flows downstream of the dam are affected, it is therefore imperative to assess the stream flow changes downstream of the dam and the effects it will have to the ecological system and water users downstream. It is also important to monitor the flows for the purpose of maintaining the reserve flow (Pyrce, 2004). It will be worth to determine the reserve flow and its reliability.

With the changes in climate, land uses and abstractions, it is expected that the groundwater will fluctuate. This fluctuation is not known but is anticipated. It is therefore worth having knowledge on the available surface water and groundwater resource and the most appropriate water allocation plan for sharing of the limited water resource for the different water uses in the basin.

1.2 Problem Statement and Justification

According to the sub-catchment management plan developed by the Mukurumudzi WRUA, there exists a conflict on domestic, irrigation and commercial water uses in the catchment. The conflict is brought about by diminishing water resource availability which leads to over abstraction, figure 1.1 shows the problem analysis. The diminishing water resource could be influenced by changes in land uses and/or climate. The catchment has two major abstractors who are quickly putting up infrastructure to start abstraction from the MRB. These are; the Kwale International Sugar Company who needs to irrigate 8,000 ha from the MRB and the Kwale Mineral Sands Project who requires 22,000 m^3/day. The flow at RGS 3KD06 (at Shimba Hills town) on 13/03/2013 was estimated at approximately 0.006 m^3/s (≅520 m^3/d), which is 53% of the lowest record daily flow for March (0.0113 m^3/s, ≅974 m^3/d). Over abstraction from the river is likely to occur due to unknown abstractors in the MRB, unknown levels of abstraction, over allocation of the water resource and unauthorized abstractions. This can be due to lack of a water allocation framework which is a tool used to mitigate conflicts over water resources and to equitably allocate the scarce water resource (Speed *et.al*, 2013). The environmental flow requirements are usually compromised when there is over abstraction and diminishing water resource, leading to environmental degradation (Tennant,1976; Reiser *et. al*., 1989) and conflicts among water users(Caissie and El-jabi, 2003).

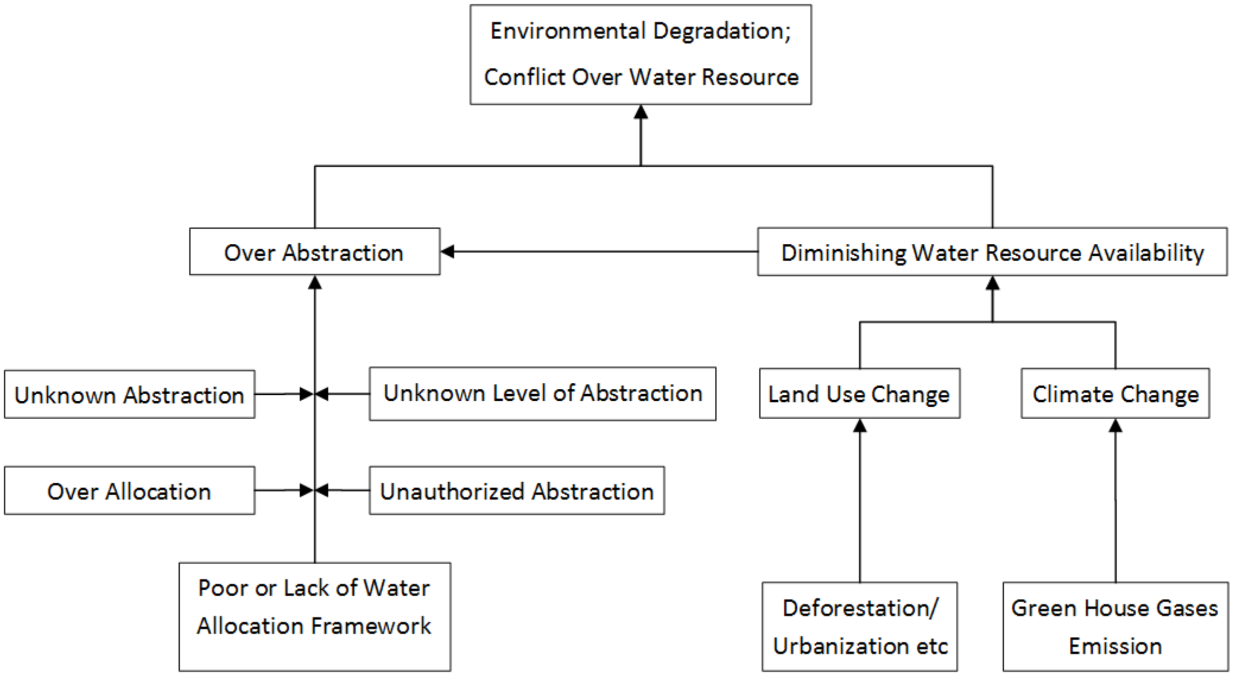

Figure 1-1: Problem Analysis

Dr. Jones (personal communication) stipulates that it is becoming increasingly clear that changes in the hydrology of MRB have occurred in the recent past on a decadal scale. It appears inevitable that such changes will continue to occur and should be proved, explained and quantified before any realistic attempt can be made to determine the further impacts (if any) of the Kwale Mineral Sands Project and the Sugarcane irrigation scheme on the hydrology of MRB.

1.3 Statement of Objectives

The overall objective of this study was to develop a water allocation framework that will be used to equitably distribute the available water resource for the different water uses in the Mukurumudzi basin in order to mitigate conflicts among water users and protection of environmental flows.

The specific objectives will be to;

1. Quantify and classify the water abstractors and level of abstractions in the Mukurumudzi river basin through an abstraction survey.
2. Assess the surface water resource availability through simulation modelling based on analysis of existing hydrological data.
3. Develop a water allocation frame work for Mukurumudzi river basin.

2. LITERATURE REVIEW

2.1 Hydrological Modeling

2.1.1 The Hydrological Cycle, GIS and Catchment Models

The Earth holds a large amount of water in different spheres which is in constant motion; this movement of water on the earth's surface and through the atmosphere is known as the hydrologic cycle. This cycle shows water as it travels through different global systems or storages by means of different processes. These processes are precipitation, runoff, evaporation, infiltration, transpiration, percolation, recharge of groundwater, interflow and groundwater discharge (Neitsch *et. Al.,* 2005).

Precipitation is water released from the atmosphere in forms such as rain, snow, sleet, or hail. This results from the evaporation of water from the earth into the atmosphere where it is temporarily held and accumulates saturating the atmosphere and eventually released. Precipitation is considered as the major input in watersheds models. *Evaporation* occurs when water is changed from a liquid state to a vapor state and moves back in to the atmosphere. This is increased by solar radiation, increases in air and wind temperature while high moisture content in the air reduces the potential for evaporation. *Transpiration* is the release of water by plants as a by-product of photosynthesis. Evapotranspiration is the combination of the two processes of evaporation and transpiration because of the difficulty in separation of the two processes (Ward, 2005). *Infiltration* is the entry of water into the soil. This is governed by different factors and as a result of this it varies from place to place. It is dependent on soil properties such as the organic matter content, density, texture, hydraulic conductivity and porosity. The soil surface conditions also affect infiltration where compacted soil will restrict infiltration, vegetation like forests slow down the water flow and allow for more infiltration as opposed to paved areas. Topography, roughness and slope and human activities that alter the soil surface like in urban and agricultural areas affect the infiltration of water in an area (Mango, 2010).

Percolation is the downward movement of water after it enters the soil by means of gravity through the soil profile. That which moves past the plant root zone toward the underlying geologic formation is called deep percolation, is out of reach of the plant roots and goes towards replenishing the groundwater supply and this process is known as groundwater recharge. Runoff is the portion of precipitation, snowmelt, or irrigation water that flows over and through the soils, eventually making its way into surface water systems. This component of the hydrological cycle is of a lot of importance in this study as it is the component that will be simulated using NAM run-off model. Contributions to it include overland flow, interflow and groundwater flow. A large percentage of surface runoff reaches streams, where it is described as stream flow or discharge. Overland flow can also occur when the soil is saturated (soil storage is filled).When all the voids, cracks and crevices of the soil profile are filled with water and the excess begins to flow over the soil surface.

Interflow may occur when the water's downward movement is restricted by an impenetrable layer of material which causes it to move laterally and discharge that may have been formed naturally or by human activities. *Groundwater recharge* or deep drainage or deep percolation is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface. *Groundwater flow* occurs in the hydrological cycle and this process creates a base flow for surface water bodies and for groundwater recharge. A large percentage of this water is used for drinking and irrigation (Mango 2010).

Geographic Information Systems (GIS) is a tool for the management, query, visualization and analysis of spatially referenced information. It can be defined as computer based tools that display, store, analyze, retrieve, and process spatial data. It can be used to preprocess information and validate its use in an environmental model and also be tightly coupled to an environmental model to provide an interactive system that allows decision-makers to quickly modify parameters and visualize the results of simulations (Ireson *et al.,* 2005). This simulation or prediction is made possible by application of a hydrological runoff model in a Geographical Information System (GIS). Models are invaluable tools for resource management. Models help resource managers develop a shared conceptual understanding of complex natural systems, allow testing of management scenarios, predict outcomes of high risk and high cost environmental manipulations, and set priorities. These are all essential components of developing regional catchment strategies and associated action plans. There will always be some degree of uncertainty because models are a simplification of reality. Uncertainties in model outputs can arise from conceptualization of the processes modeled, quality and quantity of data, constraints of the modeling technology, and assumptions used in the scenarios tested (Ireson *et al.,* 2005).

Geographic Information Systems (GIS) has become a key part of hydrologic studies because it has proved useful in hydrologic modeling processes such as the spatial and temporal distribution of inputs and parameters controlling surface runoff. Maps describing topography, land use, land cover soils, rainfall and meteorological variables may become model parameters or inputs in the simulation of hydrologic processes (Vieux, 2001). GIS is beneficial in hydrological modeling because it is able to provide a visual based simulation environment and scenario management and analysis capabilities. It is also much easier and practical to display and assess the hydrological, spatial and seasonal variability of the parameters involved in the modeling process. GIS provides well developed algorithms to deal with geographic data of high spatial detail and information content. However, depending on the watershed, a lot of this data requires preprocessing and conversion before it can be used for distributed hydrological modeling (Mango, 2010).

Hydrological models usually require a surface representation of a parameter measured at points, several methods for generating a two dimensional surface from point data have been developed and include; Kriging, Moving average, Splines, Local regression and Linear interpolation (Cressie, 1993). Values can be interpolated across distinct zones. Delineation of drainage networks from Digital Elevation Models (DEM) is another important function of GIS in hydrological modeling. GIS is also useful in the analysis of land use and land cover patterns in terms of spatial and temporal variability, soil types, population distribution.

2.1.2 Hydrological Models in Prediction of River Flow

The aim of the hydrological model is to predict the amount of discharge from a drainage basin. There are two fundamental or classical types of hydrological models: deterministic and stochastic models and these can be further described whether the description of hydrological process is empirical or physically based. There are four major types of deterministic models: physically based models, empirical lumped models, empirical distributed models, and physically based distributed models (Olsson and Pilesjo, 2002).

Empirical models are based on regression and correlation results from statistical analyses from time series data. The equations derived are based on measurement knowledge or observed phenomena without demands on understanding of the underlying process and are often referred to as black box models. Truly physical models are based on formulas of physical relations and are referred to as white box models because every part of the process is understood. Prediction of discharge from catchments and monitoring of pollutant and sediment dispersal are well suited for physical models (Abbot and Refsgaard, 1996). It is important to note that the whole conceptual understanding of a hydrological system cannot be expressed in mathematical terms thus there will always be a systematic error introduced based on the excluded or unknown relationship. This is a source of error in many physical modeling processes which gives rise to the need for calibration of the model to time series data (Olsson and Pilesjo, 2002).

In a lumped model, the model uses parameter band variables that represent average values for the entire catchment. The averages can be derived either physically or empirically which can give the model a semi-empirical appearance. These lumped models are mainly used in rainfall-runoff modelling (Mango, 2010).

Theoretically, distributed hydrological models are supposed to describe flow processes in each and every point inside a catchment. Difficulties in the general and conceptual frame work coupled with time and memory consuming programs make these models practically impossible to use. Simpler models instead try to estimate the different flow patterns discretized into nodes with orthographic spacing and these node scan be seen as center points in square shaped areas known as pixels or cells. Models based on this type of cell structure are directly compatible with remotely sensed and grid (raster) GIS data. In terms of vertical extent, each cell may be given a depth, or be discretized into a number of overlaying cells (a column). For each cell the water discharge to neighboring cells is calculated according to the active hydrological processes. The flow distribution inside the catchment is mapped and even if the processes are estimated as a continuum, the stored results are discretized into cells (Mango, 2010).

Distributed hydrological modeling is advantageous in terms of studying effects of land use changes because its distributed nature enables the simulation and estimation of spatial variations, characteristics and changes inside a catchment. It not only provides a single outlet discharge, but multiple outputs on a temporally and spatially distributed basis. The disadvantages with the distributed type of modeling are the large amount of data and the heavy computational requirements also a large number of parameters and variables that have to be evaluated. The effect of scale choice (cell size) is also an uncertainty. A stochastic model makes use of random elements drawn from statistically possible distributions meaning the simulations will yield different results when repeated with the same input data. With most stochastic models, the common approach is to conduct several simulations (the Monte Carlo technique) and produce average estimates with specified confidence intervals (Beven and Moore, 1993).

With the incorporation of computers and high quality spatial data, interest has shifted from lumped models toward spatially distributed models, where water movement within a drainage basin can be simulated. Spatially distributed hydrological modeling can be applied to movement of pollutants, simulation of nutrient leakage in agricultural lands, impact of vegetation and land use change on hydrological regimes and lastly, the impact of land surface (e.g. agriculture and forestry) management practices on hydrological regimes (Mango, 2010).

2.1.3 Description and Support of MIKE BASIN Model

There are a number of models that can be used to model catchments characteristics, the commonly used on is the Soil and Water Assessment Tool (SWAT) and MIKE Basin. SWAT is a public domain hydrologic model, developed by USDA Agricultural Research Service. It is a semi-empirical and semi-physical model. It has been used as a practical model to predict the effect of agricultural management decisions on water and sediment yields for large un-gauged rural watersheds. Moreover, SWAT is an advanced lumped model or a semi-distributed model (Mango, 2010).

MIKE BASIN is professional engineering software package and a powerful modeling tool developed by Danish Hydrologic Institute, DHI, for integrated river basin planning and management. It accommodates a basin wide representation of water availability, sector water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints (DHI, 2003).

The software package is particular useful allowing conclusions originating from studies of individual aspects to be brought together in a framework capable of undertaking an integrated analysis. It can assist decision makers in identifying a sustainable development of scarce water resources for competing uses, taking into account specified priorities, rural and urban characteristics, and socio-economic constraints.

MIKE BASIN 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.

Mike Basin couples the power of ArcGIS (either ArcView, ArcEditor or ArcInfo) with comprehensive hydrological modeling to provide basin-scale solutions. The Mike Basin philosophy is to keep modeling simple and intuitive, yet provide in-depth insight for planning and management.

It is structured as a river network model in which the river systems are represented by a network consisting of branches and nodes. Branches represent individual stream sections while the nodes represent confluences, locations where certain water activities may occur, or important locations where model results are required, figure 2.1.

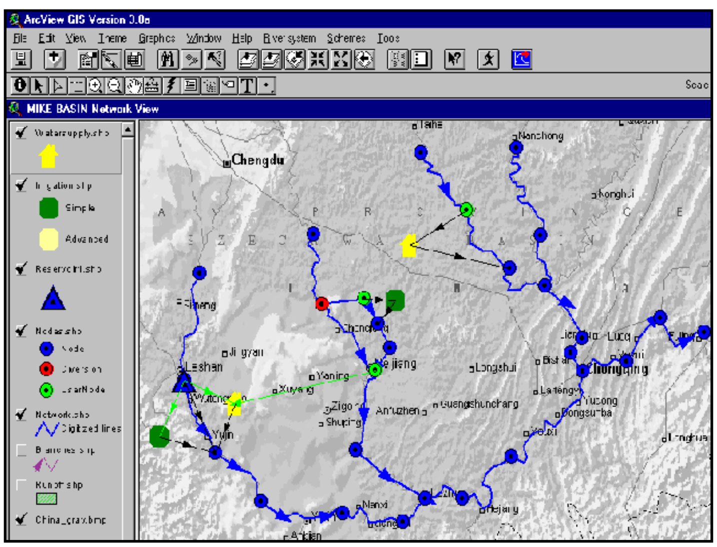

Figure 2-1 MIKE BASIN Model Window Representation (DHI, 2003)

Model results comprise information on the performance of individual reservoirs and demand schemes as well as the conditions in any part of the river system.

Typical areas of the Mike Basin application are:

1. Water availability analysis: conjunctive surface and groundwater use, optimization thereof.
2. Infrastructure planning: irrigation potential, reservoir performance, water supply capacity, waste water treatment requirements.
3. Analysis of multisectoral demands: domestic, industry, agriculture, hydropower, navigation, recreation, ecological, finding equitable trade-offs.
4. Ecosystem studies: water quality, minimum discharge requirements, sustainable yield, effects of global change. Regulation: water rights, priorities, water quality compliance.

The following elements can be given as input to Mike Basin:

1. Rivers represented by river reaches and nodes
2. Catchment area represented by an area
3. Reservoirs of 3 different types: lakes, rule curve reservoirs and allocation pool reservoirs
4. Water users, including irrigation, represents any user that abstract, consumes and returns surface and/or groundwater.
5. Hydrological information

Calibration of the model is based on observed discharge (DHI, 2003).

MIKE BASIN has been chosen for modeling MRB catchments. The following criteria was used;

1. Ability to use remotely sensed land use and land cover information
2. Ability to use spatially distributed hydro-meteorological data
3. Ability to represent in a reasonable way surface and sub-surface interaction
4. User-friendliness in set-up and implementation
5. Not too demanding in terms of input data

NAM model and MIKE basin has been used in Kenya to model stream flows of rivers and allocation assessments in Ewaso Ngiro basin (Burguret, Naromoru, etc) Lake Victoria Basin and Upper Tana rives through Water Resources Management Authority (WRMA) by DHI in collaboration with Rural Focus ltd. Not all reports on these studies have been published but the technical reports are available at WRMA offices. The most recent study was modeling stream flows of river Burguret, Naromoru, Kibos, Awach Nyang'ori, Ontulili, Likii, Demba and river Tana Sagana as impacted by climate change (DHI 2013). The WRMA has adopted the use of MIKE basin for doing hydrological studies in Kenya.

2.1.4 Rainfall Runoff Model (NAM Model) in MIKE BASIN

DHI's Nedbør-Afrstrømnings-Model (NAM) is a lumped conceptual model for simulating stream flow based on precipitation at a catchment scale. Since its creation in 1973, NAM has been used worldwide in a variety of climatic and hydrologic settings to simulate runoff from precipitation events. The model can be used independently, dynamically with MIKE 11, or to develop input time series for MIKE BASIN catchment nodes. NAM is a rainfall-runoff model that operates by continuously accounting for the moisture content in three different and mutually interrelated storages that represent overland flow, interflow, and base flow (DHI, 2003). As NAM is a lumped model, it treats each sub-catchment as one unit, therefore the parameters and variables considered represent average values for the entire sub-catchments. Water use associated with irrigation or groundwater pumping can also be accounted for in NAM. The result is a continuous time series of the runoff from the catchment throughout the modeling period. Thus, the NAM model provides both peak and base flow conditions that account for antecedent soil moisture conditions over the modeled time period. Basic data requirements for the NAM model include catchment area, initial conditions, and concurrent time series of precipitation, potential evapotranspiration (ET), and stream discharge.

Calibration of the NAM model involves adjusting the coefficients for the exchange of water between storage units and the storage unit depth so that simulated and observed discharges match as best as possible. A minimum of 3 years including periods of above-average precipitation is recommended for calibration, with longer periods resulting in a more reliable model. Disparity between simulated and observed discharge arise due to quality of time series data or other attributes. Catchment inflows can be simulated using the rainfall-runoff model, NAM. The NAM model is a lumped, conceptual rainfall-runoff model which simulates overland flow, interflow and base flow as a function of the moisture content in each of four mutually interrelated storages: snow storage, surface storage, root zone storage, and groundwater storage. Given rainfall and evaporation data, NAM calculates a runoff time series that can then be assigned to MIKE BASIN for use in the river flow simulation. For individual reservoirs, the performance of specified operating policies using associated operating rule curves can be simulated.

Rule curves define the desired storage volumes, water levels and releases at any time as a function of existing water level, the time of the year, demand for water and possibly expected inflows. For periods of drought, release from reservoirs can be reduced a certain factor for each of several critical (also termed reduction) water levels. Evaporation from the reservoir, precipitation into it, and leakage losses from it are accounted for given a height - volume - area table. Two types of reservoirs, and natural lakes, can be modeled. The standard reservoir has a physical storage that all users are drawing water from a common storage and operation rules for each user applies to the same storage. The allocation pool reservoir also has a physical storage, but the individual users have been allocated a certain storage right ("water banking"). An accounting procedure keeps track of the actual water storage in one pool for downstream minimum flow releases (water quality pool) and in the individual pools allocated for water supply users. Lakes have no operation rules, but a water level-dependent outflow.

Basic model inputs are time series data for catchment run-off, diversion, and allocation of water for the off-river nodes. Catchment runoff can be specific runoff data (from the RR Module or user defined) or gage data. Diversion nodes require either a time series of water allocation to each branch or an equation partitioning flow to each branch based on incoming flows to the diversion node. Irrigation nodes require time series data for demand, fraction of the demand satisfied by ground water, fraction of the demand returning to the river branch, and lag time for the return fraction to re-enter the stream. Water demand can be specified directly from an input time series or indirectly from agricultural use information. Once the water usage has been defined, the model simulates the performance of the overall system by applying a water mass balance method at every node. The simulation takes into account the water allocation to multiple usages from individual extraction points throughout the system. Results from the model can be viewed as:

- A time series or monthly summary in graphic or tabular form.
- A map of visualized groups of results for the entire or any specified part of the model network in the ArcMap Graphical User Interface (GUI). Map views can be stepped through time to generate animation files. The GUI can help create graduated color result presentations for many combinations of results. Several result groups can be animated simultaneously (e.g. flow in the main stem of the stream and extractions by users). Animations can be saved as a Windows movie (*.avi file) and imported into PowerPoint presentations.
- Model results are stored in a database that can be queried using Microsoft Access. The user can create programs in Microsoft Access to automatically generate reports to display results.

2.2 Water Allocation Planning

As water scarcity has increased globally, water allocation plans and agreements have taken on increasing significance in resolving international, region and local conflicts access to water. While objectives and approaches have evolved over time, ultimately water resources allocation has fundamentally remained the process of determining how much water is available for human use and how that water should be shared between competing regions and users. Challenges that have led to evolution over in water allocation planning over the centuries include; growth in water abstractions; basin ‘closure’ and the lack of availability of more sites for water infrastructure; growth and change i the economy, leading to a wider variety of water users with different water demands; the decline of freshwater ecosystems and the loss of river functions; climate change (Speed *et. al.*2013).

Approaches to water allocations are often founded on complex rules for dealing with variability, and for balancing the environmental, social, political and economic implications of different water allocation scenarios. Modern water allocation scenarios may be based on scenarios projecting how water use may respond to climate change, shifting economies, water pricing incentives and options to share the benefits of water use rather than on sharing the water itself. These approaches may be typified by; A better balance between rights to take water and protection of the environment; Sophisticated, risk-based environmental flow assessments; A better understanding of the value of water and the demands of water users; Greater flexibility in the way water is allocated. This study focuses on the balance between abstractions and protection of the environment.

2.2.1 Water Allocation Process

The water allocation process may involve allocating water at a variety of administrative and geographic levels, including at a national, basin, sub-basin or regional level. Water allocation planning involves consideration of the total water resources available within a basin. This might include both surface and groundwater supplies as well as water from inter-basin transfers. The amount of water available for allocation will be a function of this total volume, less; water that cannot in practice be used (for example, water that cannot be stored or used and passes during uncontrolled flooding) water retained in the river system to meet ecological needs (i.e. environmental flows). Water allocation plan may involve assessment of water available for allocation, existing water use and possible future demand and environmental water requirements. Figure 2.2 shows the water allocation planning. In this study the environmental water requirements have been used as the preferred indicator for basis of assessment of allocation.

