APPLICATION OF THE PITMAN AND SMAR RAINFALL-RUNOFF HYDROLOGICAL MODELS FOR WAMI RIVER BASIN OF TANZANIA

Sisay Teklu Ido

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APPLICATION OF THE PITMAN AND SMAR RAINFALL-RUNOFF HYDROLOGICAL MODELS FOR WAMI RIVER BASIN OF TANZANIA

By

Sisay Teklu Ido

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master in Integrated Water Resources Management of the University of Dar es Salaam

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: ***Application of the Pitman and SMAR Rainfall-Runoff Hydrological Models for Wami River Basin of Tanzania,*** in partial fulfillment of the requirements for the degree of Master in Integrated Water Resources Management of the University of Dar es Salaam.

Dr. S. H. Mkhandi
(Supervisor)

Date: ----------------------------

Dr. Nobert Joel
(Supervisor)

Date: ----------------------------

DECLARATION

AND

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I, **Sisay Teklu Ido,** declare that this dissertation is my own original work and that it has not been presented and will not be presented to any other University for a similar or any other degree award.

Signature ----------------------------------

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Above all, my family's love and support is always with me and of course God always helps our family.

DEDICATION

This dissertation is dedicated to my father Mr. Teklu Ido, my mother Mrs. Astede Doya and the entire family members for their love and support in my every walk of life.

ABSTRACT

The applicability of two lumped conceptual Rainfall-runoff models, the monthly time step Pitman and the daily time series Soil Moisture Accounting and Routing (SMAR) models have been tested in six selected sub-basins of Wami river basin of Tanzania. The Wami River Basin (40,000 km^2), is an important area due to its diversified use which benefits a multi-diversity of stakeholders. The study is aimed to assess the applicability and suitability of the two conceptual models for the Rainfall-Runoff system in the Wami river basin in order to solve the discharge data availability problem in the study area.

The input data to the models were average catchment rainfall and potential evaporation. Eight years record length data has been used from which the calibration and verification periods were 5.3 years (1/1/74 to 2/5/79) and 2.7 years (3/5/79 to 31/12/81) respectively. In the process of examining the applicability of the models, the simulated and observed flow sequences were compared and the results have been discussed by evaluating the goodness-of-fit in terms of Mean Annual Runoff (Mm^3), Model efficiency (R^2), and Comparative time series graphs. The attained calibration (R^2) values vary in the Range of (51.38-77.37) and (45.94-79.89) for Pitman and SMAR model respectively. Fairly good Calibration results coupled with poor verification results have been obtained for most of the sub-catchments. As a conclusion to the study, the models inadequacy related to the complex nature of the basin and the input data problem has been discussed and recommendations are given for further studies.

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LIST OF ABBREVIATIONS

BICO	Bureau for Industrial Cooperation
BRALUP	Bureau of Resource Assessment and Land Use Planning
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographical Information System
IUCN	International Union for Conservation of Nature
IVF	Index of Volumetric Fit
IWRM	Integrated Water Resources Management
LPM	Linear Perturbation Model
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MoWRT	Ministry of Water Resources of Tanzania
PBWO	Pangani Basin Water Office
SLM	Simple Linear Model
SMAR	Soil Moisture Accounting and Routing
TMA	Tanzania Meteorological Agency
UCG	University College of Galway
USGS	United States Geological Survey
WMO	World Meteorological Organization

CHAPTER ONE

INTRODUCTION

1.1 Research Background

Water is, like the air we breathe, a basic requirement for all life on Earth. It is vital for many aspects of economic and social development, e.g., for energy production, agriculture, domestic and industrial water supply, and it is a critical component of the global environment.

Water-resources assessment is the determination of the sources, extent, dependability, and quality of water resources, which is the basis for evaluating the possibilities of their utilization and control (WMO, 1994). Water-resources assessment is of critical importance to wise and sustainable management of the world's water resources.