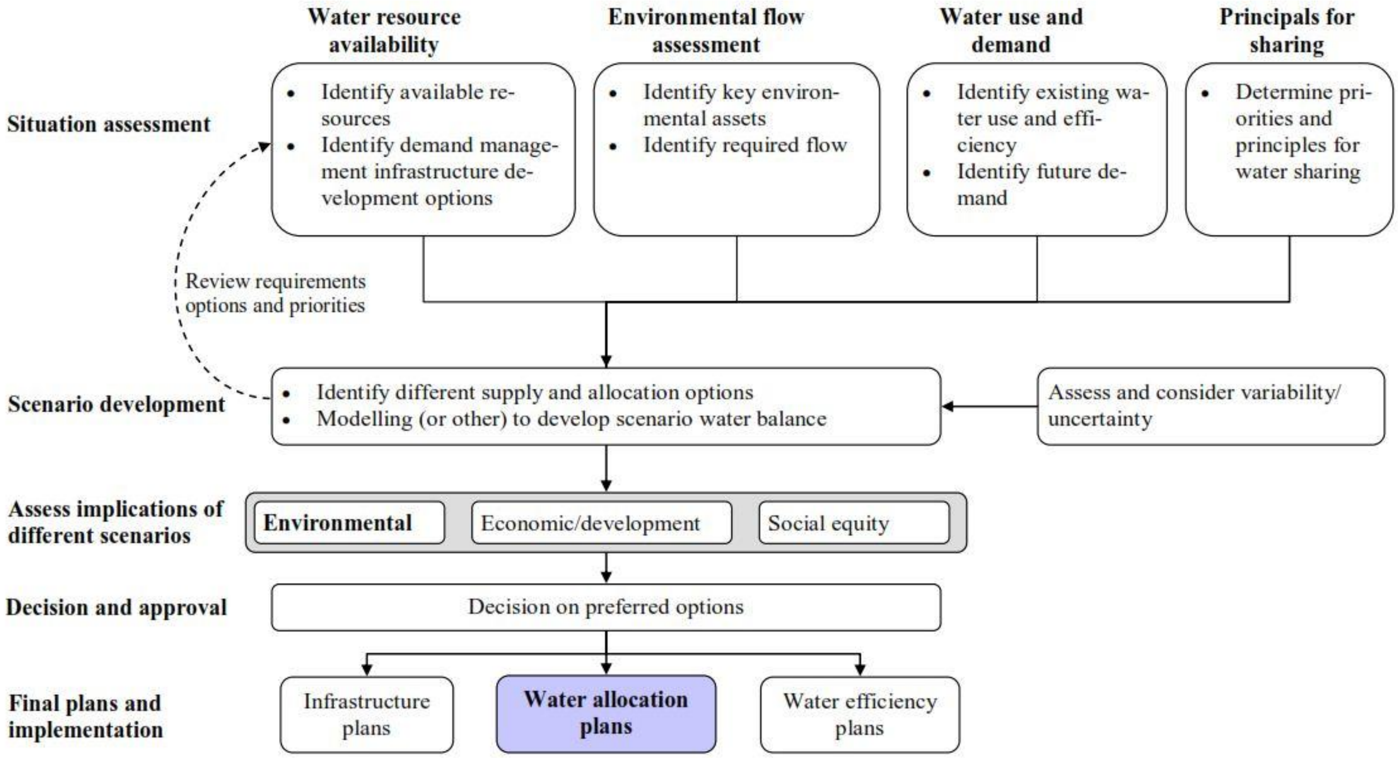

Figure 2-2 Water allocation planning process

Water allocation planning is typically undertaken to achieve a series of overarching policy objectives, i.e. equitable distribution of the limited resource, environmental protection; development priorities; balancing supply and demand and promoting the efficient use of water (Speed *et. al.* 2013).

2.3 Flow Duration Curves and Low Flows

A flow duration curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equalled or exceeded. FDC may be constructed using different time resolutions of stream flow data: annual, monthly or daily. FDCs constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river (Searcy, 1959). FDCs may be calculated: (i) on the basis of the whole available record period ('period of record FDC' (Vogel and Fennessey, 1994)), or 'long-term average annual FDCs' (FREND, 1989; Smakhtin *et al*., 1997); (ii) on the basis of all similar calendar months from the whole record period (e.g. all Januaries—'long-term average monthly FDC' (Smakhtin *et al*., 1997) or FDC of a monthly 'window' (Mngodo, 1997)). FDCs may also be constructed using all similar seasons from the whole record period (long-term average seasonal FDCs (Smakhtin *et al*., 1997)), for a particular season (e.g. summer 1992) or a particular month (e.g. January 1990).

Hughes et al., (1997) developed an operating rule model which is based on FDCs and is designed to convert the original tabulated values of estimated ecological instream flow requirements for each calendar month into a time series of daily reservoir releases. FDCs are used in abstraction licensing (Pirt and Simpson, 1983; Gustard *et al*., 1992; DWAF, 1995; Mhango and Joy, 1998), in water quality studies, e.g. to indicate the percentage of time that various levels of water pollution will occur after the introduction of a pollutant of a given volume and strength into a stream (so long as there exists an adequate correlation between the quality characteristics and discharge).

Low flow conditions in rivers and streams are of fundamental importance to the ecological status of the watercourse. Any change in the seasonal pattern of flows, for example due to exploitation of a groundwater source or abstraction of water from the river, may lead to irreversible changes to the stream ecology. Low flow analysis is also important when considering the construction of works in rivers and streams (for example, a weir), and for river restoration schemes for which an understanding of hydrological variation is important in determining appropriate restoration works. FDCs are used mainly in relation to the setting of environmental flow objectives. Environmental flow is defined as the flow that is necessary to ensure the existence of habitats in a river. Environmental flows may comprise elements from the full range of flow conditions which describe long term average flows, variability of flows including low flows and irregular flooding events (Sean, 2007). The Q95 flow (the flow exceeded 95% of the time according to the FDC) has been used historically in the UK to represent the low flow in a river. Abstraction conditions have sometimes been set to protect this flow; for example, abstraction is permitted provided the flow is greater than the Q95 (Lamb *et. al.,* 2009). In this study, monthly Q95 values were used as the environmental flow requirements.

2.4 Naturalisation, Confidence and Uncertainty

Few rivers have a wholly natural flow regime, unaffected by human activity. Naturalisation is the process by which the flow record is manipulated to remove those human influences that are quantifiable such as consumptive abstraction and effluent discharges. Such impacts are predominantly felt in the low to medium flow range and, while they may be often ignored for flood design, take on greater significance when evaluating mean or low flow conditions (Lamb *et. al.,* 2009).

Where there are artificial influences on river flows, the naturalised data should be used for assessing yields, low flow extremes or trends. This is to ensure that the analysis represents the flow regime of the catchment rather than the artificial influences, which could be highly variable. Results from the naturalised analysis can then be adjusted to represent artificial influences. The adjustment may be based on current data or on assumed scenarios such as increased abstractions. In this study naturalisation was done based on the correction of the flow data from the year the abstractions began, this information was obtained from the abstraction data.

There are different components of uncertainties in hydrological analyses; natural uncertainty (from the inherent variability of the climate); data uncertainty (from errors in the measurement of river flow); model structure uncertainty (from the choice of model such as the selection of a growth curve distribution function); model parameter uncertainty (from selection of parameters, for example, rating curve or rainfall-runoff model). Uncertainty is present in any hydrological design analysis, although there is little consensus about how to represent or communicate the uncertainty. Uncertainty can arise from a combination of natural randomness and 'knowledge uncertainty' which reflects imperfections in our understanding of nature or our ability to measure or model it (Lamb *et. al.,* 2009).

2.5 Abstraction Surveys and Water Allocation Framework in Kenya

The Water Resources Management Authority (WRMA) in Kenya has the mandate to develop water allocation plans for the different catchments in Kenya due to increased abstractors and conflicts in the limited water resource (WRM Rules 2007). Various abstraction surveys have been carried out in Kenya. Currently there are guidelines being developed on conducting abstraction and pollution loading surveys in Kenya. From these abstraction surveys conducted it is clear that the rate at which water users are increasing over the years is quite enormous. Many rivers have compromised the reserve flow and a great percentage of them are non-compliant to the water rights, in some catchments, the illegal abstractions due to over abstraction are more than 80% of the total abstractors in the catchments.

The WRMA in Kenya is very active in developing water allocation plans for the different catchments in Kenya due to increased abstractors and conflicts in the limited water resource. The comprehensive water allocation plans comprises of; a description of the class of resources and their resource quality objectives; an analysis of current and future water demands; allocation of the resource to the reserve and to different types of uses; measures to be taken to ensure that water use approvals remain true to the allocations; measures to be taken when resource availability is limited; a compliance plan; an enforcement plan; mechanisms for reviewing the allocation plan from time to time as the need arises (WRM Rules 2007).

According to the SCMP developed by the Mukurumudzi WRUA, there is unequal distribution of the water in MRB. This is attributed to the low flows and big abstractors, especially the sugar farms and rice growing in some parts of the catchment.

3. MATERIALS AND METHODS

3.1 Study Area

The Mukurumudzi River basin covers an area of approx 230 km^2 and is located in Kenya, approximately 50 km south of Mombasa (Kenya's principal port facility), and starts 30 km inland from the Indian Ocean. The Mukurumudzi River basin has the Mukurumudzi River, 40 km long, as the main river flowing from the Shimba Hills and draining into the Indian Ocean, figure 3.1. This river basin experiences a sub-humid climate, with 1100 mm to 1300 mm of rainfall (1959 to 2012) split between the long (April-June) and short (October-November) rains respectively. Mean annual evaporation is about 2170 mm/yr, giving an aridity index of approximately 0.55. The mean annual minimum and maximum temperature is 22.8 and 30.0^{o}C respectively. The warmest months are between November and April with mean temperatures of 26.0 to 28.0^{o}C while the cooler months have a temperature ranging between 24.0 and 26.0^{o}C. the mean daily evapotranspiration rate is at 4.4 mm/day. The Mkurumudzi River has a gauging site (RGS-3KD06) near Shimba Hills. The Mkurumudzi River typically has stable dry season base flows maintained by groundwater.

The land within the catchment is mainly used for; Subsistence farming of crops including maize, beans, cowpeas, millet and sorghum, okra, cassava; commercial mining; commercial farming of sugarcane; livestock husbandry (cattle, sheep, goats etc); tourism associated with the sea and Shimba Hills National Reserve and fishing mainly in the Indian ocean. The main economic activities in the catchment include; subsistence farming; livestock keeping; commercial fishing; sand harvesting; commercial farming of sugarcane and commercial mining.

The Mukurumudzi River basin lies astride the boundary between the coastal plain underlain by Pleistocene corals and sands and a line of low lying hills underlain by Pliocene sands. To the west, the Shimba Hills are underlain by faulted and moderately folded sandstones of Triassic age, the Mazeras sandstones. The groundwater flow in the study area is driven by gravity head from the west, either from the Pliocene sand dunes or from the Shimba Hills to their west/north west (Caswell, 1953).

The principal groundwater unit in the area is the Gongoni aquifer, which is a south-east to north-west aligned depression filled with Pliocene and Pleistocene sediments.

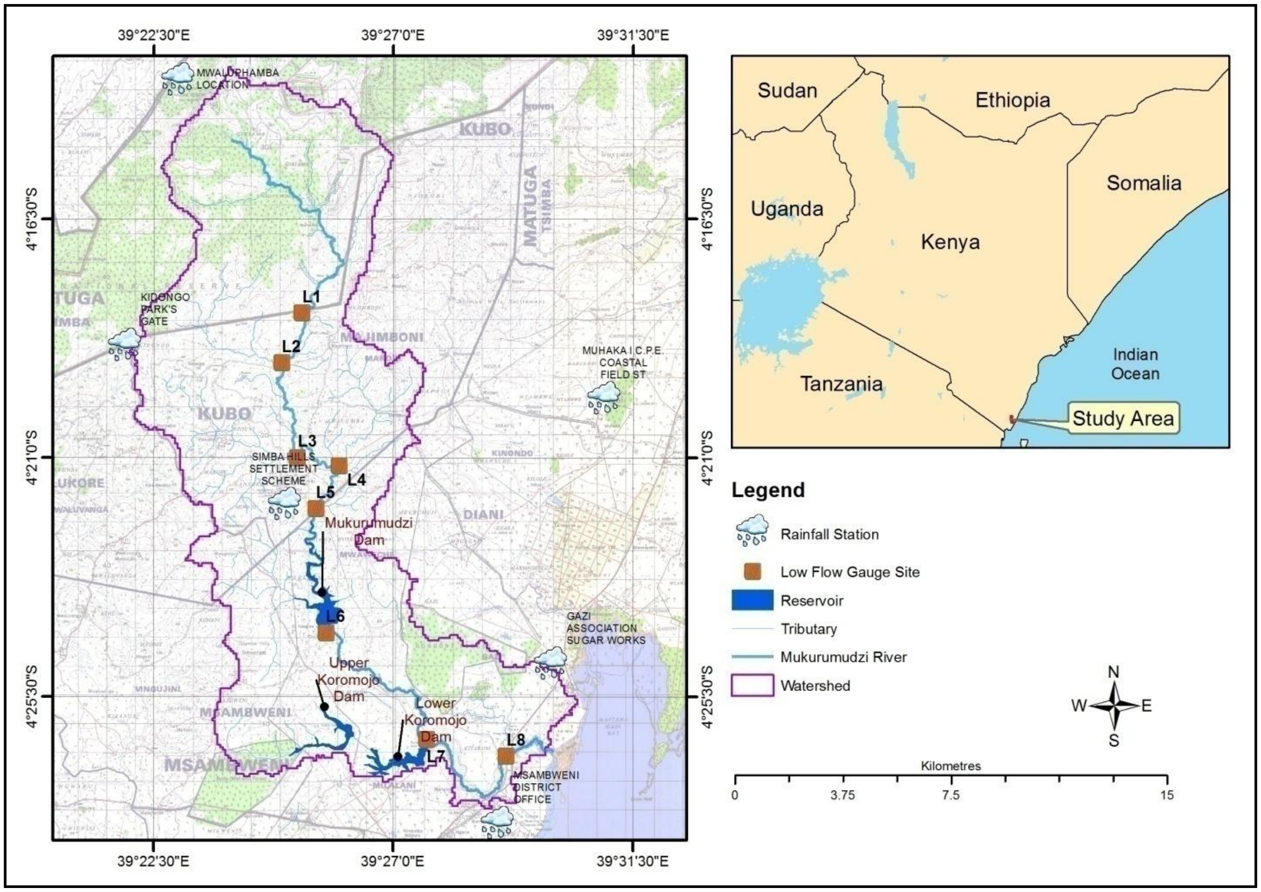

Figure 3-1 Study Area

3.2 Low Flow Survey Field Work

The low flow study gauging exercise was conducted in collaboration with WRMA and the Mkurumudzi WRUA. Eight sites were selected (L01 to L08) during a reconnaissance visit on the Mkurumudzi river. Prior to the field work consultative meetings were held with the WRUA, the County Commissioner, the Kenya Forestry Service and the Red Cross. The flow measurements were made from upstream to downstream using an Ott current meter hired from University of Nairobi, Environmental and Bio-systems Department. The mid-section (using surface velocity) method was used to calculate instantaneous discharge because the water depths were too low for 0.6 method or two point method (0.2 and 0.8).

Site L01; This site was immediately downstream of the border of the Shimba Hills National Reserve (there was one abstraction point within the reserve). This site was good for monitoring flows.

Site L02; This site was at Majimboni Centre, near a road crossing. This site was good for monitoring flows. It was easily accessible and located upstream of the existing gauging site 3KD06.

Site L03; This site was an existing gauging station for WRMA, 3KD06. Flow gauging was carried out downstream of the weir (the gauge plate was damaged at the time of the study).

Site L04; Site L04 was downstream of 3KD06 at a bridge crossing at the river NNE of Shimba Hills centre. Upstream of this site was "Odhiambo's waterfall". This site was a good site for discharge monitoring as it was easily accessible.

Site L05; This site was on a road crossing, it was approximately 300m upstream of the flood line of the Mukurumudzi dam high water mark at RL 58m. It offered a good flow gauging site for the purpose of monitoring low flows entering into the dam, and was already part of KMSP water resources monitoring network.

Site L06; Site L06 was located downstream of the Mkurumudzi dam at the Kivumiro road crossing; Flow measurement was carried out downstream of the crossing.

Site L07; This site was in the flood plain of the Mkurumudzi river near the Lower Koromojo dam and downstream of the confluence of the Mwabanda and Mkurumudzi. There was no flow coming from the Mwabanda catchment into the Mkurumudzi since there was no compensation flow released from the Lower Koromjo dam. There was a weir being constructed by KISCOL on the river Mkurumudzi near Lower Koromojo, the aim of which was to pump water from a collector box to the Lower Koromojo dam.

Site L08; This site was near the A14 road crossing of the Mkurumudzi. The area selected was good for gauging but subject to tidal effects.

There were no other suitable sites for low flow monitoring downstream of the Mkurumudzi dam other than those selected, since the topography flattens out and the river becomes boggy and over grown with vegetation.
All the sites were monitored for low flows; these sites are shown in figure 3.2.

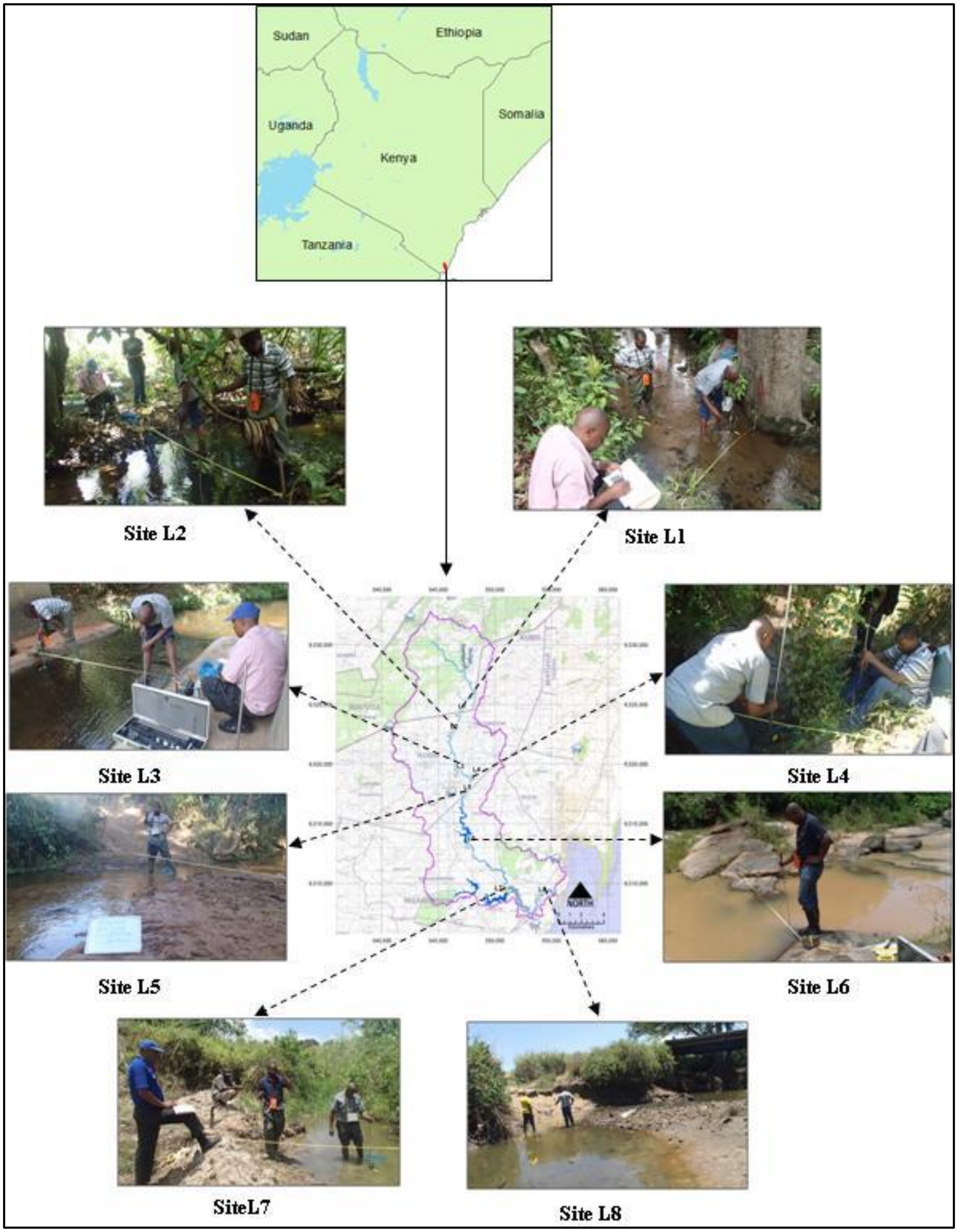

Figure 3-2 Low Flow Study Sites

3.3 Abstraction Survey Field Work

An abstraction survey was conducted during the dry season so as to document the abstractors when water demand was typically at its highest and resource availability at its lowest. The survey started from the edge of the forest where the river leaves the Shimba Hills National Reserve; it was known from the outset that there was only one abstraction point inside the Reserve, which was captured after obtaining approval from the KWS to enter the Reserve. The abstraction survey team comprised of two WRMA professionals, two members of the WRUA, a Community Liaison Officer from KMSP, two drivers and two vehicles. Since the river was narrow it was easy to survey both banks at the same time, from the source, upstream to downstream direction all the way to the mouth at Indian Ocean. The survey was conducted using questionnaires developed in consultation with WRMA, Appendix D. Every abstractor was interviewed on information regarding the point of abstraction, the purpose of abstraction, storage, permit status of the abstraction point etc among other questions. The information was used in the analysis of the abstractors to quantify the abstraction amounts, types of abstraction and permit status as well as in the water balance.

3.4 Hydrological Data Acquisition and Processing

Rainfall, stream flow, evapotranspiration and abstraction data was acquired from the Water Resources Management Authority, regional office, Machakos. The length of the stream flow data (river gauging ststion 3KD06) was from 1956 to 2011, the length of the rainfall data was from 1959 to 2013. The rainfall stations included;

1) Msambweni District Office
2) Kwale Agricultural Department
3) Gazi Association Sugar Works
4) Shimba Hills Mrere No.1
5) Shimba Hills Settlement Scheme

The evapotranspiration data was not available hence this was generated from CLIMWAT for use in the analyses. The stream flow data and the rainfall data sets had gaps. Quality analysis and quality control was undertaken to ascertain the reliability, homogeneity and consistency of the datasets, this was achieved through double mass curve analysis for both datasets.

3.5 Rainfall-Runoff Modelling Using the NAM Model

The rainfall runoff modelling was carried out with the NAM model. It is a Danish rainfall-runoff model (NAM is an abbreviation for the Danish word Nedbør-Afstrømnings model) developed in the 1970s and which is the rainfall-runoff module in the M11 software package (Nielsen and Hansen, 1973; DHI, 2011).

The NAM / M11 Rainfall Runoff (RR) model is a conceptual representation of the land phase of the hydrological cycle. The structure of the model is shown in Figure 3.3. The hydrological model simulates the rainfall-runoff processes occurring at the catchment scale. This rainfall-runoff model can either be applied independently or used to represent one or more contributing catchments that generate lateral inflows to the river network in a MIKE 11 Hydrodynamic (HD) model. In this manner it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels within the same modelling framework.

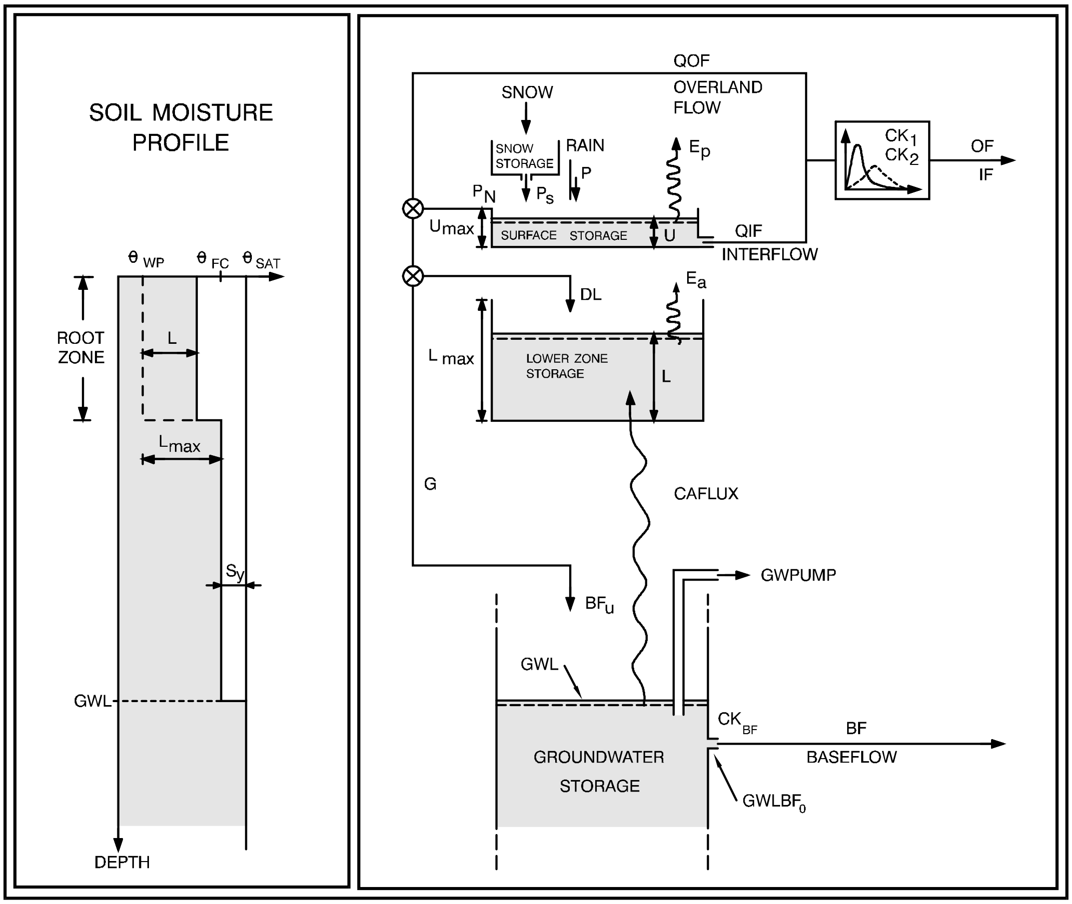

Figure 3-3 NAM/MIKE 11 RR Model Structure

Lmax = Upper limit of the amount of water in the lower zone storage
L = Moisture content in the lower zone storage;
U = Moisture content in the upper storage;
Ep = Evapotranspiration;
Ea = Rate at which water is withdrawn by root activity from the lower zone storage, when U<Ep;
L/Lmax = Relative soil moisture content of the lower zone storage;
PN = Excess water, when U>Umax;
QOF = Part of PN that contributes to overland flow, it is proportional to PN and varies linearly with the relative soil moisture content, L/Lmax, of the lower zone storage;
CQOF = Overland flow runoff coefficient (0<CQOF<1)

TOF = Threshold value for overland flow (0<TOF<1)
DL = Portion of water available for infiltration, PN-QOF;
G = Remaining amount of infiltration moisture, this percolates deeper and recharge the groundwater Storage;
QIF = Interflow contribution, it is proportional to U and varies linearly with the relative moisture content of the lower zone storage;
CKIF = Time constant for interflow;
TIF = Root zone threshold value for interflow (0<TIF<1);
OF = overland flow (mm/hour);
OFmin = Upper limit for linear routing (=0.4 mm/hour), and b =0.4, b is a constant corresponding to manning formula for modelling the overland flow;
TG = Root zone threshold value for groundwater recharge (0<TG<1);
CK = Time constant;
BF = Baseflow;

The equations are as follows;

Evapotranspiration;

$$\boldsymbol{Ea = (Ep - U)\frac{L}{Lmax}} \qquad \textbf{Equation 1}$$

Overland flow;

$$\boldsymbol{QOF} = \begin{bmatrix} \boldsymbol{CQOF\frac{\left(\frac{L}{max}-TOF\right)}{1-TOF}PN} & \boldsymbol{for\frac{L}{Lmax}} > TOF \\ \boldsymbol{0} & \boldsymbol{for\ L/Lmax \le TOF} \end{bmatrix} \qquad \textbf{Equation 2}$$

Interflow;

$$\boldsymbol{QIF} = \begin{bmatrix} \boldsymbol{CQIF^{-1}\frac{\left(\frac{L}{max}-TIF\right)}{1-TIF}PN} & \boldsymbol{for\frac{L}{Lmax}} > TIF \\ \boldsymbol{0} & \boldsymbol{for\ L/Lmax \le TIF} \end{bmatrix} \qquad \textbf{Equation 3}$$

Interflow and overland flow routing;

$$\boldsymbol{CK} = \begin{bmatrix} \boldsymbol{CK_{12}} & \boldsymbol{for\ OF < OF_{min}} \\ \boldsymbol{CK_{12}(\frac{OF}{OF_{min}})^{-\beta}} & \boldsymbol{for\ OF \ge OF_{min}} \end{bmatrix} \qquad \textbf{Equation 4}$$

The equation above ensures in practise that the routing of the real surface is kinematic, while subsurface flow being interpreted by NAM as overland flow (in catchments with no real surface flow component) is routed as linear reservoir.

Groundwater recharge;

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{(PN - QOF)\frac{\left(\frac{L}{max}-TG\right)}{1-TG}} & \boldsymbol{for\frac{L}{Lmax}} > TG \\ \boldsymbol{0} & \boldsymbol{for\ L/Lmax \le TG} \end{bmatrix} \qquad \textbf{Equation 5}$$

Soil moisture content;

$$\boldsymbol{\Delta L = PN - QOF - G} \qquad \textbf{Equation 6}$$

Table 3.1 below shows the required input data and the time-series format;

Table 3-1 Input data requirements for NAM

	Variable	**Type**	**Unit**	**TS Type**
1	Daily rainfall	Rainfall	Mm	Step Accumulated
2	Daily potential evapotranspiration	Evaporation	Mm	Step Accumulated
3	Daily discharge	Discharge	M^3/s	Instantaneous

Model Input Requirements

The basic data requirmnets for the NAM model consist of;

- Model and catchment parameters; this comprised of catchment area
- Initial conditions; this was based on the 9 parameters, these we adjusted during calibration
- Meteorological data; the basic meteorological data used was rainfall time series and evpotranspiration from 1959 to 1989.
- Streamflow data for model calibration and validation; the period of data from 1959 to 1989 was used.

The raw data discharge times series, rainfall and evapotranspiration is shown in Figures 3.4 and 3.5. The evapotranspiration (ET) was sourced from CLIMWAT. Rainfall and discharge data was sourced from WRMA. The ET data was recycled through the years from 1959.

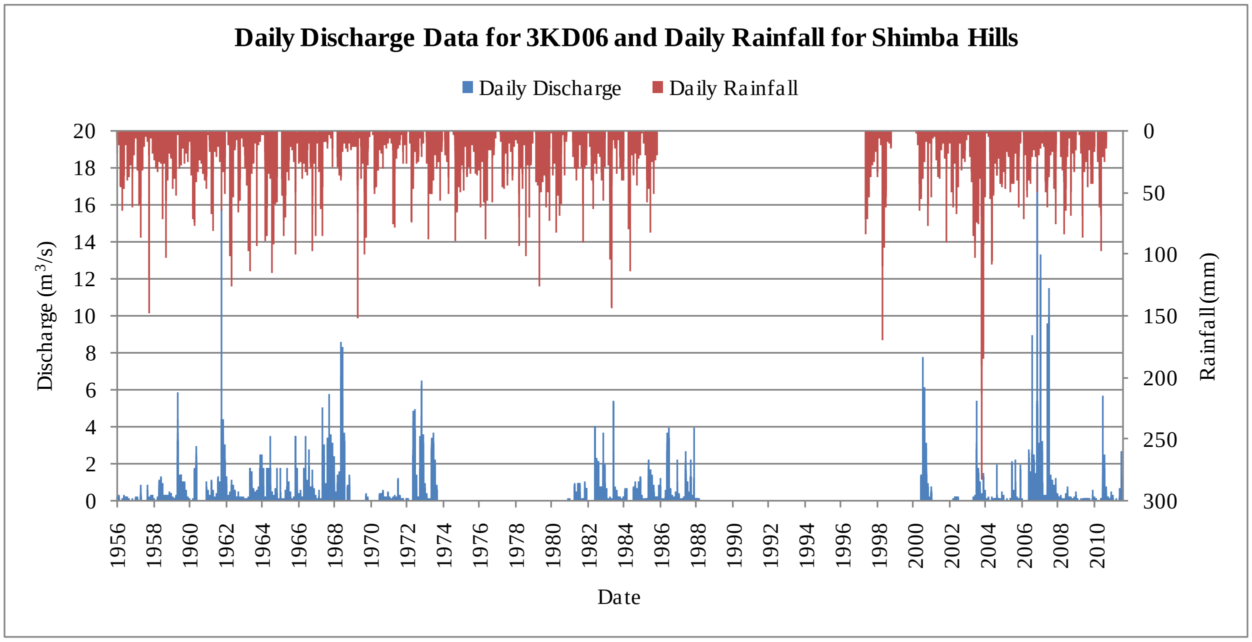

Figure 3-4 Discharge and Rainfall Time Series (Raw Data)

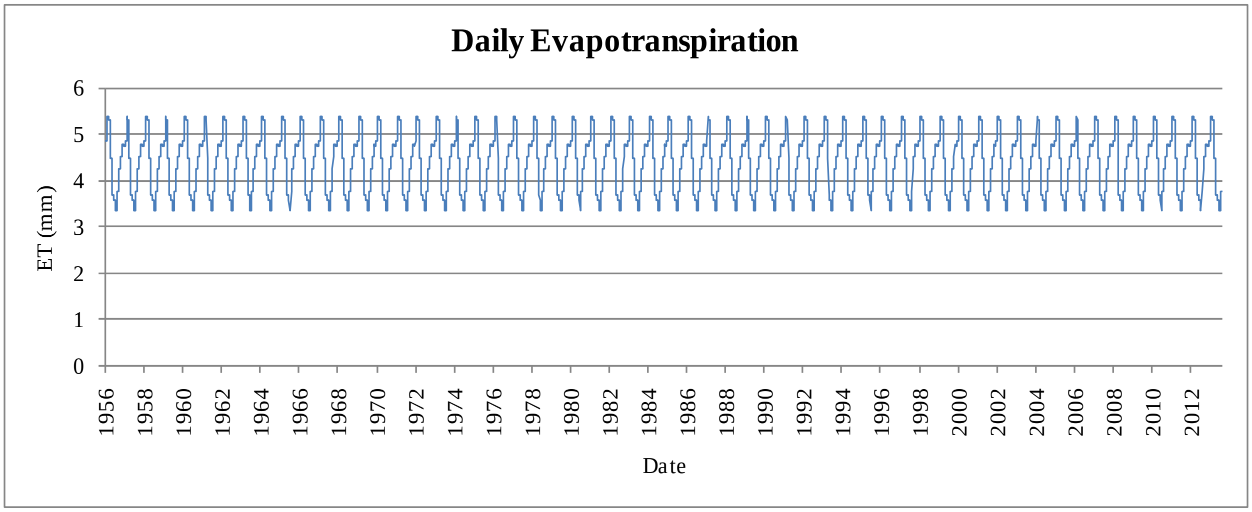

Figure 3-5 Daily Evapotranspiration

Model Outputs

Based on these meteorological inputs, NAM / MIKE 11 RR simulates catchment runoff as well as information about other elements of the land phase of the hydrological cycle, such as the temporal variation of the evapotranspiration, soil moisture content, groundwater recharge, and groundwater levels. The resulting catchment runoff was split conceptually into overland flow, interflow and base flow components figure 3.6.

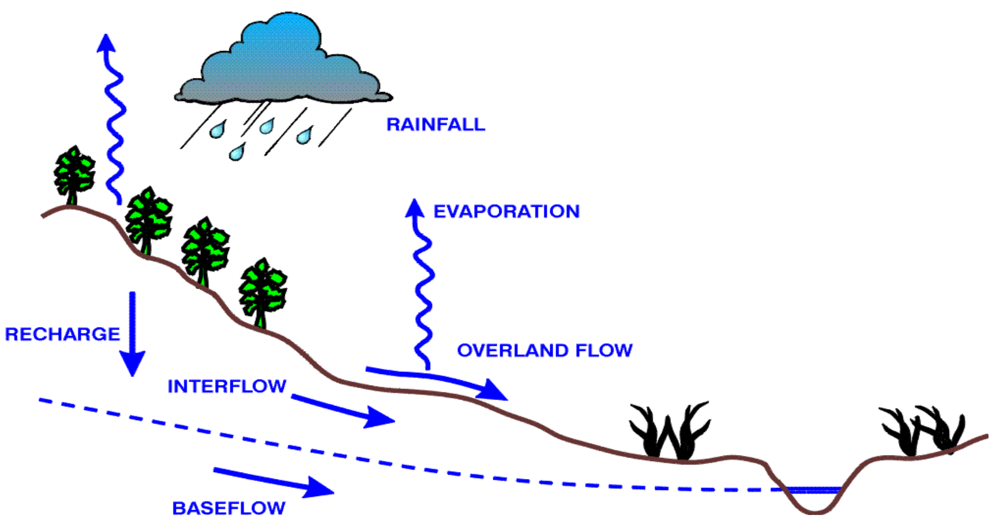

Figure 3-6 NAM Model processes

The amount of infiltrating water recharging the groundwater storage depended on the soil moisture content in the root zone. Base flow from the groundwater storage was calculated as the outflow from a linear reservoir using a time constant. The groundwater level was calculated from a continuity consideration accounting for recharge, capillary flux, net groundwater abstraction, and base flow. The inclusion of capillary flux and groundwater pumping were optional.

NAM / MIKE 11 RR simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are:

- Snow storage
- Surface storage
- Lower or root zone storage
- Groundwater storage

NAM / MIKE 11 RR allows treatment of man-made interventions in the hydrological cycle such as irrigation and groundwater pumping. In these cases, time series of irrigation and groundwater abstraction rates are required to maintain the proper water balance in the model.

The groundwater level is calculated continuously as a measure of the amount of water in the groundwater storage. This is influenced by:

- Groundwater recharge, which depends on the soil moisture in the root zone
- Base flow, which is calculated as the outflow from a linear reservoir using a time constant.
- Capillary flux to the root zone (optional)
- Groundwater abstraction (optional)

During calibration, the catchment parameters were adjusted until a good fit between the simulated flow contributions, (overland flow, interflow and base flow) and gauged stream flow was attained. The Root Mean Square Error-observations standard deviation ratio (RSR) and Nash-Sutcliffe Efficiency (NSE) was used to evaluate the simulated data. The closer the RSR is towards 0 the better the results while the closer the NSE is to unity the better the results.

Table 3.2 lists the parameters available for adjustment in calibrating the NAM / MIKE 11 RR model.

The following objectives were considered during the model calibration:

1. A good agreement between the average simulated and average observed catchment runoff, (i.e., a good water balance.)
2. A good overall agreement of the shape of the hydrograph
3. A good agreement of the peak flows with respect to timing, rate and volume
4. A good agreement for base flows

Table 3-2 Model calibration parameters

Parameter	**Description**	**Effects**
U_{max}	Maximum water content in surface storage	Overland flow, infiltration, evapotranspiration, interflow
L_{max}	Maximum water content in lower zone/root storage	Overland flow, infiltration, evapotranspiration, base flow
C_{QOF}	Overland flow coefficient	Volume of overland flow and infiltration
C_{KIF}	Interflow drainage constant	Drainage of surface storage as interflow
TOF	Overland flow threshold	Soil moisture demand that must be satisfied for overland flow to occur
TIF	Interflow threshold	Soil moisture demand that must be satisfied for

		interflow to occur
TG	Groundwater recharge threshold	Soil moisture demand that must be satisfied for groundwater recharge to occur
CK1	Timing constant for overland flow	Routing overland flow along catchment slopes and channels
CK2	Timing constant for interflow	Routing interflow along catchment slopes
CK_{BF}	Timing constant for base flow	Routing recharge through linear groundwater recharge

In the calibration process, the different calibration objectives (1)-(4) were taken into account. For a general evaluation of the calibrated model, the simulated runoff was compared with discharge measurements.

An automatic calibration module available in NAM / MIKE 11 RR, allowing calibration of the nine most important model parameters, was initially used to get a close good balance in the parameters then there after the parameters were re-adjusted till a good correlation was obtained. The auto-calibration tool was based on a simultaneous optimization of up to four different objectives, including water balance, overall hydrograph shape, peak flows and low flows. For a model calibration that included all nine parameters, a maximum number of model evaluations in the range 1000-2000 ensured an efficient calibration, and this was typically done in 30-60 CPU seconds.

3.6 MIKE Basin Model

The MIKE basin model was set up in ArcGIS 10.0 and the water users and reservoirs were digitized and their time series of abstraction rates uploaded onto them. Figure 3.7 shows the graphic user interphase of MIKE basin model. The model was run without the abstraction time series to establish the environmental water requirements at the mouth of the river, the model was then run again with all existing current abstractions to establish a time series for the mouth of the river, and this time series was then used to compute the monthly Q95 values which were compared to the EWR for the mouth of the river to assess the water balance and allocations.

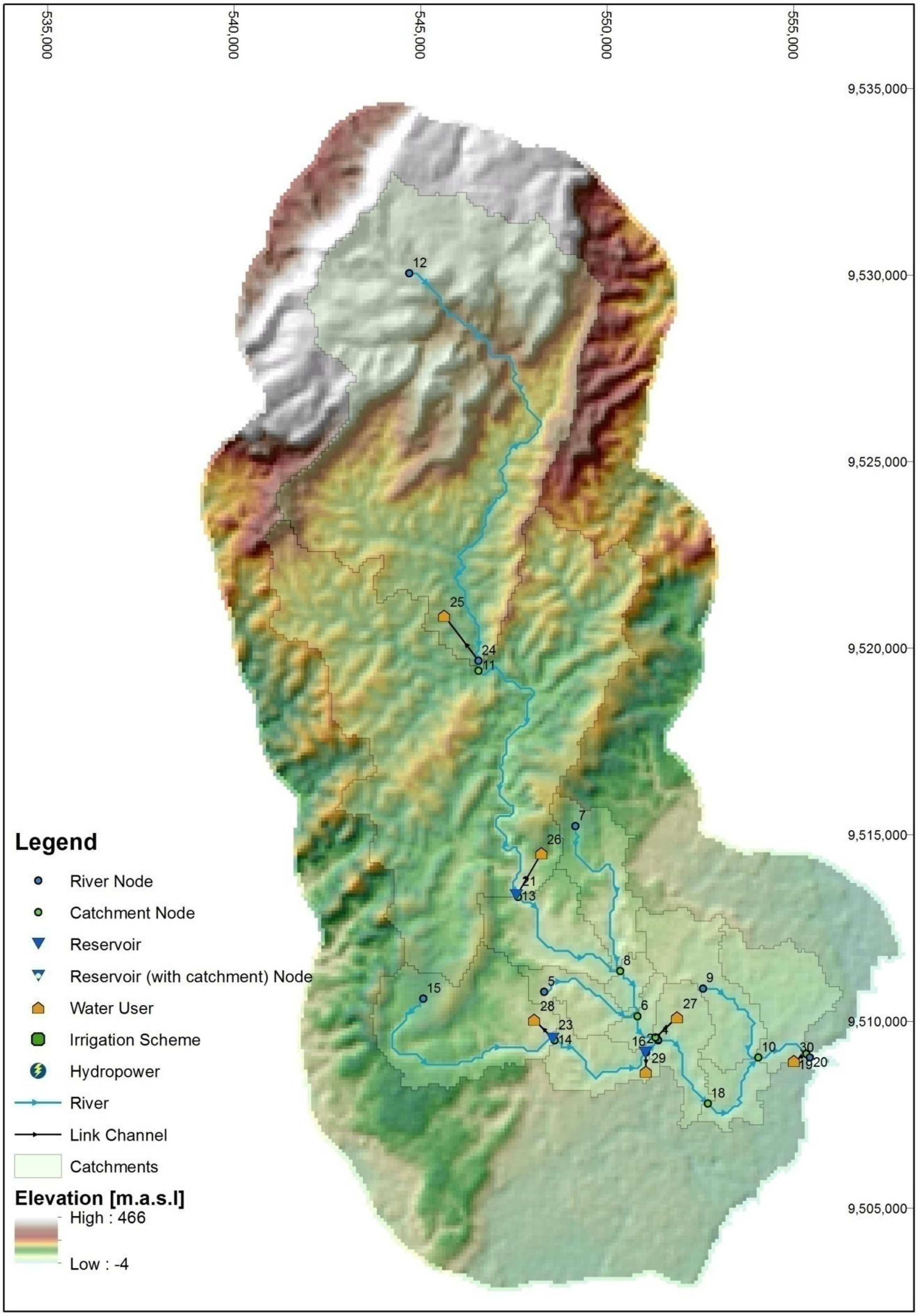

Figure 3-7 MIKE Basin GUI Model (datum: Arc1960 UTM 37S)

4. RESULTS AND DISCUSSIONS

4.1 Low Flow Assessment

4.1.1 Low Flow Study Sites

Table 4.1 shows the flows recorded at the selected sites. The sites are shown on figure 8.1 in Appendix A.

Table 4-1 Flow Measurement Results

Site ID	Easting (Datum: Arc 1960)	Northing (Datum: Arc 1960)	Gauging date	Flow Recorded [m^3/s]
L01	546781	9524244	13-03-2013	0.0276
L02	546037	9522463	13-03-2013	0.0360
L03	546593	9519224	13-03-2013	0.0219
L04	548039	9518924	13-03-2013	0.0368
L05	547236	9517449	13-03-2013	0.0317
L06	547975	9513089	14-03-2013	0.0395
L07	551076	9509437	14-03-2013	0.0360
L08	553821	9508767	15-03-2013	0.0432

4.1.2 Low Flow Discharge

Figure 4.1 shows the flow profile from upstream towards the mouth of Mkurumudzi river; the flow generally increased downstream, this shows that the catchment is sustained by base flows.

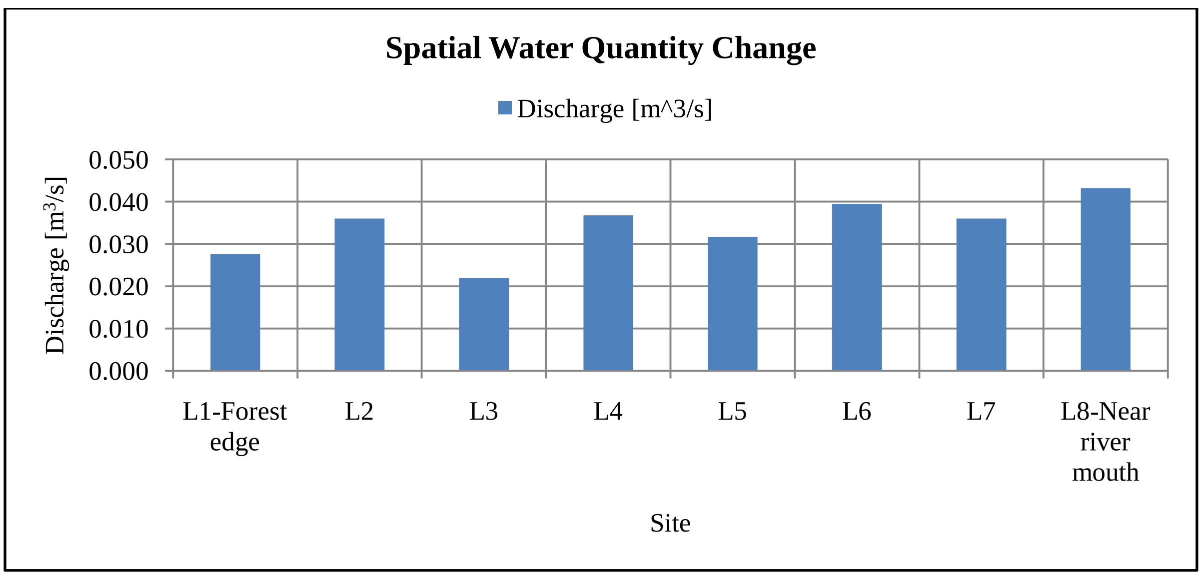

Figure 4-1: Daily Low Flow Profile from forest edge to estuary during March 2013

4.2 Abstraction Survey Results

4.2.1 Authorised Abstractions

Information on authorised and anticipated abstraction was obtained from WRMA. This data is presented in Appendix B.

A total of 18 abstraction points were identified in the entire Mkurumudzi Basin as shown in Appendix B. Six of these were dams, 3 were the main dams for use by the abstractors, the other three were future plans.

4.2.2 Type of Abstractor and Method of Abstraction

Abstractors were broadly categorized as either individuals, groups or institutions. Figure 4.2 gives the category of abstractors by percent of the total number of abstractors and Figure 4.3 by percent of the volume of total abstraction.

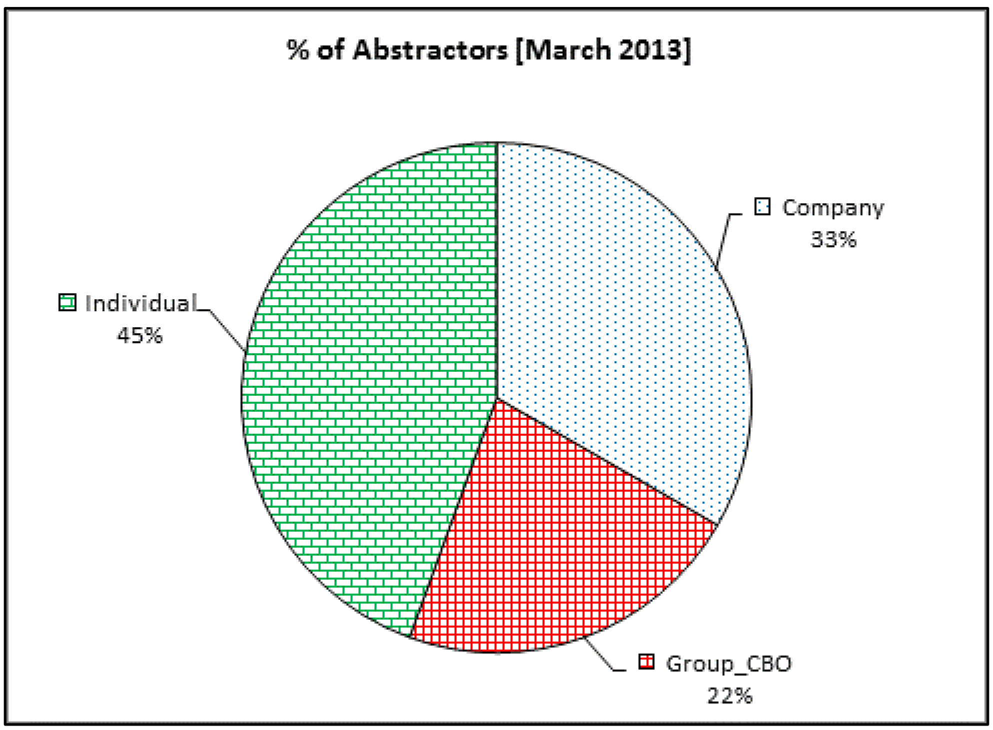

Figure 4-2: Types of Abstractor (March 2013)

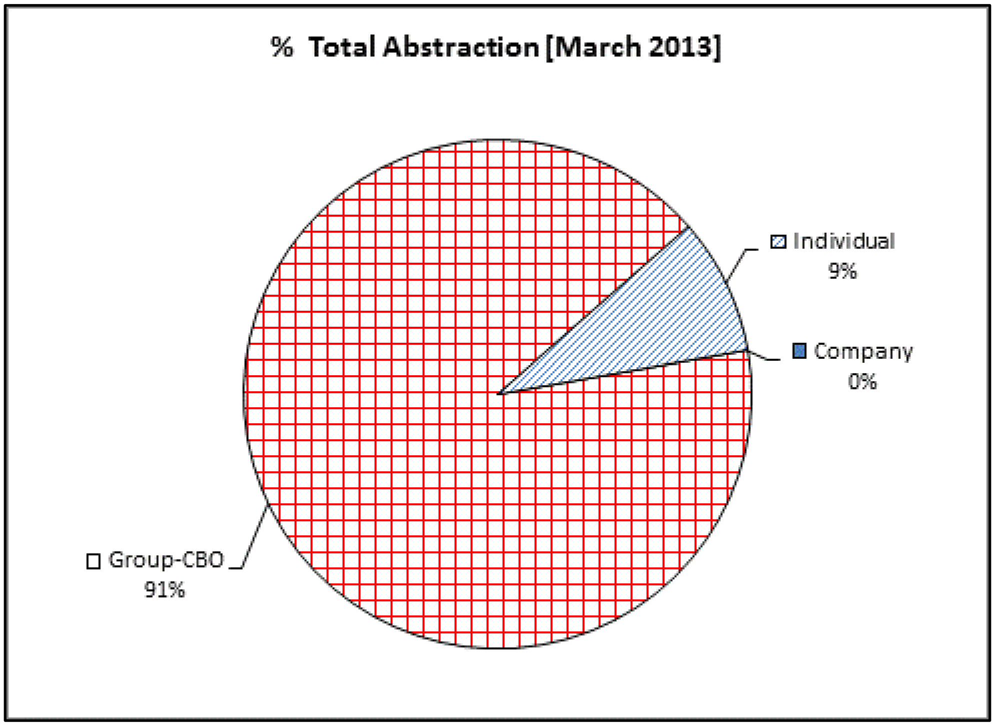

Figure 4-3: Type of abstractor by % of total volume of abstraction (March 2013)

Individual abstractors (45%) account for only 9% of the total abstraction volume and the other 91% of the total volume is as a result of 22% of the abstractors. This 22% comprises community based organisations (water projects). Companies were not abstracting at the time of the abstraction survey.

The main methods used for abstractions were categorized as portable pumps, weir and furrow, weir and fixed pump, and dam. Figure 4.4 and 4.5 shows the abstraction method used by abstractors.

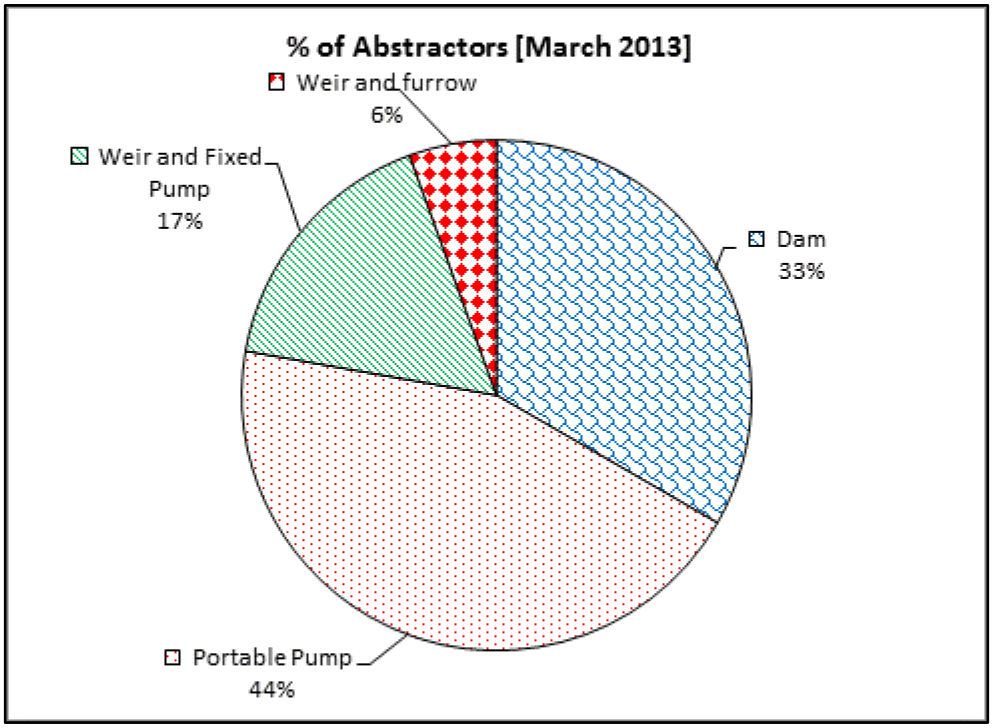

Figure 4-4: Method of abstraction (March 2013)

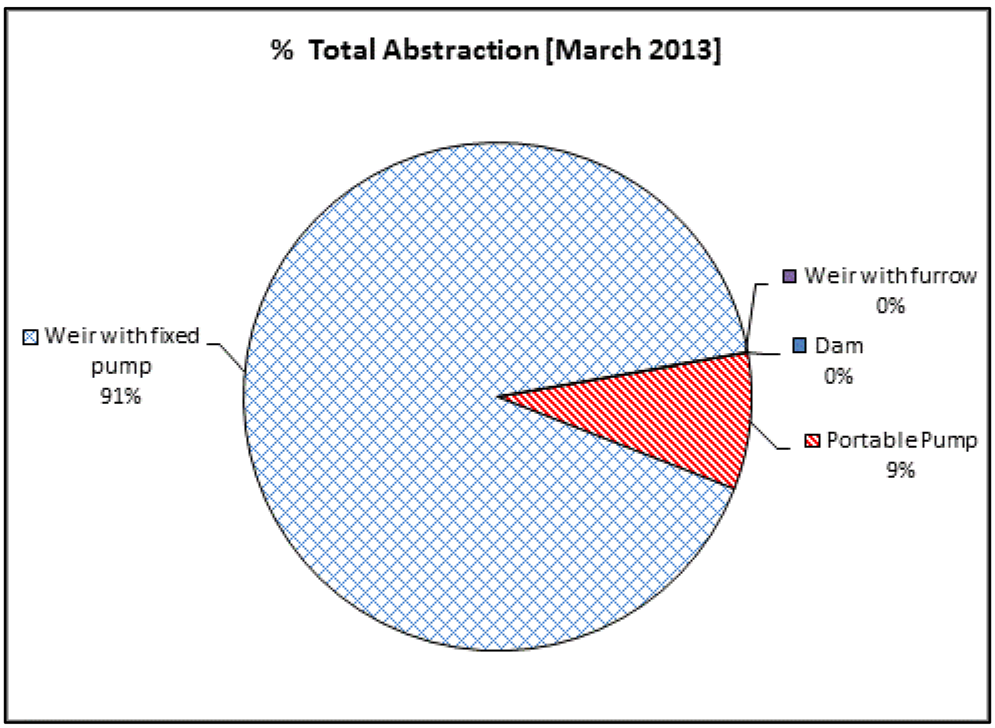

Figure 4-5: Method of abstraction by % of total volume of abstraction (March 2013)

The most prevalent method of abstraction was the use of portable pumps (44%) which accounted for only 9% of the total abstraction volume. Conversely, weirs and fixed pumps account for 17% of the abstractors and 91% of the total abstracted volume; dams and weirs with furrow were not abstracting any water at the time of abstraction survey.

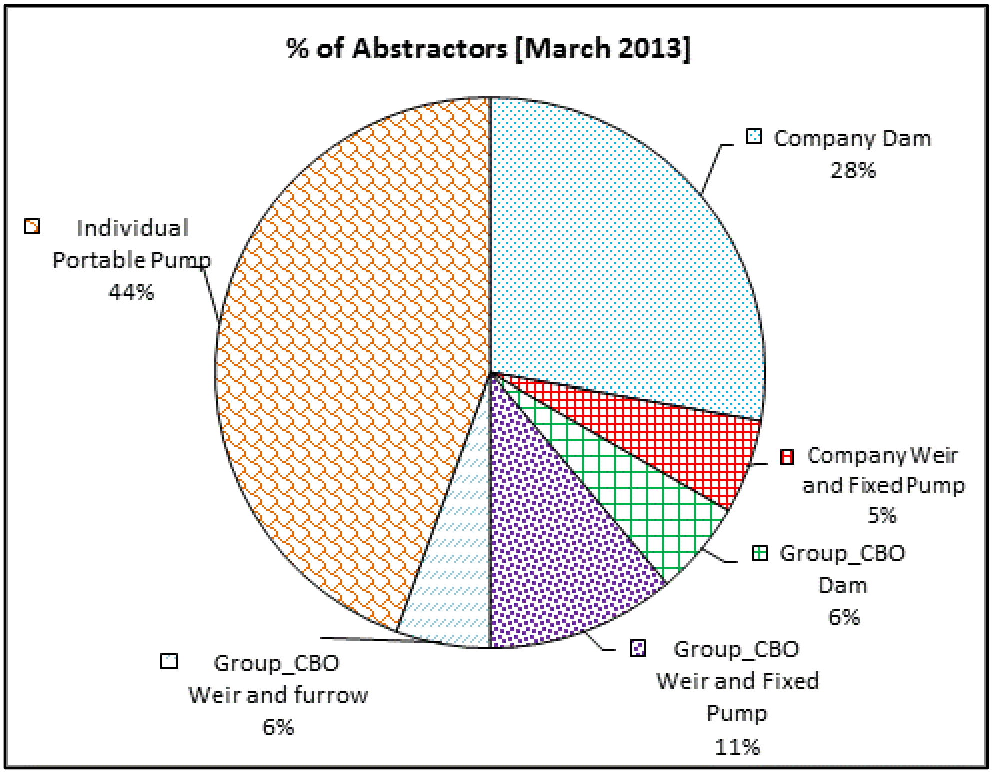

Figure 4-6: Type of abstractor and method of abstraction (March 2013)

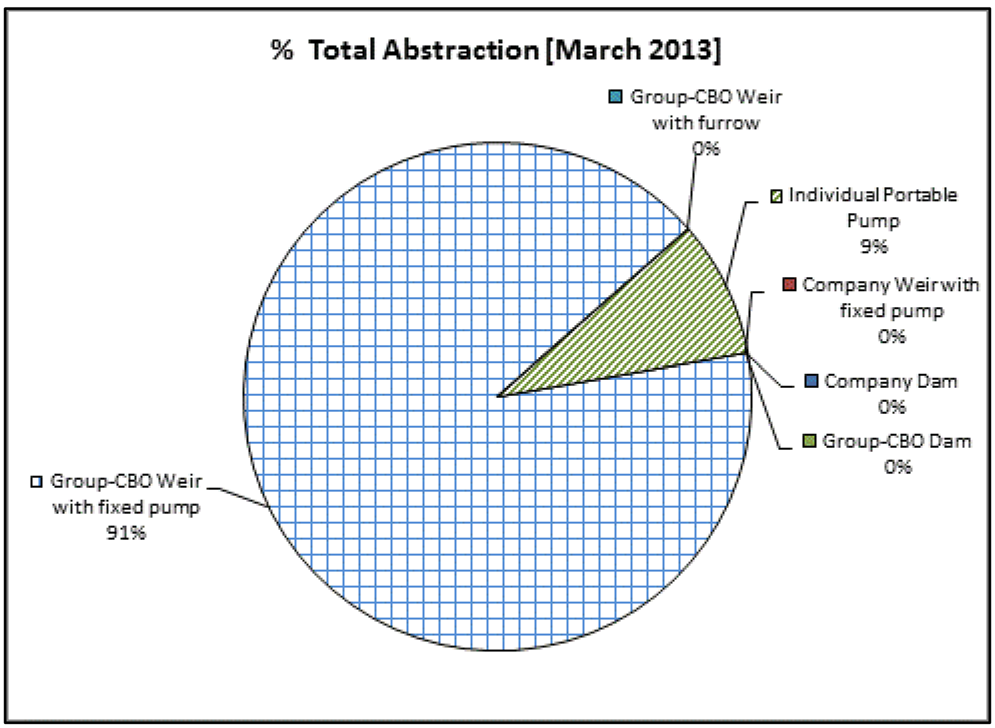

Figure 4-7 Type of abstractor and method of abstraction by % of total abstraction (March 2013)

Figure 4.7 shows that groups/CBOs accounted for 91% of the abstracted volume. In terms of defining a strategy for enforcement, these results show that WRMA should focus on companies and CBOs.

4.2.3 Permit Status

The abstractors were classified using the threshold in Table 4.2 based on the measured flows during the abstraction survey and for the abstractors who were not operational; the authorized abstraction rates were used for classification;

Table 4-2 Surface Water Threshold for Mkurumudzi Catchment

Threshold in m^3/day			
Class A	**Class B**	**Class C**	**Class D**
Up to 10	>10 to 100	>100 to 5,000	>5,000

Table 4.3 presents a list of abstractors in Mkurumudzi catchment with authorizations from WRMA and their classes;

Table 4-3 Legal Status of Abstractor

Name of Applicant	Infrastructure	Authorised Amount [m^3/d]		Legal Status	Class of Abstractor
		Flood Flow	Normal Flow		
KISCOL	Mkurumudzi Weir	30,000	-	Valid Authorisation	Class D
KISCOL	Lower Koromojo Dam	30,000	-	Valid Authorisation	Class D
KISCOL	Upper Koromojo Dam	30,000	-	Valid Authorisation	Class D
KISCOL	Kitaruni Dam	12,000	-	Valid Authorisation	Class D
KISCOL	Mkurumudzi dam	10,000	-	Valid Authorisation	Class D
KMSP	Mkurumudzi dam	22,000	2,000	Valid Authorisation	Class D

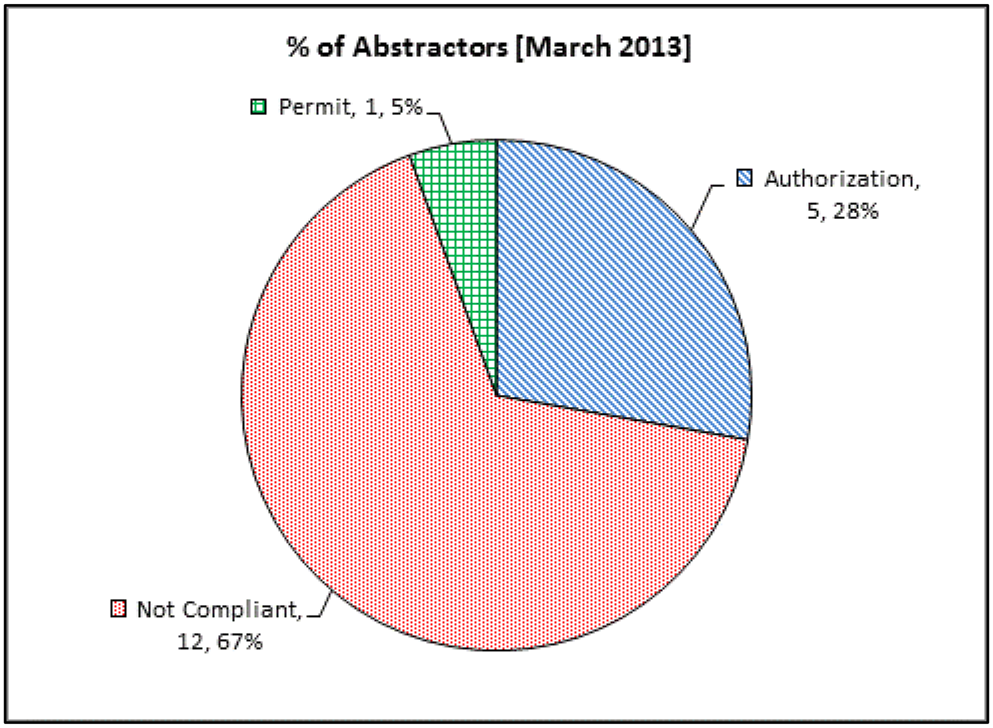

Figure 4-8: Permit status of abstractors, Number and Percent of total (March 2013)

Figure 4.8 shows that only 1 abstractor had a permit, 5 had authorizations and 12 abstractors were not compliant. The single valid permit belonged to KISCOL for the Lower Koromojo Dam. An authorization is usually issued to allow the abstractor to construct works while a permit is issued to allow the abstractor to abstract water, therefore, abstraction under an authorisation is technically against the WRM Rules 2007.

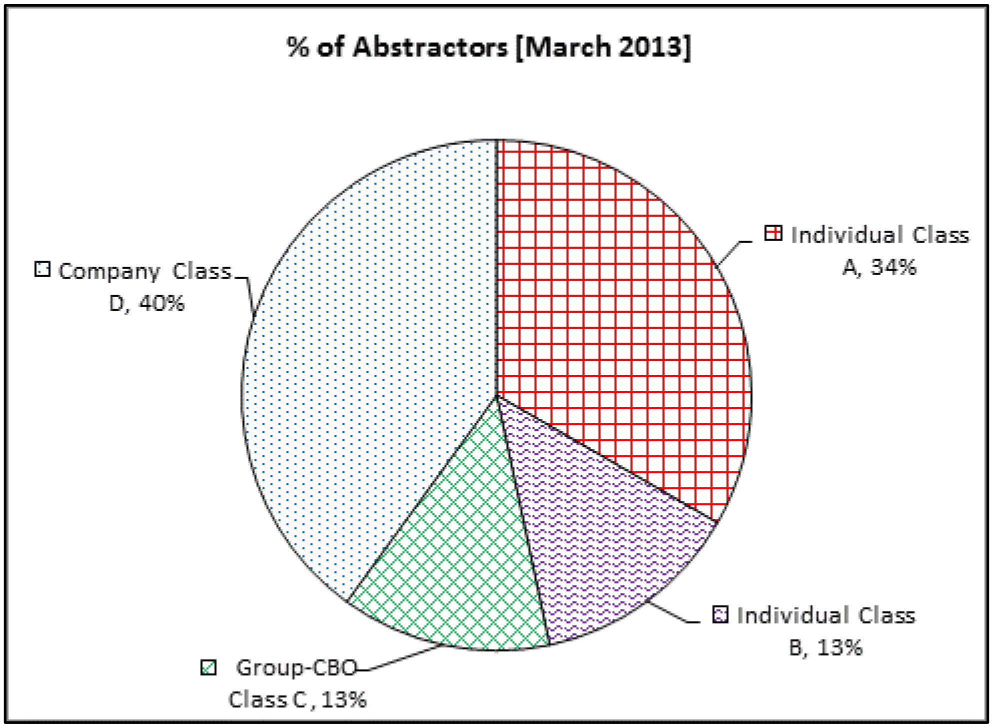

Figure 4-9: Abstractor Category and Class (March 2013)

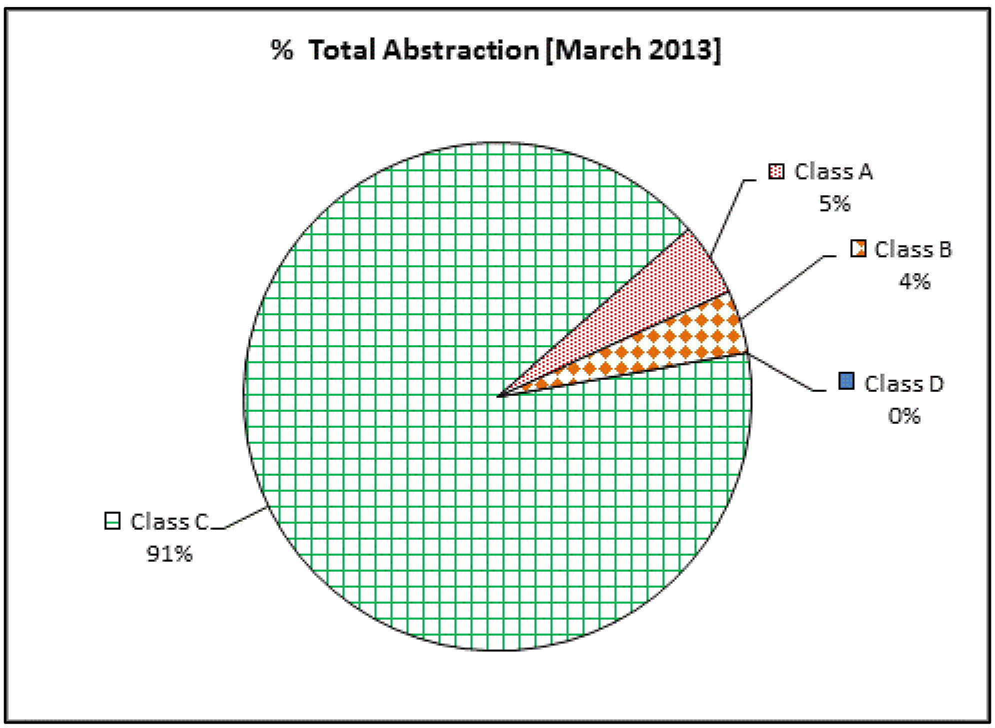

Figure 4-10: Abstraction Class by % of total Volume (March 2013)

47% of the individual abstractors were in Class A and B (figure 4.9) and they accounted for 9% of the total volume abstracted while Class C was comprised of CBO groups which accounted for 91% of the total volume abstracted, figure 4.10. Class D water uses were not abstracting any volume *yet* but they had been allocated a total of 1.2 m^3/s from flood flows and 0.023 m^3/s from normal flows.

4.3 Hydrological Analysis Results

4.3.1 Data Availability

Figure 4.11 provides a data availability chart.

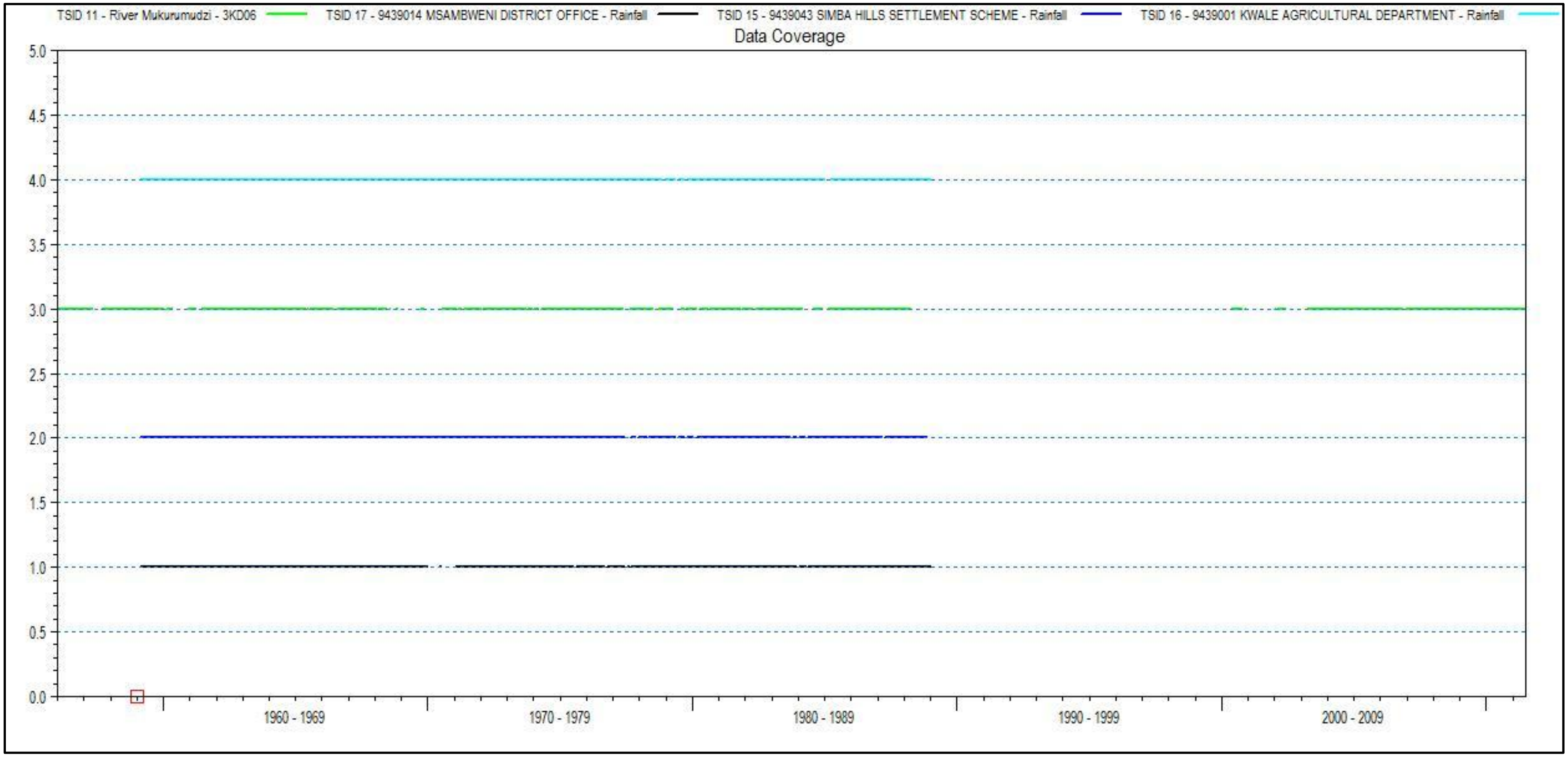

Figure 4-11: Data Coverage Chart

4.3.2 Data Reliability

A double mass curve was plotted for Shimba Hills Settlement Scheme versus Msambweni District office (Figure 4.12) and Kwale Agricultural Department rainfall versus Shimba Hills Settlement Scheme rainfall (Figure 4.13). The coefficient of correlation for Shimba hills rainfall vs Msambweni District office was 99.9%.

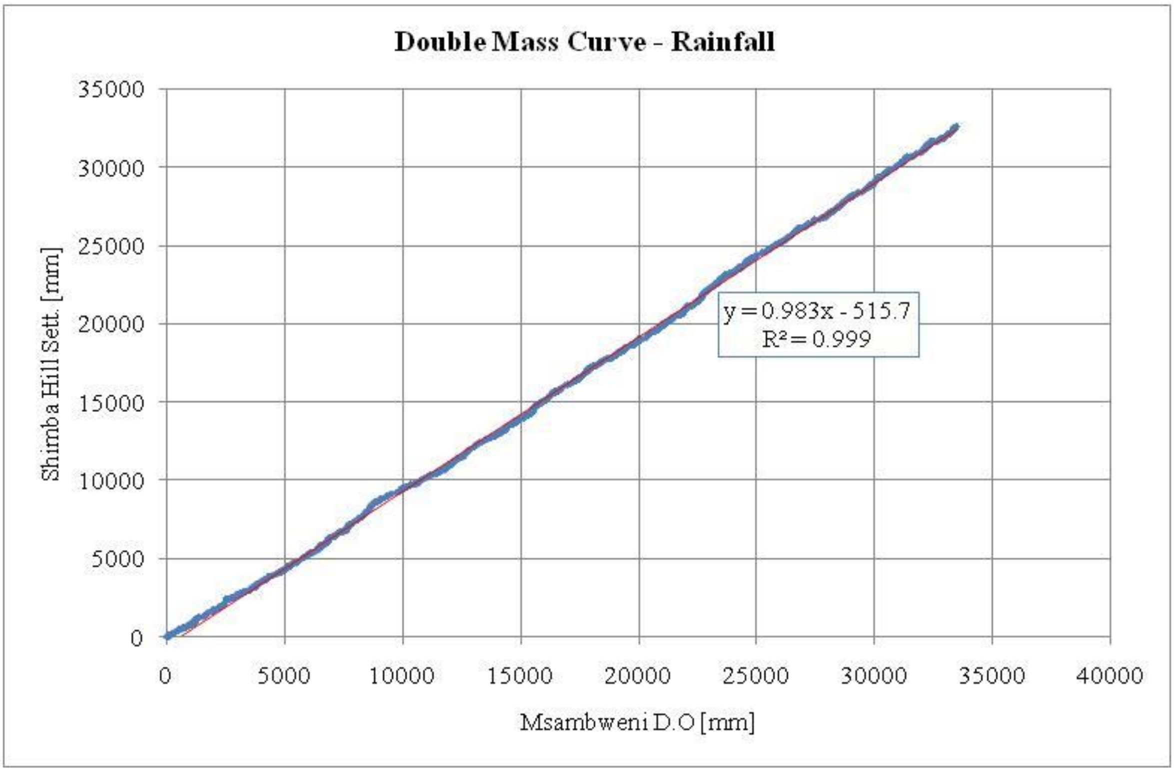

Figure 4-12: Double Mass curve (Msambweni vs. Shimba Hills)

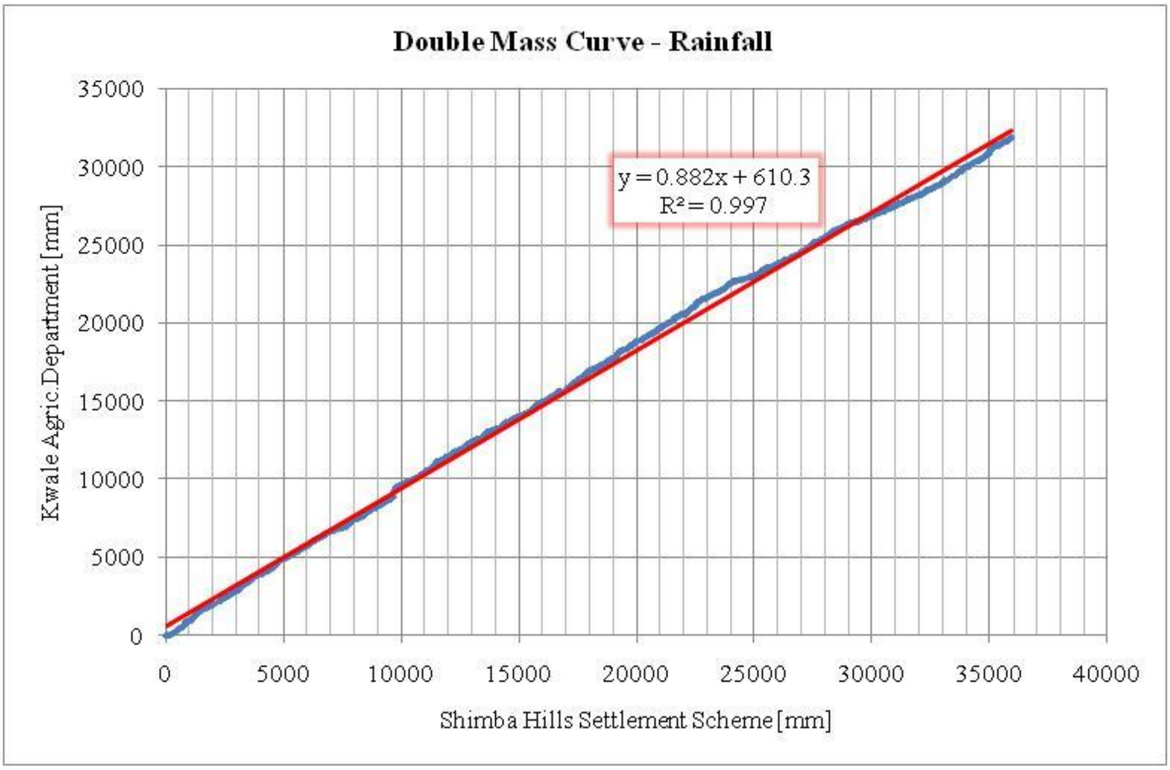

Figure 4-13: Double Mass Curve (Shimba Hills vs. Kwale Agric.)

The relationship between the Kwale Agriculture Department and Shimba Hills Settlement Scheme rainfall was fairly good with a coefficient of correlation of 99.7% although there were some slight deviations.

4.3.3 Rainfall

The mean monthly and annual rainfall for the Shimba hills rainfall station was analysed and the results showed that the Shimba hills area receives on average a total of 1204 mm of rainfall every year, figures 4.14 and 4.15 shows mean monthly rainfall and mean annual rainfall respectively for shimba hills rainfall station.

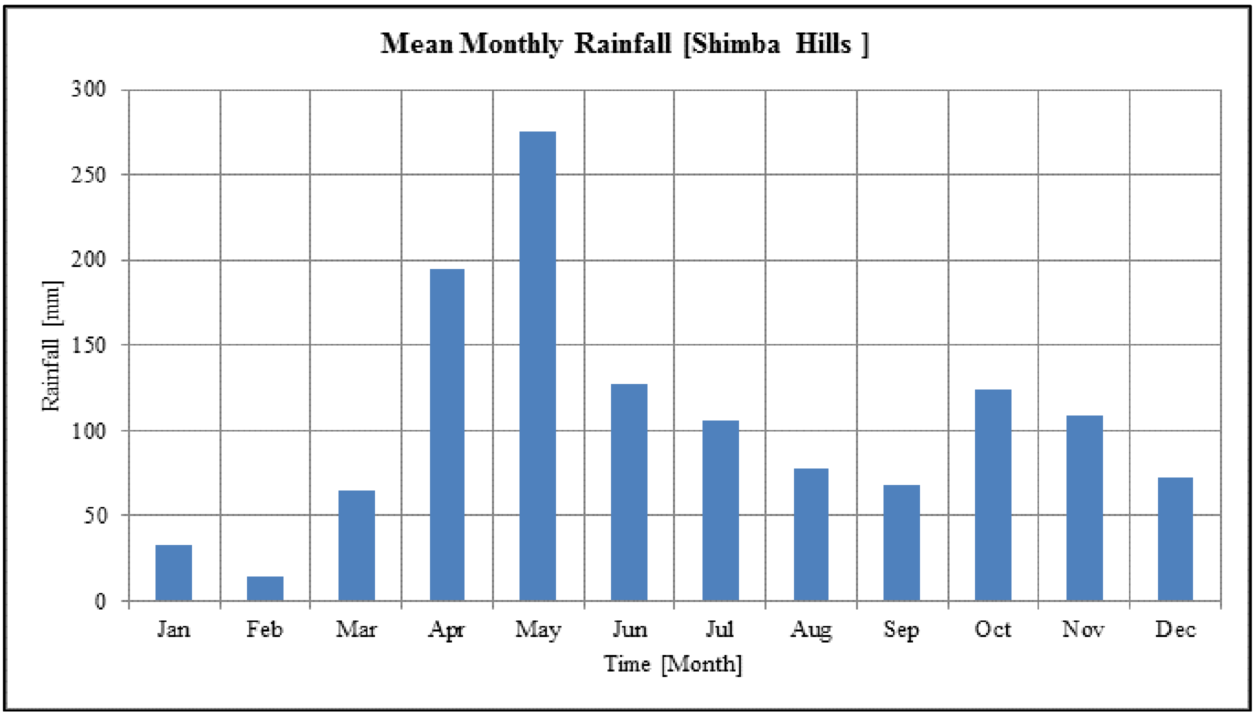

Figure 4-14: Mean Monthly Rainfall [Shimba Hills Rainfall 1959-1988]

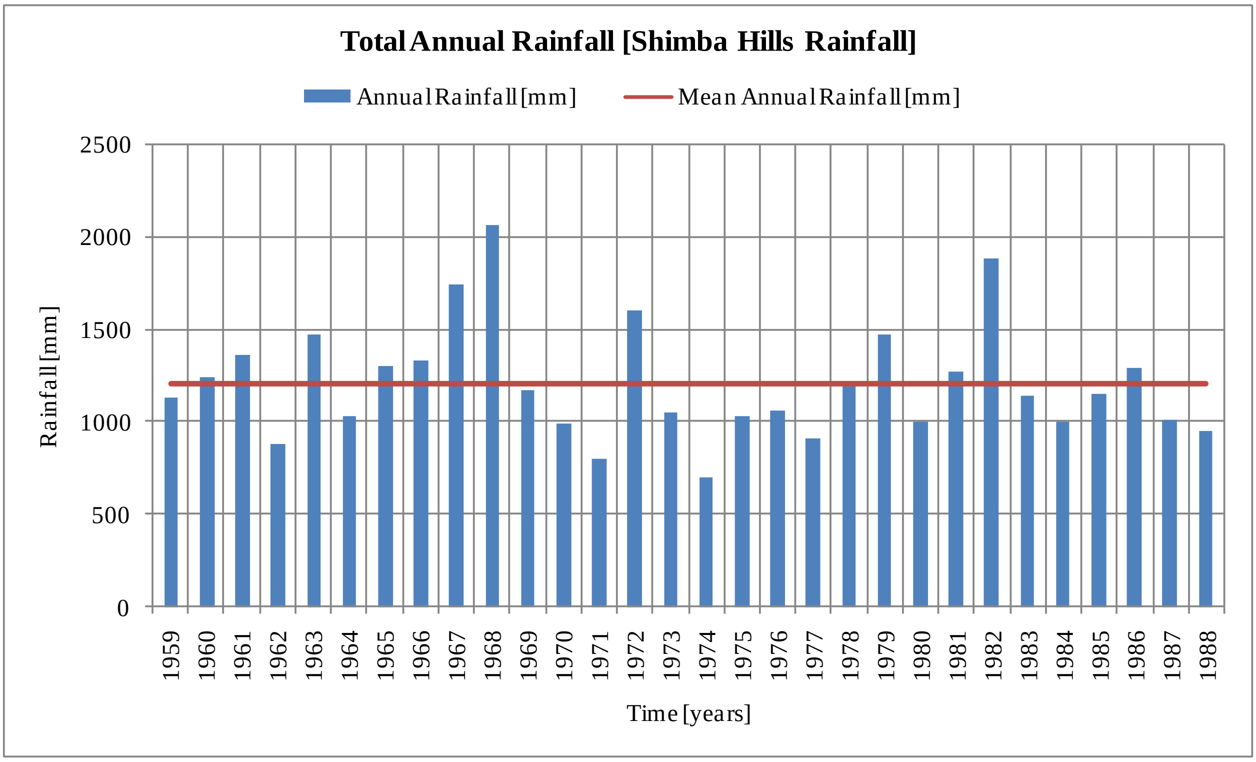

Figure 4-15: Total Annual Rainfall [Shimba Hills Rainfall, 1959-1988]

4.3.4 Evapotranspiration

The daily monthly evapotranspiration for the Mukurumudzi catchment was analysed and the results, figure 4.16, showed that the Mukurumudzi basin has a mean daily evapotranspiration of 4.4 mm/day.

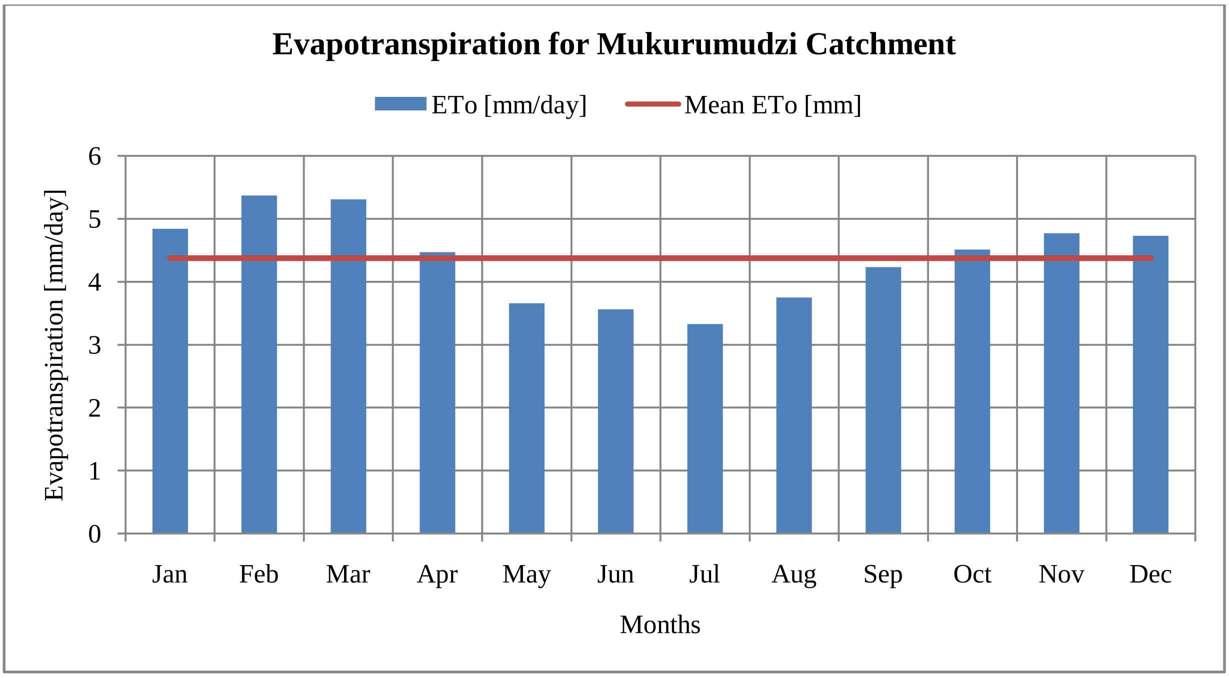

Figure 4-16 Mean Daily Evapotranspiration

4.3.5 Discharge Analysis

RGS 3KD06 was built in 1955/56 as a sharp crested weir with data collection starting in January 1956. By March 2013 the weir plate was severely rusted and this significantly affected accuracy of data, especially dry weather flows, although it is not known when the erosion of weir plate became significant.

4.3.6 Rating Curve

The water level data and the miscellaneous gauge heights versus corresponding discharges (H/Q data) were collected from WRMA Regional Office (Machakos) and are presented in Table 4.4.

The analysis of the data indicated a number of outliers, which are highlighted in the Table 4.4. The remaining data were used to generate a rating curve, as shown in Figure 4.17.

Table 4-4 Gauge height versus Corresponding Discharge

Date	Water Level [m]	Discharge 3KD06 [m^3/s]	Date	Water Level [m]	Discharge 3KD06 [m^3/s]	Date	Water Level [m]	Discharge 3KD06 [m^3/s]
27-09-61	0.83	5.852	23-02-78	0.09	0.038	26-03-82	0.35	0.096
12-07-66	0.46	0.999	07-03-78	0.07	0.030	16-07-82	0.55	0.959
23-11-66	0.14	0.189	03-04-78	0.12	0.199	08-06-83	0.64	2.584
10-01-67	0.09	0.097	26-04-78	0.15	0.093	15-02-84	0.56	0.082
16-02-67	0.09	0.104	03-05-78	0.46	0.851	21-06-84	0.23	0.357
23-05-67	0.45	0.948	15-05-78	0.52	1.460	17-07-84	0.27	0.443

Date	Water Level [m]	Discharge 3KD06 [m^3/s]	Date	Water Level [m]	Discharge 3KD06 [m^3/s]	Date	Water Level [m]	Discharge 3KD06 [m^3/s]
21-01-69	0.30	0.522	20-05-78	0.51	1.220	16-08-84	0.18	0.252
26-02-69	0.26	0.478	23-06-78	0.55	1.589	11-09-84	0.16	0.264
06-07-70	0.22	0.487	16-08-78	0.22	0.256	11-11-84	0.99	0.108
25-03-71	0.09	0.083	21-09-78	0.11	0.049	17-11-84	0.24	0.430
20-11-74	0.07	0.026	21-11-78	0.25	0.349	26-04-85	0.06	0.074
24-07-75	0.07	0.063	23-01-79	0.16	0.10	08-05-85	0.39	1.104
09-09-75	0.05	0.050	04-07-79	0.47	1.008	16-05-85	0.57	3.698
25-09-75	0.07	0.059	02-10-79	0.03	0.351	25-07-85	0.21	0.336
11-11-75	0.54	1.356	17-11-79	0.33	0.303	31-07-85	0.33	0.633
03-10-77	0.06	0.030	23-02-80	0.09	0.044	15-08-86	0.13	0.130
08-10-77	0.08	0.036	16-07-80	0.09	0.039	20-11-86	0.08	0.086
02-11-77	0.26	0.578	26-09-80	0.11	0.144	26-03-87	0.06	0.060
08-11-77	0.64	2.230	05-01-81	0.05	0.043	26-03-87	0.22	2.110
08-12-77	0.18	0.298	17-07-81	0.10	0.075	06-05-87	0.14	0.166
22-12-77	0.24	0.360	11-11-81	0.17	0.227	06-05-87	0.53	5.860
26-01-78	0.10	0.052	26-01-82	0.06	0.015			

The rating equation is

For $0 < H < 0.64$
$Q = 3.951\ H^{1.670}$, ($R^2 = 90.9\%$) **Equation 7**

Where:
Q = discharge (m^3/s)
H = depth of flow over the weir (m)

Analysis of the H/Q data for different time periods or for multiple sections does not result in any improvement in the goodness of fit. One rating curve equation was therefore adopted for the entire data period.

The H/Q data has a maximum H value of 0.64 m. The water level data has a maximum value of 2.5 m. The water level values above 0.64 m lack a degree of confidence in the discharge values.

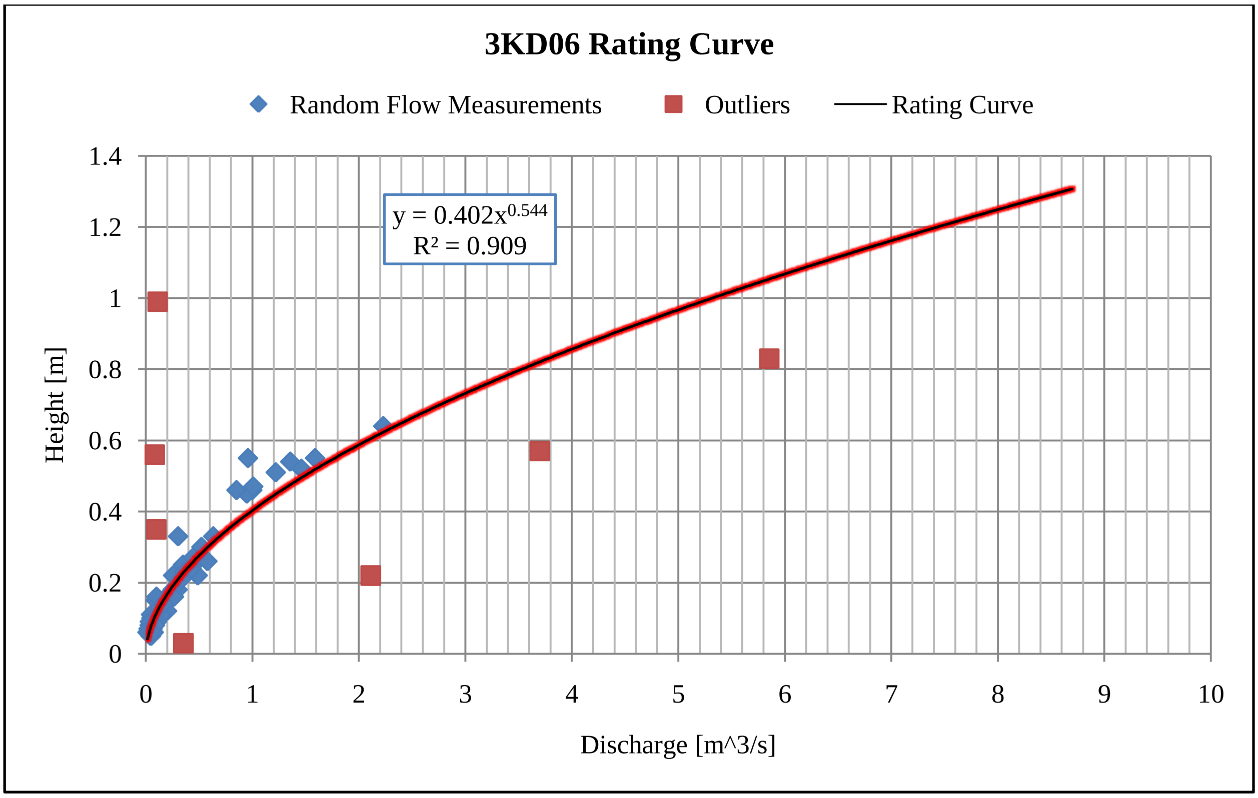

Figure 4-17: Rating Curve H vs Q

Discharges were calculated from the water level data using the rating curve in Figure 4.17.

4.3.7 Comparison of Discharge with Rainfall

A double mass curve between discharge and rainfall at 3KD06 was developed and analysed to establish the consistency of the discharge data, figure 4.18.

The Shimba Hills Settlement Scheme rainfall was used to check the consistency of the discharge at 3KD06 because its location was near the river gauging station 3KD06.

The double mass curve showed a change in regime in the discharge dataset from 21st August 1973 to 16th November 1980. The period prior to this year had a different regime. The reason for this could only be speculated and could be due to any or all of the following; change in land cover, the flow control characteristics for 3KD06 changed, or the gauging weir was blocked by debris, etc.

The gap was eliminated and the double mass curve re-plotted. It yielded a better relationship with a correlation coefficient of 0.9956, figure 4.19.

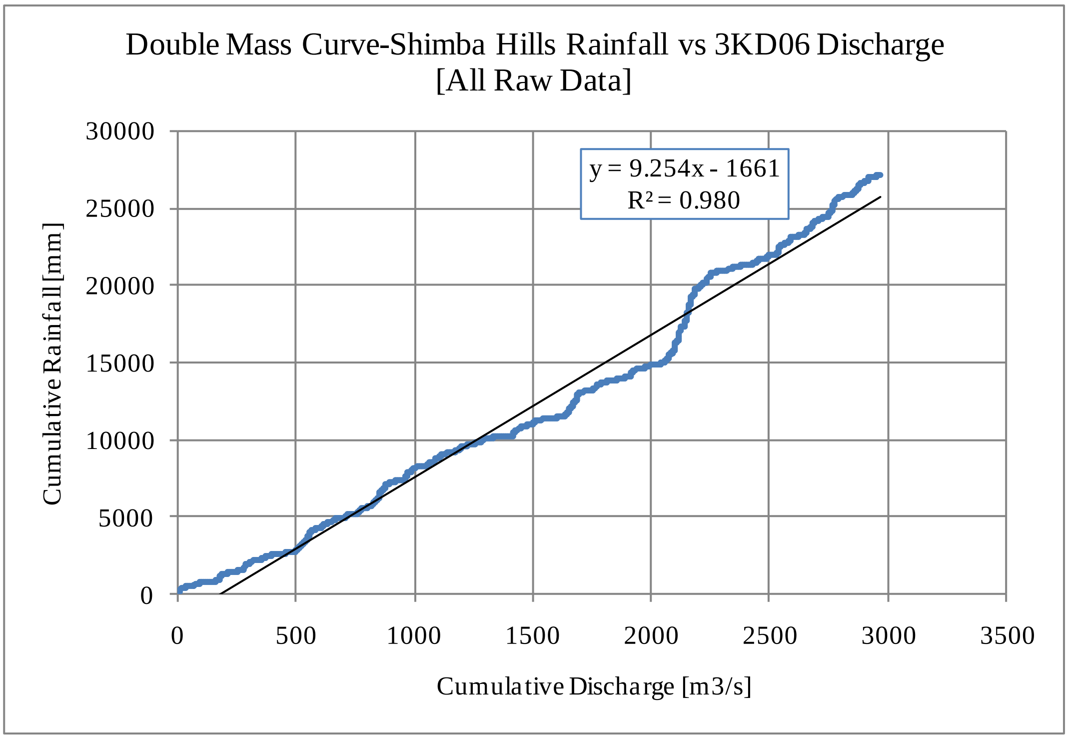

Figure 4-18: Double Mass Curve –Shimba Hills Rainfall vs 3KD06 Discharge

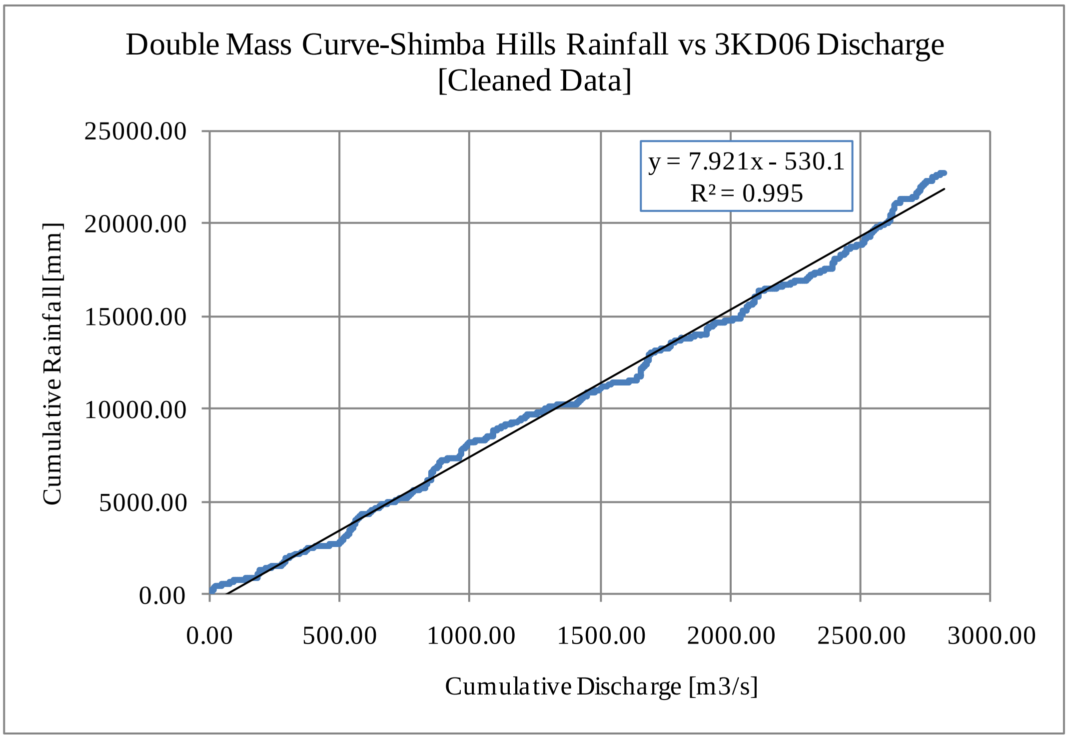

Figure 4-19: Double Mass Curve –Shimba Hills Rainfall vs 3KD06 Discharge

4.3.8 NAM Model Results

The discharge data cleaned through the DMC analysis was used in the NAM model. A section of the discharge data that had continuous data (>=3 years) was compared to the rainfall and evapotranspiration time series to ensure there were no gaps, this time series (>=3 years) were then used in the rainfall-runoff model to calibrate the nine parameters and generate the runoff time series for the whole period. The model was calibrated for the period of 1959 to 1963. Figures 4.20 and 4.21 shows the rainfall runoff simulation results and water balance. The calibrated model was then validated using the observed data for the period of 1/2/1959 to 28/10/1988, this represented a climatic period.

4.3.9 NAM Model Calibration and Validation

The results showed a good correlation between simulated and observed flows. The calculated Root Mean Square Error-observations standard deviation ratio (RSR) was 0.364 while Nash-Sutcliffe Efficiency (NSE) was 0.868. The NSE approached unity indicating that the predicted and the observed discharge values had a good correlation hence the model can fairly simulate the catchment response. The RSR approached 0.0 indicating that the root mean square errors are minimal hence the model can satisfactorily simulate the catchment responses with reasonable accuracy. A value of 0.364 is within a very good range of model performance according to Moriasi *et. al.* (2007). The RSR value indicated that the model was applicable to simulate catchment response in the Mkurumudzi catchment.

The FDC for the simulated discharge and observed discharge is shown in figure 4.22; the relationship was good at low flows, the percent difference between total stream water simulated and observed values was (-2.6%) less than 10% (Jingfen *et. al.* 2009) suggesting a very good relationship between the simulated and observed flows. Very good validation results were achieved for simulating low flows; the high flows were simulated with less accuracy. The overall validation results suggested a satisfactorily model performance and that the model adequately represented the baseline flow conditions in the watershed. The flow duration curve for observed and simulated discharge matched very well at low flows. The simulated discharge time series was converted into specific run-off (figure 4.23) and used in the MIKE BASIN model to do the water balance analysis so as to generate the Environmental Water Requirements (EWR).
Figure 4.24 shows the monthly simulated versus observed flows.

```
*********************************************************
*                                                       *
*     RAINFALL RUNOFF SIMULATION                        *
*     PARAMETER FILE    :      RRPar20130926_2.rr11     *
*     SIMULATION DATE   : 26-SEP-2013  10:37:04         *
*                                                       *
*********************************************************
```

SIMULATED PERIOD : From: 1959/ 2/ 1 12:00   To: 1988/10/28 12:00

TIMESTEP   : 24.00 HOURS

(Accumulated values in mm)

Catchment: MUKURUMUDZI, Area=   68.97 km2

Period	Q-obs	Q-sim	%diff	Rainfall	PotEvap	ActEvap	CapFlux	Recharge	Pumping	Irrig.	OF	IF	BF
1959/ 2/ 1 - 1960/ 2/ 1	232.3	266.8	-14.8	1159.5	1595.9	1100.4	0.0	181.7	0.0	0.0	39.3	9.6	217.8
1960/ 2/ 1 - 1961/ 2/ 1	582.0	260.2	55.3	1232.8	1595.3	944.5	0.0	231.3	0.0	0.0	48.1	14.6	197.5
1961/ 2/ 1 - 1962/ 2/ 1	334.2	191.6	42.7	1401.5	1595.3	1135.7	0.0	164.4	0.0	0.0	33.4	9.7	148.5
1962/ 2/ 1 - 1963/ 2/ 1	70.3	95.7	-36.1	834.5	1595.6	900.0	0.0	7.4	0.0	0.0	7.1	0.0	88.5
1963/ 2/ 1 - 1964/ 2/ 1	259.6	310.8	-19.8	1609.7	1601.0	1125.1	0.0	301.7	0.0	0.0	60.1	16.1	234.6
1964/ 2/ 1 - 1965/ 2/ 1	125.9	96.3	23.5	971.6	1595.3	993.7	0.0	18.7	0.0	0.0	11.3	0.0	85.0
1965/ 2/ 1 - 1966/ 2/ 1	145.9	179.0	-22.7	1255.0	1595.3	1045.1	0.0	174.6	0.0	0.0	38.9	6.6	133.6
1966/ 2/ 1 - 1967/ 2/ 1	273.7	302.6	-10.5	1308.2	1595.6	1041.9	0.0	248.0	0.0	0.0	46.9	13.0	242.7
1967/ 2/ 1 - 1968/ 2/ 1	423.4	467.5	-10.4	1750.3	1601.0	1117.6	0.0	473.0	0.0	0.0	81.4	36.6	349.5
1968/ 2/ 1 - 1969/ 2/ 1	588.1	766.9	-30.4	2106.1	1595.3	1305.9	0.0	604.6	0.0	0.0	102.0	53.8	611.1
1969/ 2/ 1 - 1970/ 2/ 1	113.0	220.3	-95.1	1232.9	1595.3	1100.7	0.0	74.2	0.0	0.0	25.3	1.5	193.6
1970/ 2/ 1 - 1971/ 2/ 1	89.9	151.5	-68.6	891.0	1595.6	894.5	0.0	95.3	0.0	0.0	21.3	2.7	127.5
1971/ 2/ 1 - 1972/ 2/ 1	43.5	61.2	-40.8	865.9	1601.0	817.8	0.0	37.5	0.0	0.0	11.6	0.7	48.9
1972/ 2/ 1 - 1973/ 2/ 1	289.2	333.8	-15.4	1560.2	1595.3	1054.9	0.0	366.3	0.0	0.0	67.7	15.8	250.3
1973/ 2/ 1 - 1974/ 2/ 1	342.0	299.7	12.4	1072.7	1595.3	903.5	0.0	174.1	0.0	0.0	33.6	12.7	253.4
1974/ 2/ 1 - 1975/ 2/ 1	343.8	51.3	85.1	698.0	1595.6	700.3	0.0	4.5	0.0	0.0	4.5	0.0	46.8
1975/ 2/ 1 - 1976/ 2/ 1	295.0	135.5	54.1	1006.8	1601.0	841.5	0.0	119.2	0.0	0.0	26.7	8.1	100.8
1976/ 2/ 1 - 1977/ 2/ 1	244.7	86.6	64.6	1103.1	1595.3	999.5	0.0	59.5	0.0	0.0	17.3	1.7	67.7
1977/ 2/ 1 - 1978/ 2/ 1	195.3	33.7	82.8	902.1	1595.3	804.9	0.0	20.5	0.0	0.0	12.1	0.0	21.6
1978/ 2/ 1 - 1979/ 2/ 1	145.8	95.4	34.6	1368.0	1595.6	1180.1	0.0	84.1	0.0	0.0	26.7	4.7	64.0
1979/ 2/ 1 - 1980/ 2/ 1	96.5	293.1	-203.6	1279.4	1601.0	1117.2	0.0	250.7	0.0	0.0	50.6	11.7	230.8
1980/ 2/ 1 - 1981/ 2/ 1	46.2	82.2	-78.0	1021.5	1595.3	951.7	0.0	30.3	0.0	0.0	12.7	0.2	69.4
1981/ 2/ 1 - 1982/ 2/ 1	107.8	115.0	-6.7	1259.2	1595.3	1116.2	0.0	99.7	0.0	0.0	29.4	1.2	84.4
1982/ 2/ 1 - 1983/ 2/ 1	465.5	527.4	-13.3	1891.0	1595.6	1218.3	0.0	523.5	0.0	0.0	88.7	48.8	389.9
1983/ 2/ 1 - 1984/ 2/ 1	132.6	409.1	-208.4	1143.4	1601.0	897.8	0.0	247.7	0.0	0.0	44.2	22.6	342.3
1984/ 2/ 1 - 1985/ 2/ 1	107.5	94.6	12.0	1028.5	1595.3	923.4	0.0	36.3	0.0	0.0	13.8	0.2	80.6
1985/ 2/ 1 - 1986/ 2/ 1	110.1	107.0	2.8	1127.7	1595.3	1033.4	0.0	76.4	0.0	0.0	21.6	2.3	83.1
1986/ 2/ 1 - 1987/ 2/ 1	131.7	340.9	-158.9	1324.6	1595.6	959.7	0.0	317.0	0.0	0.0	56.0	11.0	273.8
1987/ 2/ 1 - 1988/ 2/ 1	121.7	184.2	-51.4	986.2	1601.0	850.8	0.0	125.5	0.0	0.0	27.9	4.4	152.0
1988/ 2/ 1 - 1988/10/28	15.1	80.3	-431.2	929.4	1141.6	757.0	0.0	63.2	0.0	0.0	16.6	2.0	61.7
1959/ 2/ 1 - 1988/10/28	6472.4	6640.2	-2.6	36320.9	47447.7	29833.0	0.0	5210.8	0.0	0.0	1076.7	312.2	5251.3

Coefficient of determination: R2 = 0.368

Figure 4-20 NAM Rainfall-Runoff Simulation Results

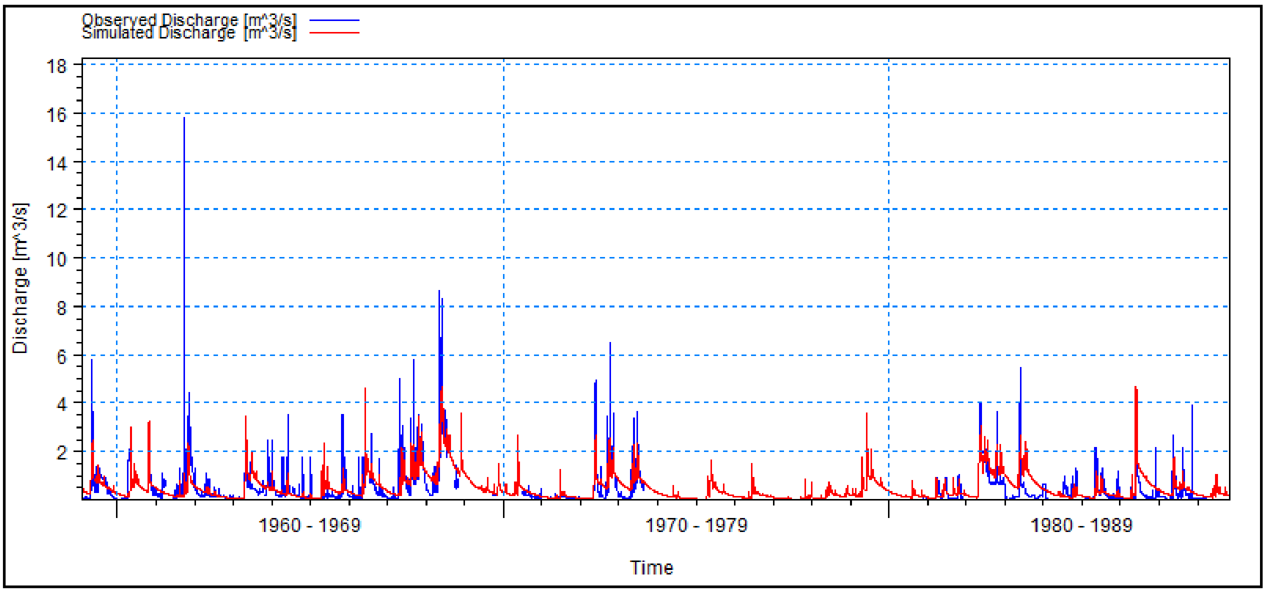

Figure 4-21 Simulated Discharge vs Observed Discharge

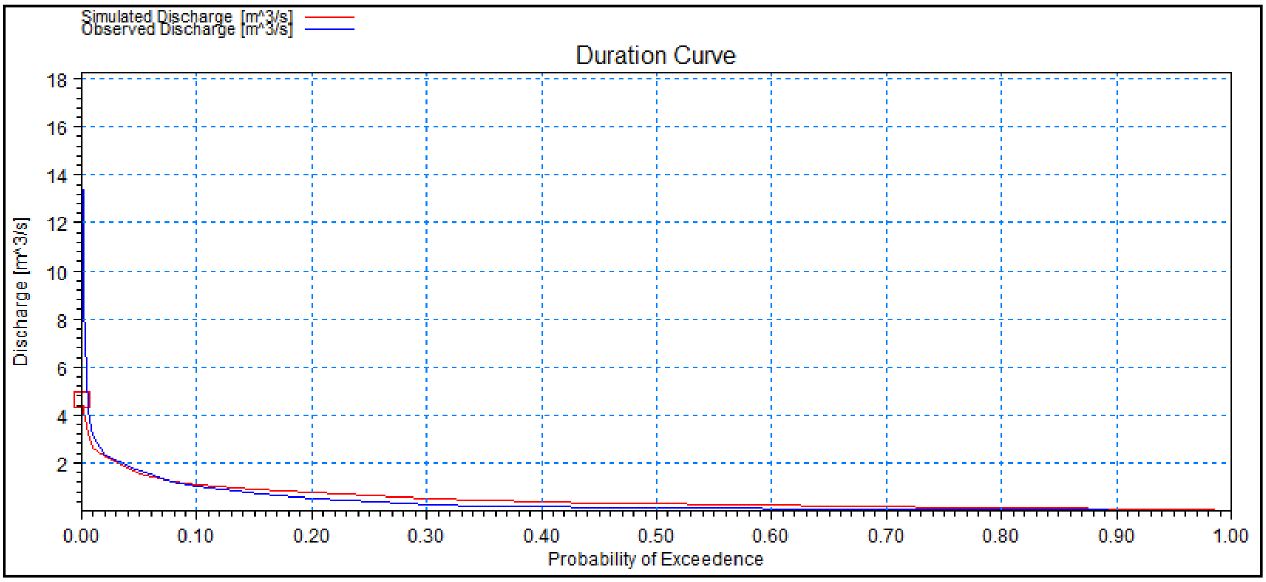

Figure 4-22 FDC for Simulated Discharge and Observed Discharge

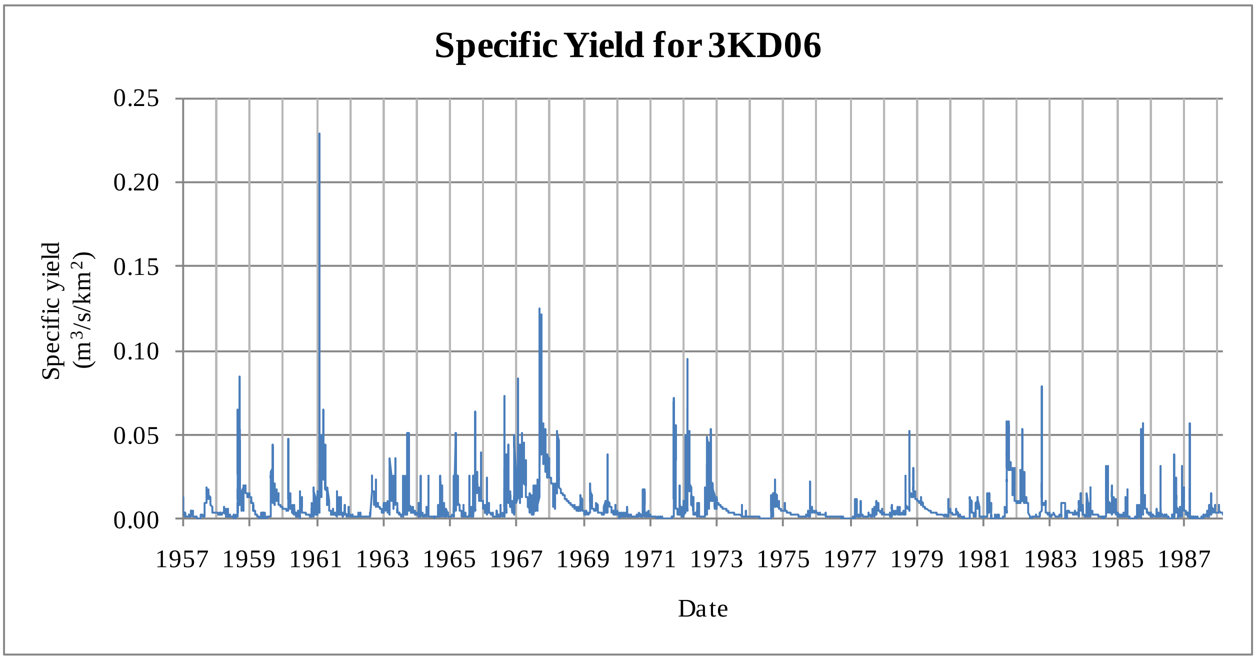

Figure 4-23 Specific Yield for 3KD06

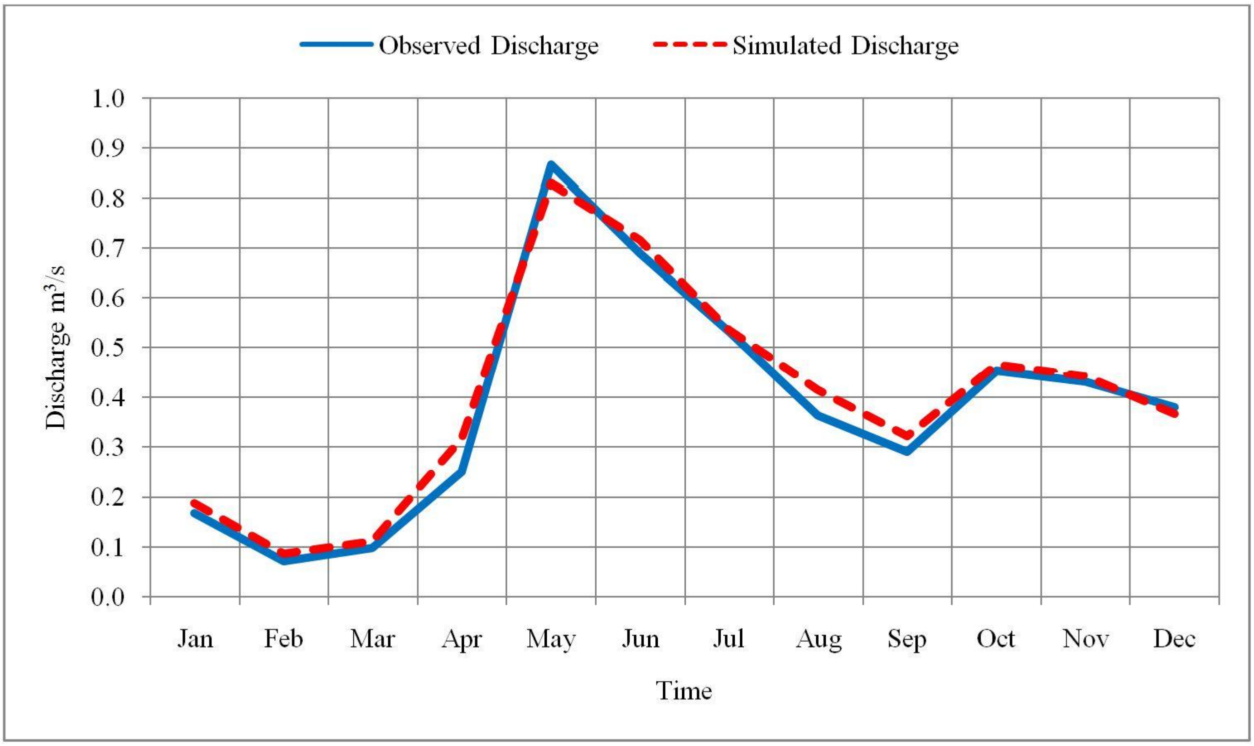

Figure 4-24 Monthly simulated versus observed flows

4.3.10 Mean and Annual Flows

The mean annual discharge and the mean discharge are presented in Figures 4.25 and 4.26 and tabulated in Appendix C. The mean annual flow was found to be 0.413 m^3/s. Highest mean monthly flows were found to occur in May, 0.792 m^3/s while the lowest mean monthly flows were occurring in Feb, 0.128 m^3/s.

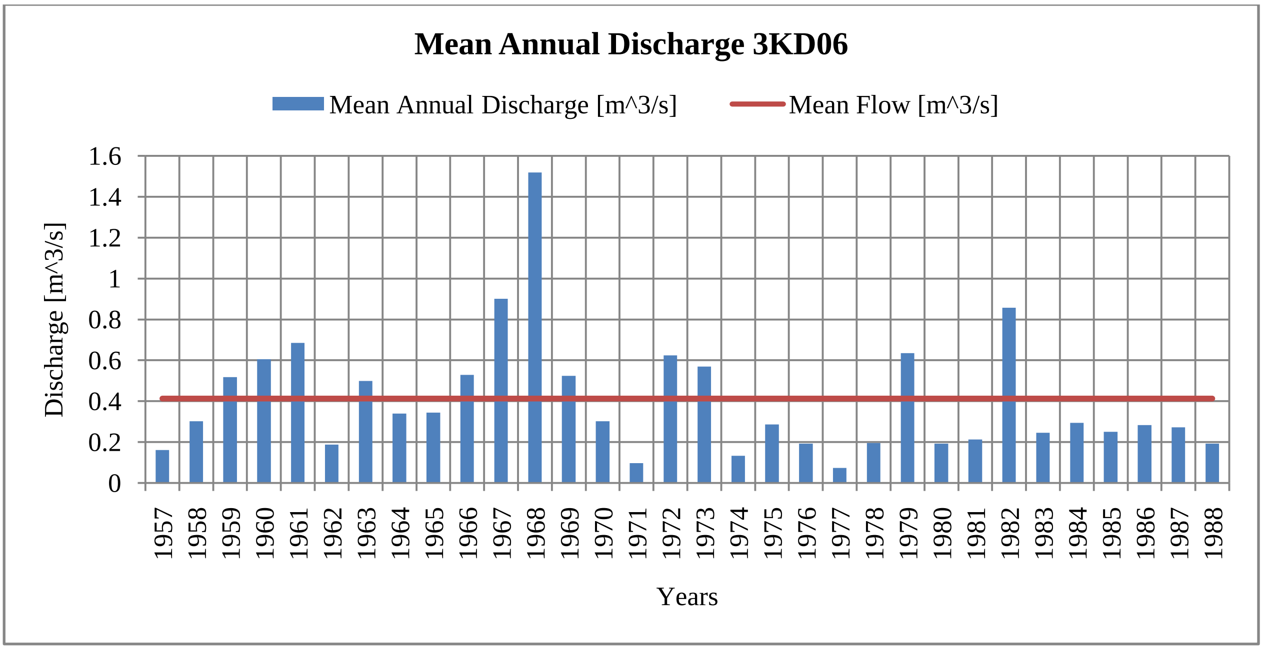

Figure 4-25: Mean Annual Flows for 3KD06

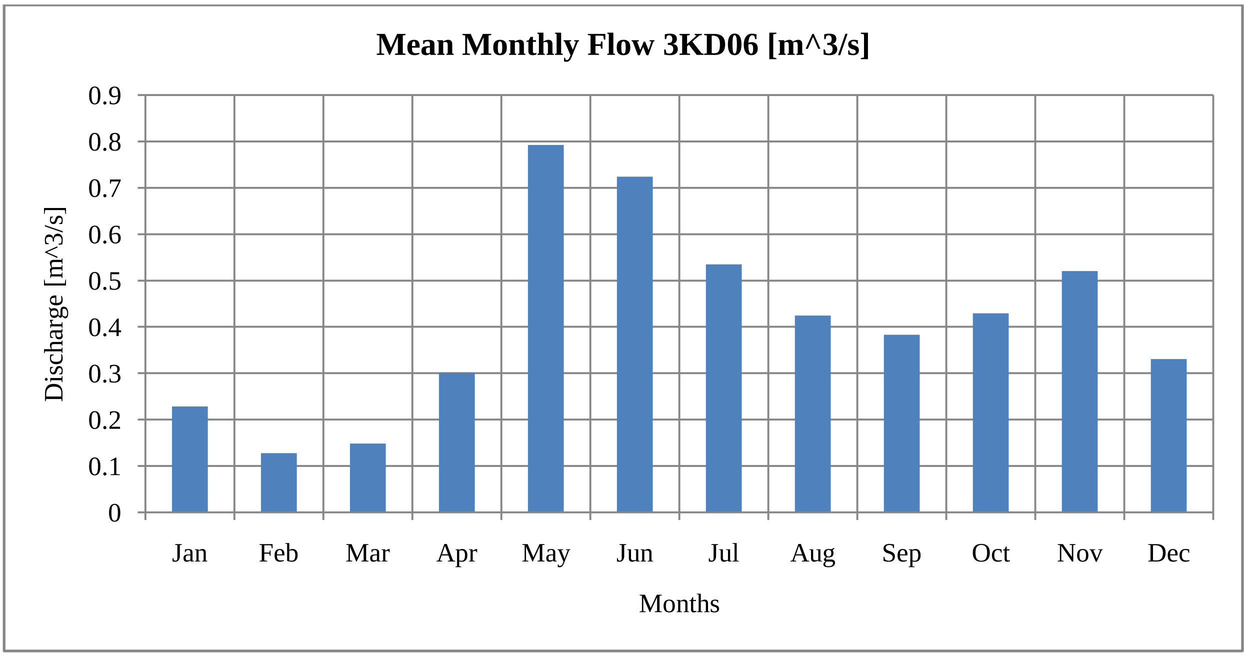

Figure 4-26 Monthly Average Flows

4.3.11 Catchment area and Mean Annual Rainfall

The catchment area of 3KD06 was calculated from watershed delineation using MIKE BASIN and a 90 m SRTM digital elevation model (DEM), the 30 m ASTER DEM was not used becaused it had errors around forested areas in the catchment, it was picking the tree heights as the ground elevation above sea level. The catchment area to 3KD06 was found to be 68.967 km^2 while that at the Mukurumudzi dam (owned by KMSP) site was established as 131.842 km^2. The catchment area for the upper Koromojo dam (owned by

KISCOL) was found to be 12.713 km^2 while that at lower Koromojo dam (owned by KISCOL) was found to be 16.629 km^2.

Mean annual rainfall contours were generated for the Mkurumudzi catchment using the Shimba Hills Settlement Scheme, Msambweni District Office, Gazi Association Works, Kidongo Parks, Mwaluphamba and Kwale rainfall stations, using the Inverse Distance Weighted method in Spatial Analyst Extension in ArcGIS 10.0. The dam site catchments mean annual rainfall are as tabulated in table 4.5.

Table 4-5 Catchment area and Mean Annual Rainfall

Site	Catchment Area [km^2]	Mean Annual Rainfall [mm]
3KD06	68.967	1300
Mukurumudzi Dam (KMSP)	131.842	1300
Upper Koromojo Dam	12.713	1300
Lower Koromojo Dam	16.629	1300

The catchment area relationship was then used to compute the Q95 for dam site with the following relationship;

$$\boldsymbol{Q95_{dam} = Q95_{3KD06} \times \frac{A_{dam}}{A_{3KD06}}}$$ **Equation 8**

Where;

$Q95_{dam}$ – A flow with a probability of being exceeded 95 percent of the time at the dam site (m^3/s)
$Q95_{3KD06}$ – A flow with a probability of being exceeded 95 percent of the time at the 3KD06 site (m^3/s)
A_{dam} - Catchment area at the dam site (Km^2)
A_{3KD06} – Catchment area at 3KD06 (Km^2)

4.3.12 Flow Duration Analysis

The flow duration curve for 3KD06 and the operational dam sites are presented in Figure 4.27 and tabulated in Table 4.6. The flow duration curves are based on all the naturalized daily discharge values for the period 2/09/1957 to 30/09/1988. Naturalized flows are observed flows when there are no abstractions taking place.

Table 4-6 Flow Duration Values for 3KD06 and Dams

P(x)	Discharge - 3KD06 [m^3/s]	Discharge - Mukurumudzi Dam [m^3/s]	Discharge - Upper Koromojo Dam [m^3/s]	Discharge - Lower Koromojo Dam [m^3/s]	Discharge - Mouth of River [m^3/s]
0.95	*0.03*	*0.05*	*0.005*	*0.006*	*0.07*
0.90	0.05	0.09	0.009	0.011	0.13
0.85	0.06	0.11	0.011	0.014	0.16
0.80	*0.07*	*0.14*	*0.013*	*0.017*	*0.19*
0.75	0.08	0.16	0.016	0.020	0.23

P(x)	Discharge - 3KD06 [m^3/s]	Discharge - Mukurumudzi Dam [m^3/s]	Discharge - Upper Koromojo Dam [m^3/s]	Discharge - Lower Koromojo Dam [m^3/s]	Discharge - Mouth of River [m^3/s]
0.70	0.10	0.19	0.018	0.024	0.27
0.65	0.11	0.22	0.021	0.028	0.31
0.60	0.15	0.28	0.027	0.036	0.40
0.55	0.17	0.32	0.031	0.040	0.45
0.50	0.19	0.37	0.035	0.046	0.52
0.45	0.23	0.43	0.041	0.054	0.61
0.40	0.26	0.50	0.048	0.063	0.71
0.35	0.31	0.60	0.058	0.076	0.85
0.30	0.39	0.74	0.071	0.093	1.04
0.25	0.49	0.93	0.090	0.117	1.32
0.20	0.60	1.15	0.111	0.145	1.63
0.15	0.75	1.43	0.138	0.181	2.03
0.10	1.04	1.99	0.192	0.251	2.82
0.05	1.66	3.17	0.306	0.400	4.49

The Q95 and Q80 represent thresholds for the Reserve and Normal Flow, as defined in the Water Resource Management Rules 2007.

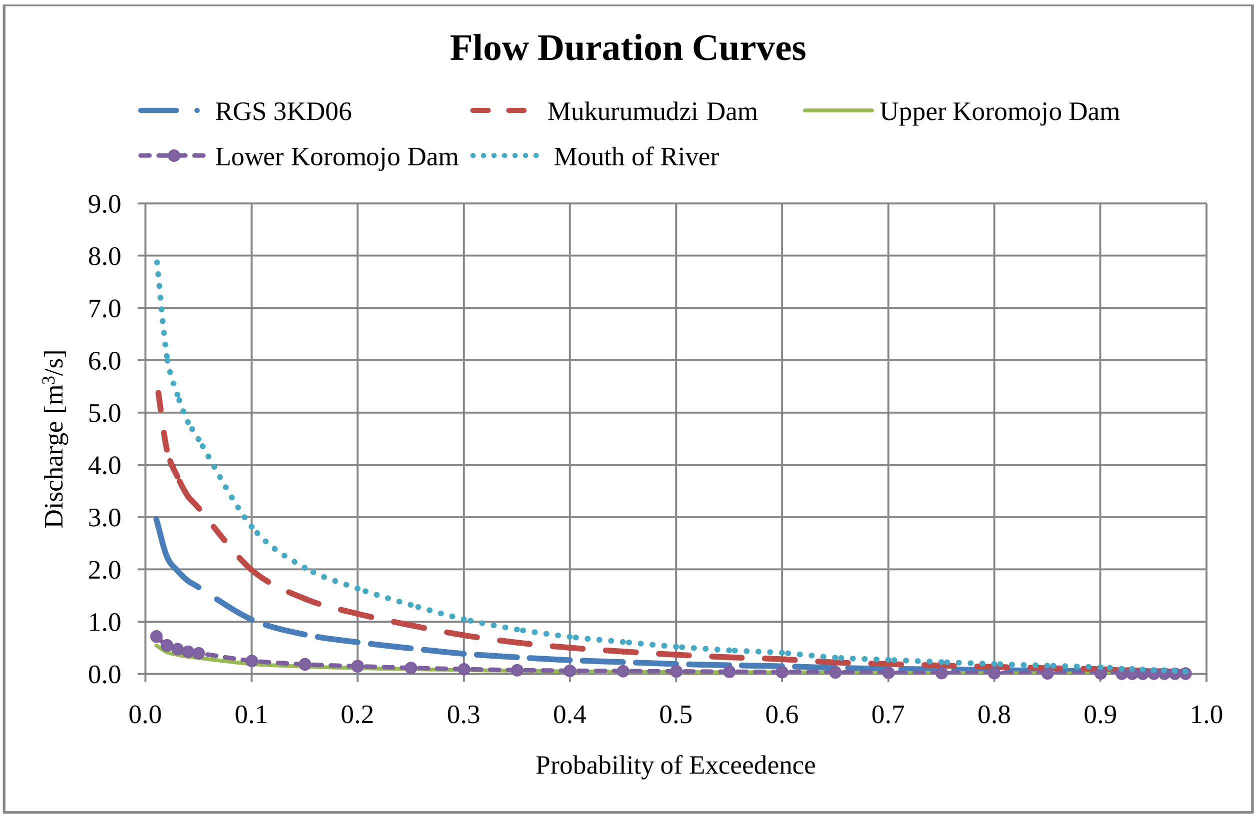

Figure 4-27: Flow Duration Curve for 3KD06 and the Dams

From the shape of the FDC (gentle slope of the FDC), it is evident that the river in this catchment is majorly sustained by groundwater base flow throughout the year and having few high flow events due to its permeable nature.

4.3.13 Water Balance and Allocation

From the flow duration curve in figure 4.27, the available water resource was analysed to check if the surface water resource was sufficient to supply the abstractions. The abstraction allocations used in the model are shown in table 4.7.

Table 4-7 Water Apportionment in Mukurumudzi Basin as at March 2013

Name of Applicant	Infrastructure [Abstraction Point]	Authorised Amount [m^3/s]	
		Flood Flow	**Normal Flow**
KISCOL	Mkurumudzi Weir	0.347	-
KISCOL	Lower Koromojo Dam	0.347	-
KISCOL	Upper Koromojo Dam	0.347	-
KMSP	Mkurumudzi dam	0.255	0.0234
Majimboni Water Project	Weir with fixed pump		0.00145 *[measured]*
Majimboni Muungano Self Help Water Project	Weir with fixed pump		0.0039 *[measured]*
Individual Abstractors	Portable Pump		0.000509 *[measured]*

These are the abstraction points that existed at the time of the study. The water resource available was tested against different demands to ascertain the balance so as to pick up any compromise on normal flows or the reserve flows (EWR). The results are shown in Table 4.8.

Table 4-8 Water Resource Available and Allocation

Flow Condition	Water Resource Available for Allocation	Water Resource Available for Allocation [m^3/day]	Abstraction Demand	Demand or Abstraction [m^3/day]	Balance [m^3/day]	Indication
Reserve Flows/EWR	Q95	6,048	Q95	6,048	-	
Normal Flows	Q80 - Q95	10,368	Domestic Abstraction Demand	506	9,862	
Flood Flows	Q50 - Q80	28,512	Irrigation Abstraction Demand	90,000	(61,488)	Flood flows insufficient to support Irrigation demand, *Normal Flows and EWR Compromised*
Flood Flows	Q50 - Q80	28,512	Mining Abstraction Demand	22,000	6,512	Flood flows sufficient to support demand for mining activities, 0% of the time in a year

This analysis was based on run of the river, and it was used to get an understanding of the water balance and allocation. The water balance results indicated that;

- Normal flows available for allocation is sufficient to meet the domestic water demand (March 2013);
- Flood flows available for allocation are sufficient to support the Mining Processing Water Demand (March 2013), 50% of the time in a year;
- Flood flows available for allocation is not sufficient to meet irrigation purposes (March 2013);

This implies that flows for the Reserve and Normal flows might be used to support irrigation activities. The water balances will however change when storage is introduced and this was modelled and scenarios were run so as to further ascertain to what extent and exactly which flow conditions are compromised.

4.3.14 Environmental Water Requirements

The EWR were used as the indicator of over allocation in this study. The EWR were assessed based on scenarios. The MIKE Basin Model was run to simulate the flows at the abstraction points (nodes) with the following scenarios;

1. Scenario 1: When there is no abstraction;
2. Scenario 2: When all abstractors are operational and releasing EWR;

Scenario 1 yielded the naturalised flows at all the abstraction points from which the EWR were determined based on the Q95 flow indice (Lamb *et.al.,* 2009), Table 4.11. The EWR were analysed on a monthly basis (monthly EWR were selected because they represented the seasonal variations of the river flows), the focus was on the EWR (Q95) at the mouth of the river. Table 4.9 and Figure 4.28 below shows the monthly Q95 flow values for 3KD06, the dams and the river's mouth in the catchment.

Table 4-9 Scenario 1: Monthly EWR Flows Expected Before Abstractions

Month	EWR-Upper Koromojo Dam [m^3/s]	EWR-Lower Koromojo Dam [m^3/s]	EWR-Mukurumudzi Dam [m^3/s]	EWR-3KD06 [m^3/s]	EWR Mouth of River [m^3/s]
Jan	0.002	0.002	0.017	0.009	0.024
Feb	0.001	0.001	0.008	0.004	0.012
Mar	0.0003	0.0004	0.003	0.001	0.004
Apr	0.003	0.004	0.028	0.015	0.040
May	0.005	0.007	0.055	0.029	0.078
Jun	0.007	0.009	0.071	0.037	0.101
Jul	0.010	0.014	0.108	0.057	0.153
Aug	0.007	0.009	0.071	0.037	0.101
Sep	0.004	0.005	0.040	0.021	0.057
Oct	0.004	0.005	0.040	0.021	0.057
Nov	0.004	0.005	0.040	0.021	0.057
Dec	0.003	0.004	0.028	0.015	0.040

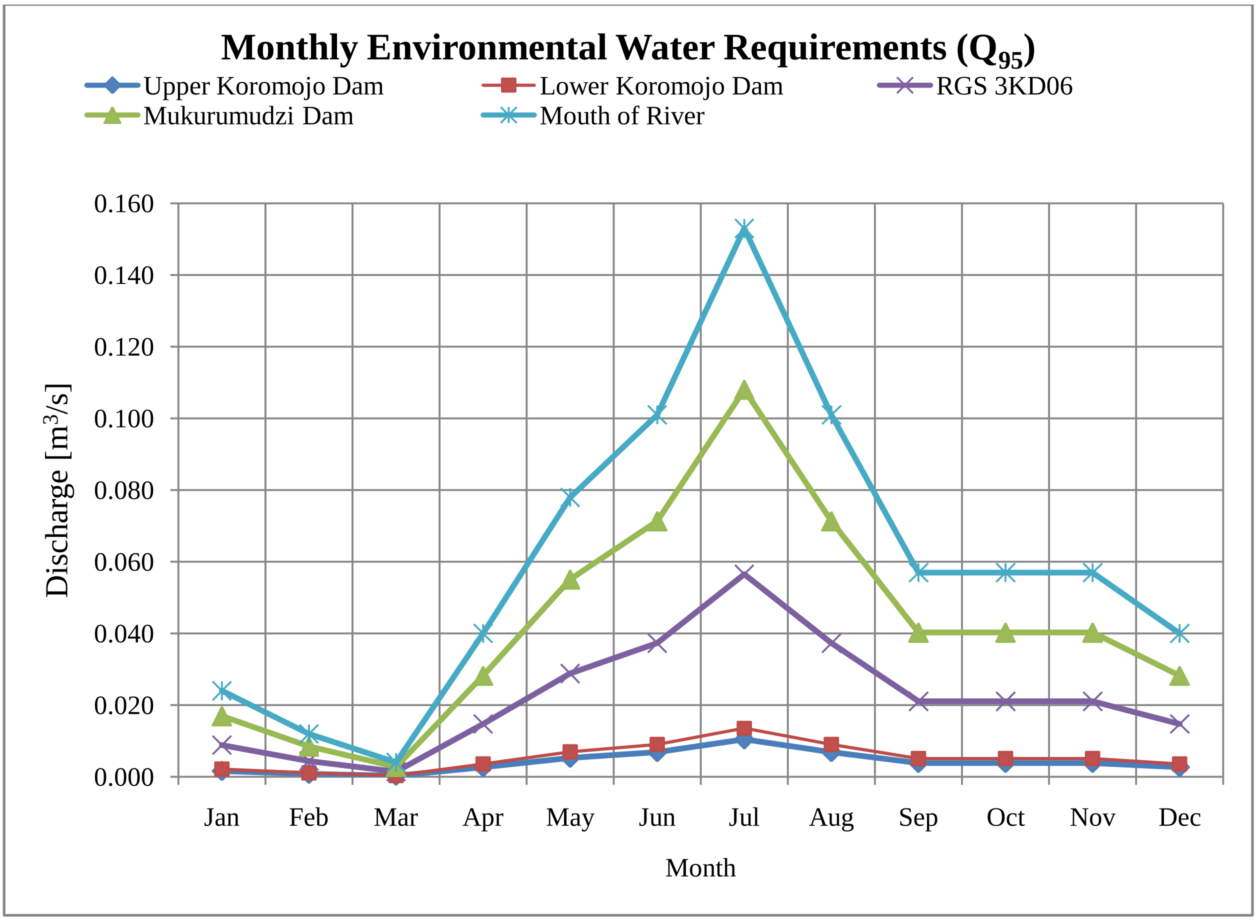

Figure 4-28 Scenario 1: Monthly EWR Flows Expected Before Abstractions

Scenario 2 yielded flows at the abstraction points when all the abstractions were operational, the simulated released EWR are shown in Table 4.10 and Figure 4.29.

Table 4-10 Scenario 2: Monthly EWR Flows Released after Abstractions

Month	EWR-Upper Koromojo Dam [m^3/s]	EWR-Lower Koromojo Dam [m^3/s]	EWR-Mukurumudzi Dam [m^3/s]	EWR-3KD06 [m^3/s]	EWR Mouth of River [m^3/s]
Jan	0.002	0.003	0.021	0.011	0.030
Feb	0.001	0.002	0.012	0.006	0.017
Mar	0.001	0.001	0.007	0.004	0.010
Apr	0.003	0.004	0.030	0.015	0.042
May	0.006	0.007	0.059	0.031	0.084
Jun	0.007	0.009	0.075	0.039	0.106
Jul	0.009	0.012	0.092	0.048	0.130
Aug	0.006	0.008	0.064	0.033	0.090
Sep	0.005	0.006	0.047	0.025	0.067
Oct	0.004	0.006	0.046	0.024	0.065
Nov	0.004	0.006	0.045	0.023	0.063
Dec	0.003	0.004	0.032	0.017	0.045

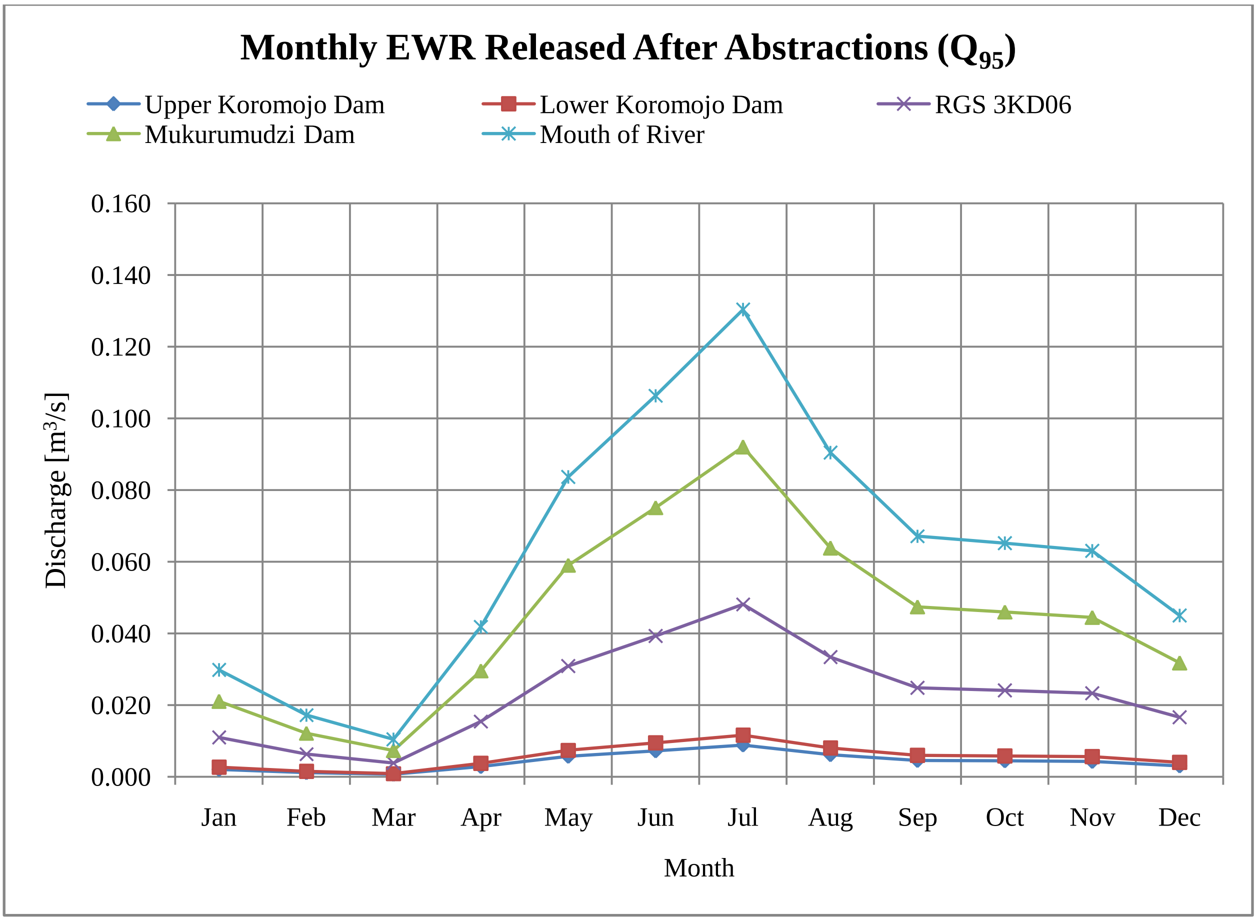

Figure 4-29 Scenario 2: Monthly EWR Flows Released after Abstractions

The difference between **Scenario 2** and **Scenario 1** yields the deficit in EWR. This was analysed and the results are shown in Table 4.11.

Table 4-11 Impact on Environmental Flows After Abstractions

	Surplus (+) or Deficit (-) in EWR				
Month	**EWR-Upper Koromojo Dam [m³/s]**	**EWR-Lower Koromojo Dam [m³/s]**	**EWR-Mukurumudzi Dam [m³/s]**	**EWR-3KD06 [m³/s]**	**EWR Mouth of River [m³/s]**
Jan	*+0.0004*	*+0.0005*	*+0.004*	*+0.002*	*+0.006*
Feb	*+0.0004*	*+0.0005*	*+0.004*	*+0.002*	*+0.005*
Mar	*+0.0004*	*+0.0006*	*+0.005*	*+0.002*	*+0.006*
Apr	*+0.0001*	*+0.0002*	*+0.001*	*+0.001*	*+0.002*
May	*+0.0004*	*+0.0005*	*+0.004*	*+0.002*	*+0.006*
Jun	*+0.0004*	*+0.0005*	*+0.004*	*+0.002*	*+0.005*
Jul	*-0.002*	*-0.002*	*-0.016*	*-0.008*	*-0.023*
Aug	*-0.001*	*-0.001*	*-0.007*	*-0.004*	*-0.011*
Sep	*+0.001*	*+0.001*	*+0.007*	*+0.004*	*+0.010*
Oct	*+0.001*	*+0.001*	*+0.006*	*+0.003*	*+0.008*
Nov	*+0.000*	*+0.001*	*+0.004*	*+0.002*	*+0.006*
Dec	*+0.000*	*+0.000*	*+0.004*	*+0.002*	*+0.005*

From the simulations of scenarios 1 and 2, the environmental flows will be compromised in the months of July and August with a total deficit of 0.023 m^3/s and 0.011 m^3/s respectively, in all the other months the EWR releases from the abstraction points will be sufficient to satisfy environmental water requirements. The EWR before and after abstraction for the Mukurumudzi catchment is shown in Figures 4.30.

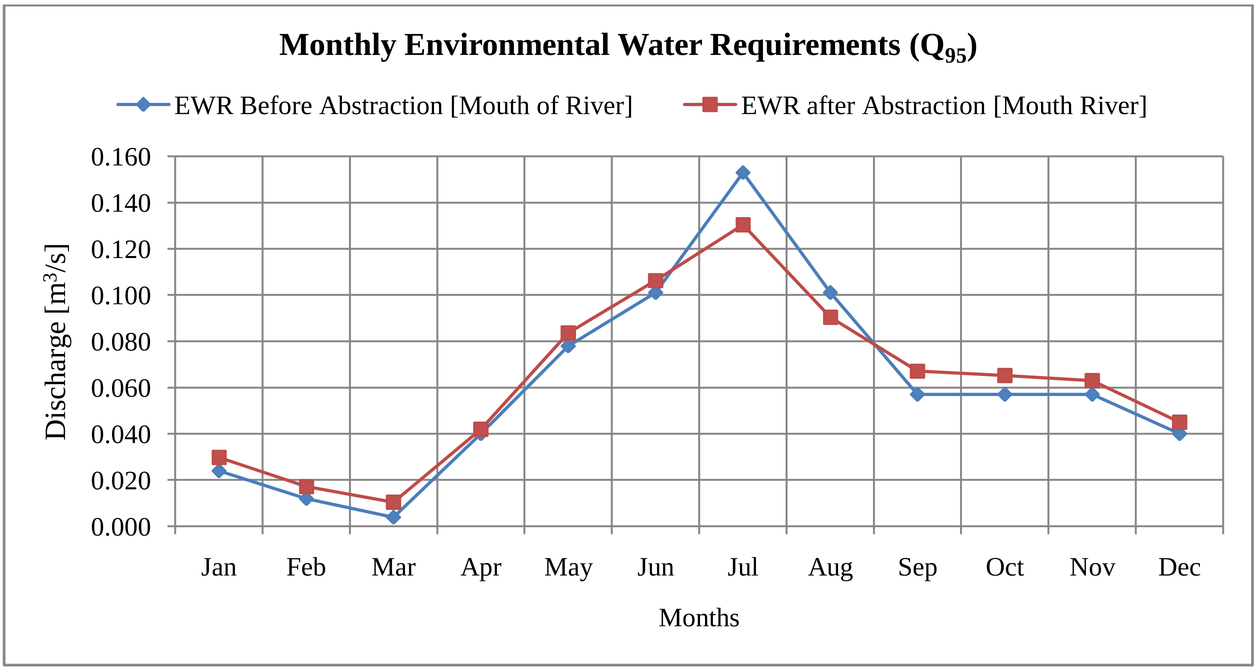

Figure 4-30 EWR before and after abstraction at Mouth of River

According to the WRM Rules 2007, all abstractor are required to release the EWR, permits of abstractions are usually given on condition that reservoirs have compensation flow arrangements and it is always recommended that an independent river gauging site downstream and upstream of the reservoir is monitored by WRMA for flows.

4.3.15 Water Allocation Framework

After all the abstractions had taken place the remaining available water resource was analysed and used as a framework for any future allocations. The table 4.12 shows the allocation framework on monthly basis for any new abstractor for the Mukurumudzi basin based on the remaining water resource after all other abstractions as at March 2013 documented abstractors.

Table 4-12 Water Allocation Framework for new abstractors

	Flows (m^3/s)			Available Resource for Allocation (m^3/s)	
Month	**Reserve Flow**	**Normal Flow**	**Flood Flow**	**Normal Flows**	**Flood Flows**
Jan	0.03	0.04	0.06	0.01	0.02
Feb	0.02	0.02	0.04	0.00	0.02
Mar	0.01	0.02	0.03	0.01	0.01
Apr	0.04	0.06	0.08	0.01	0.02

	Flows (m^3/s)			Available Resource for Allocation (m^3/s)	
Month	**Reserve Flow**	**Normal Flow**	**Flood Flow**	**Normal Flows**	**Flood Flows**
May	0.08	0.11	0.47	0.03	0.36
Jun	0.11	0.14	0.67	0.03	0.54
Jul	0.13	0.18	0.41	0.05	0.22
Aug	0.09	0.12	0.24	0.03	0.12
Sep	0.07	0.08	0.18	0.02	0.09
Oct	0.07	0.08	0.13	0.01	0.06
Nov	0.06	0.07	0.16	0.01	0.09
Dec	0.04	0.06	0.12	0.01	0.07

In the month of February, no allocation is permitted for normal flows; abstractors might be required to have water storage facilities to store water for use in this period.

On average, water available for allocation is 0.02 m^3/s from normal flows and 0.13 m^3/s from flood flows, Figure 4.31 shows a graphical representation of the monthly available resource for allocation.

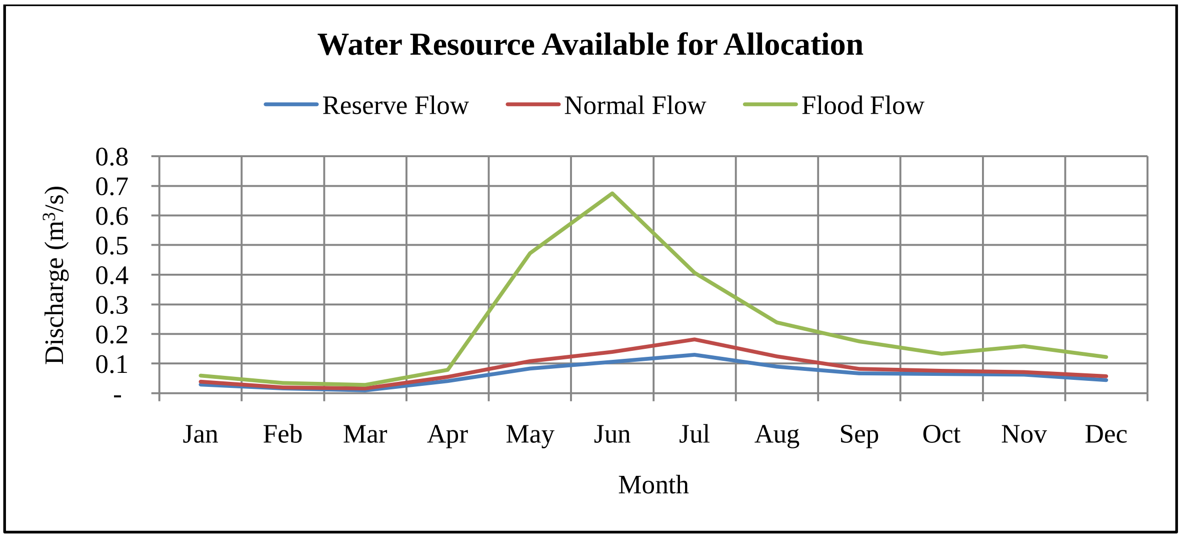

Figure 4-31Water Resource Available for Allocation on Monthly Basis

5. CONCLUSIONS AND RECCOMENDATIONS

The catchment had a total of 18 abstractors as at April 2013. The total authorised normal flow abstractions with valid documentation was 0.023 m^3/s while the total authorised flood flow abstractions with valid documentation was 1.20 m^3/s. The natural flow conditions do result in extreme low flows (± 0.006 m^3/s). This condition may not arise from excessive or illegal abstraction, or from modifications to the river hydrology due to the dams, but is actually a natural possibility based on rainfall and catchment conditions. The low flow study indicated that there is a marginal increase in flows downstream along the river profile. This is attributed to groundwater discharge during the dry season.

The available water resource in the catchment before any abstractions was 0.07 m^3/s as reserve flow, 0.19 m^3/s as normal flows and 0.52 m^3/s as flood flows according to the WRM Rules 2007 guidelines. The water resource available for allocation after allocating the 18 abstractors was 0.02 m^3/s from normal flows and 0.13 m^3/s from flood flows. Any new abstractor should be allocated water based on these values. This study assessed the environmental flow requirements (EWR) on a monthly basis so as to capture the seasonal variations in flows. If all the abstractors in the catchment release the monthly EWR at their abstraction points including the reservoirs, there will be no deficit in EWR expect in the months of July and August, they should release an extra 0.023 m^3/s and 0.010 m^3/s in July and August respectively (176,774 m^3 every year) to satisfy the EWR for the survival of the mangrove forest at the mouth of the river, however, this flow will not be necessary if in those months the rainfall will be enough to increase the flows in the river high enough to satisfy the EWR. A river gauging station should be established below all abstraction point to monitor environmental flows. The MIKE Basin model should be updated and re-run to re-assess the water allocation framework as new data gets collected on the catchment's hydrology and as new abstractors come in place.

The dam's storage dynamics (operational rules) should be studied to quantify the sustainability of the volumes stored for the abstraction purposes. A River Gauging Station should be installed downstream of all the abstractors in the catchment to monitor the EWR. The EWR at the mouth of the river will be impacted when more dams and other abstraction points are constructed in the catchment. The Water Resources Management Authority (WRMA) should ensure that the Water Resource Users Association (WRUA) members and the wider community are aware of the natural discharge data, and make reference to this when there are concerns regarding the impacts of abstractions and in-stream works.

All the commercial abstractors are abstracting water not only from the surface water streams but also groundwater; a hydro-geological model should therefore be generated to study the GW quantity and quality fluctuations as impacted by these abstractions.

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7. APPENDICES

7.1 APPENDIX A - Map of Catchment Area and Mean Annual Rainfall

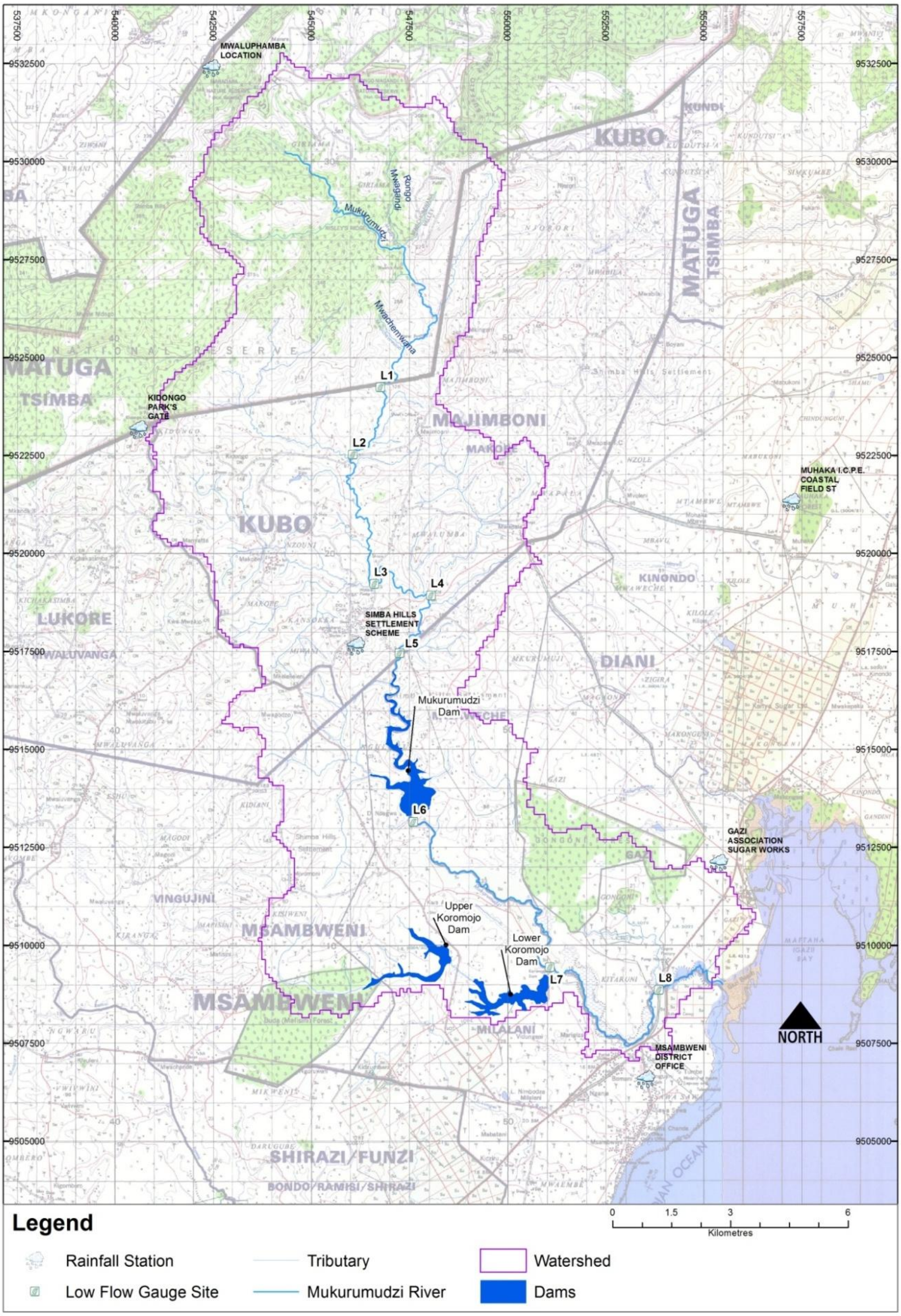

Figure 7-1: Low Flow Study Sites

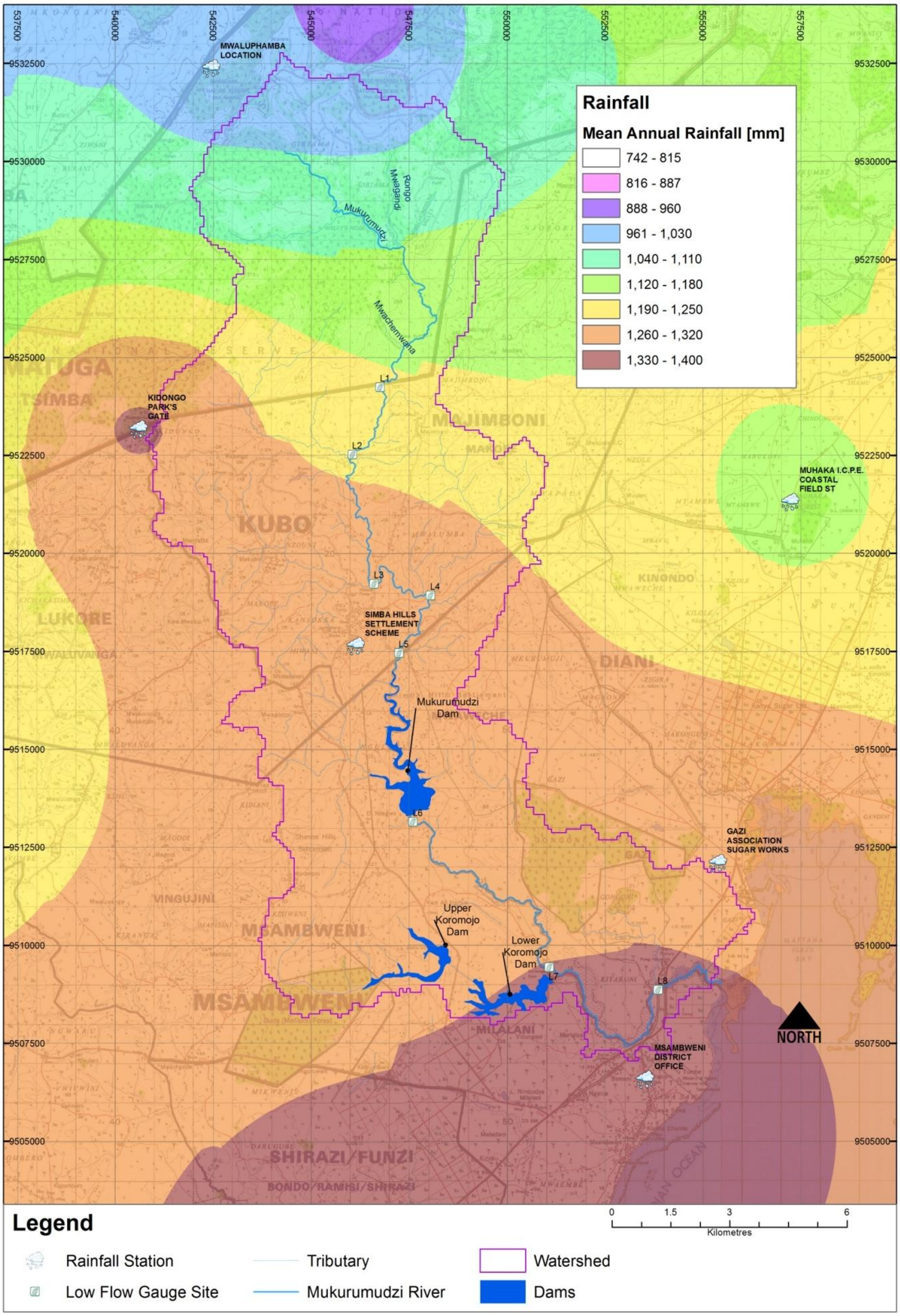

Figure 7-2: Mean Annual Rainfall Surface

7.2 APPENDIX B - Approved Abstractions from Mkurumudzi River

Table 7-1Authorised Surface Water Abstractions on Mkurumudzi Catchment (Source: Field work March 2013)

Sno.	River	Easting	Northing	Name	Category of Abstractor	Abstraction Structure	Measured Abstraction Rate [m^3/day]	Authorized Abstraction Rate		Class of Abstractor	Compliance	Notes
								Flood Flow [m^3/day]	Normal Flow [m^3/day]			
1	Mkurumudzi	547911	9525580	Majimboni Water Project	Group-CBO	Weir with fixed pump	125.00			**Class C**	Not Compliant	
2	Mkurumudzi	546277	9522653	Shake Mshimba	Individual	Portable Pump	5.00			**Class A**	Not Compliant	Pumps once every 3 Months
3	Mkurumudzi	546611	9523094	Christine Machila	Individual	Portable Pump	10.12			**Class B**	Not Compliant	Pumps once every 3 Months
4	Mkurumudzi	546242	9522616	Peter Mwadime	Individual	Portable Pump	2.44			**Class A**	Not Compliant	Pumps once every 3 Months
5	Mkurumudzi	546500	9519734	Henry Musa Mwakalu	Individual	Portable Pump	3.11			**Class A**	Not Compliant	Pumps once every 6 Months
6	Mkurumudzi	546500	9519734	Mutuku Kyengo	Individual	Portable Pump	3.11			**Class A**	Not Compliant	Pumps once every 6 Months
7	Mkurumudzi Tributary	544678	9521982	Kiseko Dam	Group-CBO	Dam					Not Compliant	Community Dam
8	Mkurumudzi	546121	9521460	John Muli	Individual	Portable Pump	10.00			**Class A**	Not Compliant	Pumps once every 3 Months
9	Mkurumudzi	546588	9519202	Majimboni Muungano Self Help Water Project	Group-CBO	Weir with fixed pump	336.96			**Class C**	Not Compliant	

Sno.	River	Easting	Northing	Name	Category of Abstractor	Abstraction Structure	Measured Abstraction Rate [m^3/day]	Authorized Abstraction Rate Flood Flow [m^3/day]	Authorized Abstraction Rate Normal Flow [m^3/day]	Class of Abstractor	Compliance	Notes
10	Mkurumudzi	547132	9519303	Unknown	Individual	Portable Pump					Not Compliant	
11	Mkurumudzi	547715	9519118	Ndunge Robert	Individual	Portable Pump	10.12			**Class B**	Not Compliant	
12	Mkurumudzi	547403	9513291	Mkurumudzi Dam	Company	Dam	0.00	22,000	2,000	**Class D**	Authorization	Under Development
13	Mkurumudzi	549709	9509670	KISCOL Mkurumudzi Dam	Company	Dam	0.00	10,000		**Class D**	Authorization	Under Development
14	Mwabanda River	548531	9509585	Upper Koromojo Dam	Company	Dam	0.00	-		**Class D**	Authorization	Under Development
15	Mwabanda River	550945	9509231	Lower Koromojo Dam	Company	Dam	0.00	30,000		**Class D**	Permit	
16	Mkurumudzi	551111	9509393	Mkurumudzi Weir	Company	Weir with fixed pump	0.00	30,000		**Class D**	Authorization	Under Development
17	Lagga into Mkurumudzi	551629	9509565	Kitaruni Dam	Company	Dam	0.00	12,000		**Class D**	Authorization	Under Development
18	Mkurumudzi	552608	9507657	Msambweni Irrigation Project-MoWI	Group-CBO	Weir with furrow					Not Compliant	

7.3 APPENDIX C - Hydrological Data

Table 7-2 Mean Annual Flows 3KD06 (Source: WRMA)

Year	Mean Annual Discharge [m^3/s]	Year	Mean Annual Discharge [m^3/s]
1957	0.161	1973	0.569
1958	0.301	1974	0.133
1959	0.517	1975	0.287
1960	0.605	1976	0.193
1961	0.686	1977	0.074
1962	0.188	1978	0.195
1963	0.499	1979	0.635
1964	0.340	1980	0.193
1965	0.344	1981	0.212
1966	0.528	1982	0.858
1967	0.902	1983	0.246
1968	1.519	1984	0.295
1969	0.523	1985	0.250
1970	0.302	1986	0.283
1971	0.096	1987	0.272
1972	0.624	1988	0.192

Table 7-3 Mean Evapotranspiration and Precipitation Values in Mukurumudzi [3KD06] Catchment (Source: CLIMWAT and WRMA)

Month	ETo [mm/day]	Mean Monthly Rainfall [mm]
Jan	4.84	33
Feb	5.37	14
Mar	5.31	65
Apr	4.47	195
May	3.66	275
Jun	3.56	127
Jul	3.33	106
Aug	3.75	78
Sep	4.23	67
Oct	4.51	124
Nov	4.77	109
Dec	4.73	72

7.4 APPENDIX D – Data Collection Form

Abstractor/Polluter Questionnaire Sheet Number: __________

ABSTRACTOR/POLLUTER QUESTIONNAIRE

Name of WRUA		Date	
Name of Data Collector		Contact Number	
Details of Physical Location			
Name of Water Body			
Right or Left Bank (looking d/s)	Right Bank ☐	Left Bank ☐	
Grid Reference of point of abstraction/pollution (Taken by GPS with units set as Decimal Degrees i.e. DD.DDDD)		Latitude (Northing)	Longitude (Easting)
Details of Land		L/R Number	
		Sub-location	
		Location	
		Division	
		District	
Details of Abstractor/Polluter			
Name of Informant			
Name of Abstractor/Polluter			
Relationship of water user to land owner (tick one)		Land owner ☐ Family member ☐ Leases land ☐ Don't know ☐	
Category of Abstractor/Polluter (tick one)		Individual ☐ Group (CBO, Society) ☐ Company ☐ Institution ☐	
Contact details of Abstractor/Polluter	Postal Address	Telephone	Email
Water Use Activity (tick one or more)			
Surface Water	Groundwater	Pollution	Other
Diversion ☐ In-stream works ☐ Abstraction ☐ Storage ☐	Shallow well ☐ Borehole ☐	Effluent Discharge ☐	Swamp Drainage ☐
Purpose of Water Use Activity (tick one or more)	Domestic ☐ Livestock ☐	Subsistence Irrigation ☐ Commercial Irrigation ☐	Industry/Commercial ☐ Hydropower ☐ Effluent disposal ☐
Details of Abstraction Point			
Type of Diversion Infrastructure			
Weir ☐	Height ______________ (m) Length ______________(m) Materials ___________________ Permanent ☐ Temporary ☐		

	Is their compensation flow arrangements? Yes ☐ No ☐ Compensation Flow arrangement Pipe ☐ Channel ☐ Other ☐	
Pump	Permanent Pump House Yes ☐ No ☐ Power source Electricity ☐ Diesel ☐ Petrol ☐ Water ☐Manual ☐ Other ☐	
Type of Conveyance	Furrow/canal ☐	Pipe ☐
	Top Width ________________ (m) Bottom Width ______________ (m) Depth of flow ______________ (m) Surface velocity ___________(m/s) Capacity ________________(m^3/s) Material _____________________	Pipe diameter _____________(mm) Material PVC ☐ GI ☐
Water Use		
Domestic	Number of households __________________ Average number per household _____________	
Institution	School ☐ Day Students ___________Boarding Students_______________ Health centre ☐ Religious institution ☐ Hotel ☐ No. of beds _______________ Other ☐	
Livestock	Cattle number __________________ Shoats ______________________ Pigs ________________________ Chickens ____________________	
Irrigation	Area under irrigation _________________ (ha) Irrigation technology Drip ☐ Overhead/sprinkler ☐ Furrow/surface ☐ Crop _______________________________	
Industry	Tea processing ☐ Coffee processing ☐ Other ☐	Water demand __________(m^3/day)
Estimate of Abstraction/discharge		
Volumetric	Start Time _____ End Time _______ Total Time ____ (sec) Volume measured ____________________________ (m^3)	
Pumping rate	Pumping rate _____(m3/hr) Hours pumped per day ___________ (hr/day)	
Gauging	Start time ___________ End time _____________ U/S discharge _____ (m^3/s) D/S discharge _______ (m^3/s)	
Irrigated area	Irrigation application rate ___________ (m^3/ha/day) Irrigated area _________ (ha)	
Abstraction Rate	Abstraction rate __________ (m^3/s) Abstraction rate __________ (m^3/day)	
Source of effluent		
Agricultural	☐	
Municipal	☐	
Processing/industrial	☐	
Single Hotel	☐	
Other ☐	Specify ________________________________	
Estimate of Storage volume supplied by abstraction		
	Total Volume (m3)	

Tanks		
Dams		
Pans		
Measuring device		
	Water meter/measuring device	☐	☐
Comments		
Signature of Data Collector		
Name of WRUA Official		
Signature of WRUA officials		

ABSTRACTOR/POLLUTER COMPLIANCE CHECKLIST

Name of WRUA		**Date**	
Name of Data Collector		**Contact Number**	
Details of Physical Location			
Name of Water Body			
Grid Reference of point of abstraction/pollution (Taken by GPS with units set as Decimal Degrees i.e. DD.DDDD)		**Latitude (Northing)**	**Longitude (Easting)**
Details of Land		**L/R Number**	
		Sub-location	
		Location	
		Division	
		District	
Details of Abstractor/Polluter			
Name of Informant			
Name of Abstractor/Polluter			
Relationship of water user to land owner (tick one)		**Land owner** ☐ **Family member** ☐ **Leases land** ☐ **Don't know** ☐	
Category of Abstractor/Polluter (tick one)		**Individual** ☐ **Group (CBO, Society)** ☐ **Company** ☐ **Institution** ☐	
Contact details of Abstractor/Polluter	**Postal Address**	**Telephone**	**Email**
Water Use Activity (tick one or more)			
Surface Water	**Groundwater**	**Pollution**	**Other**
Diversion ☐ **In-stream works** ☐ **Abstraction** ☐ **Storage** ☐	**Shallow well** ☐ **Borehole** ☐	**Effluent Discharge** ☐	**Swamp Drainage** ☐
Purpose of Water Use Activity (tick one or more)	**Domestic** ☐ **Livestock** ☐	**Subsistence Irrigation** ☐ **Commercial Irrigation** ☐	**Industry/Commercial** ☐ **Hydropower** ☐ **Effluent disposal** ☐
Compliance			
Status of Permit (tick if yes)	**Applied for** ☐	**Date:** ______________	
	Authorisation issued ☐	**Date issued:** ________	**Number**
	Permit issued ☐	**Date issued:** ________ **Expiry Date:** _________	**Number**
If no valid permit, what is the reason?			
	Category of user	**A** ☐ **B** ☐ **C** ☐	**Comment**

		D ☐ Don't know ☐	
Compliance to conditions of permit/authorisation		Condition Required (tick if yes)	Condition Implemented (tick if yes)
	Water meter/measuring device	☐	☐
	Storage	☐	☐
	Payment of water use charges	☐	☐
	WQ Sampling	☐	☐
Volume of Abstraction/Pollution (m3/day)			
	Authorised	Actually Abstracted	Comment
Normal Flow			
Flood Flow			
Lake			
Water Use Data			
Is abstraction/pollution discharge measured on a regular basis?		Yes ☐	No ☐
Perceptions of Abstractor/Polluter			
Has your abstraction point been inspected by a WRMA staff?		Yes ☐	No ☐
Is your water use activity vulnerable to water use activities upstream?		Yes ☐	No ☐
Can your water use activity negatively affect water users downstream?		Yes ☐	No ☐
How should WRMA communicate to water users? (tick one or more)		WRUA ☐ Radio ☐ Newspaper ☐ Posting at Chief's office ☐ Other ☐	
Comments			
Signature of Data Collector			
Name of WRUA Official			
Signature of WRUA officials			

7.5 APPENDIX E – Mukurumudzi Catchment Field Work Photographs

Figure 7-3 Repaired 3KD06 River Gauging Station

Figure 7-4 Mukurumudzi Catchment-Shimba Hills

Figure 7-5 River Mukurumudzi at Source

Figure 7-6 3KD06 RGS

Figure 7-7 Low Flow Gauge Site L01

Figure 7-8 Low Flow Gauge Site L02

Figure 7-9 Low Flow Gauge Site L03

Figure 7-10 Low Flow Gauge Site L04


Figure 7-11 Low Flow Gauge Site L05


Figure 7-12 Low Flow Gauge Site L06


Figure 7-13 Low Flow Gauge Site L07


Figure 7-14 Low Flow Gauge Site L08


Figure 7-15 Fish Pond in the Catchment


Figure 7-16 Portable Pump Abstractor (a)


Figure 7-17 Portable Pump Abstractor (b)


Figure 7-18 Measuring Flow in a Pipe

Figure 7-19 'Odhiambos Waterfall'

Figure 7-20 Weir Intake Under Construction

Figure 7-21 'WRUAs Initiative'

Figure 7-22 Mouth of River (tidal zone)

Figure 7-23 Upper Koromojo Dam

Figure 7-24 Lower Koromojo Dam

Figure 7-25 Mukurumudzi Dam

Figure 7-26 Intake for a Water project