Only with reliable data and information on the status and trends of the water resources, including quantity, quality, statistics on such events as floods, and use for human purposes, can wise decisions be made on how best to manage water. To a large extent, water-resources assessment is a prerequisite for all aspects of water-resources development and management.

For efficient water resources assessment, longer stream flow time series data are required than are frequently available. Getting long reliable and continuous river flow data in most countries is difficult as streamflow observations are rather sparse and good records cover relatively short periods. In order to remedy the situation, the rainfall-runoff modelling approach is often used to make up for the missing data and satisfy the minimum record length requirement.

Taking in to account the data availability problem in most of the Tanzania river basins, this study assesses the applicability of Pitman and Soil Moisture Accounting and Routing (SMAR) Rainfall-Runoff models in the Wami river basin of Tanzania. The two models have been selected due to their relatively less data requirement compared to other models. The output of the Pitman model can be used for water resources assessment purposes both from gauged and ungauged catchments and the output of the SMAR model can be used for river flow forecasting.

1.2 Problem Statement

The social and economic development which results in increased water demand in the different water uses and also the increasing need for environmental flow requirement due to the establishment of the Sadani National Park (SANAPA) and the Wami-Mbiki Wildlife Management Area (WMA) in the Wami drainage basin area indicates the need for the development and efficient utilization of the water resources potential available. However, efficient utilization of water resources potential is only possible through good planning and design of the water resources projects. Such projects include; water supply, Irrigation, flood control, hydroelectric power generation, etc. River flow analysis is of utmost importance in the design and efficient operation of these projects.

In most of the drainage basins in Tanzania including Wami river basin, there has been shortage of longer discharge data series which is required for efficient river flow analysis. Moreover, Wami river basin lacks Rainfall-runoff modelling studies which can be used as hydrological assessment tools.

Therefore this study helps to assess the application of Pitman and Soil Moisture Accounting and Routing (SMAR) Rainfall-Runoff models in the Wami river basin which can be used to generate a long representative time series of streamflow volumes from which water resources structures can be designed.

1.3 Significance of the Study

The Wami Rivers basin is an important area due to its diversified use which benefits a multi-diversity of stakeholders (Madulu, 2005). The important socio-economic activities in the basin include large scale irrigated sugarcane and rice farming, biodiversity and environmental conservation, domestic water supply, livestock water needs, and fishing. Wami River delta is known to support a variety of biodiversity, including Mangroove forest which among other protects the coastline against destructive waves, help in microclimatic stabilization, and enhance water quality in coastal stream and estuaries. Wami river also form part of the Wami-Ruvu drainage basin which is the main source of water supply to Dar es Salaam city.

Efficient management and utilization of the water resources supported with hydrological assessment tools is necessary in order to address the water use requirement of the different uses and also maximize the benefits of the precious resources of the basin.

As hydrological assessment tool, the output of this study can be used to study and design water resources development projects like estimating irrigation potential area within the basin, assessing the hydropower potential of the basin which is estimated about 150MW (Kalinga,1998), Flood forecasting and Design of hydraulic structure. Furthermore, the study will help to quantify the total volume of water flowing in the basin in different seasons. Thus it will help to support efficient planning and management of the available water resources within the basin.

1.4 Objectives of the Study

Main objective:

The aim of this study is testing the applicability and suitability of Pitman and Soil Moisture Accounting and Routing (SMAR) models for the Rainfall-Runoff system in the Wami river basin of Tanzania.

Specific Objectives:

The project has the following specific objectives:-

- Assessment of the applicability of the Pitman model to the Rainfall-runoff system of the Wami river basin of Tanzania
- Assessment of the applicability of the SMAR model to the Rainfall-runoff system of the Wami river basin of Tanzania

1.5- Description of the Study Area

1.5.1 Location

The Wami drainage basin is located between 5^o -7^o Southern latitudes and between 36^o -39^o Eastern longitudes on the Eastern side of Tanzania. The location map of the study area is shown in Fig.1.1below.

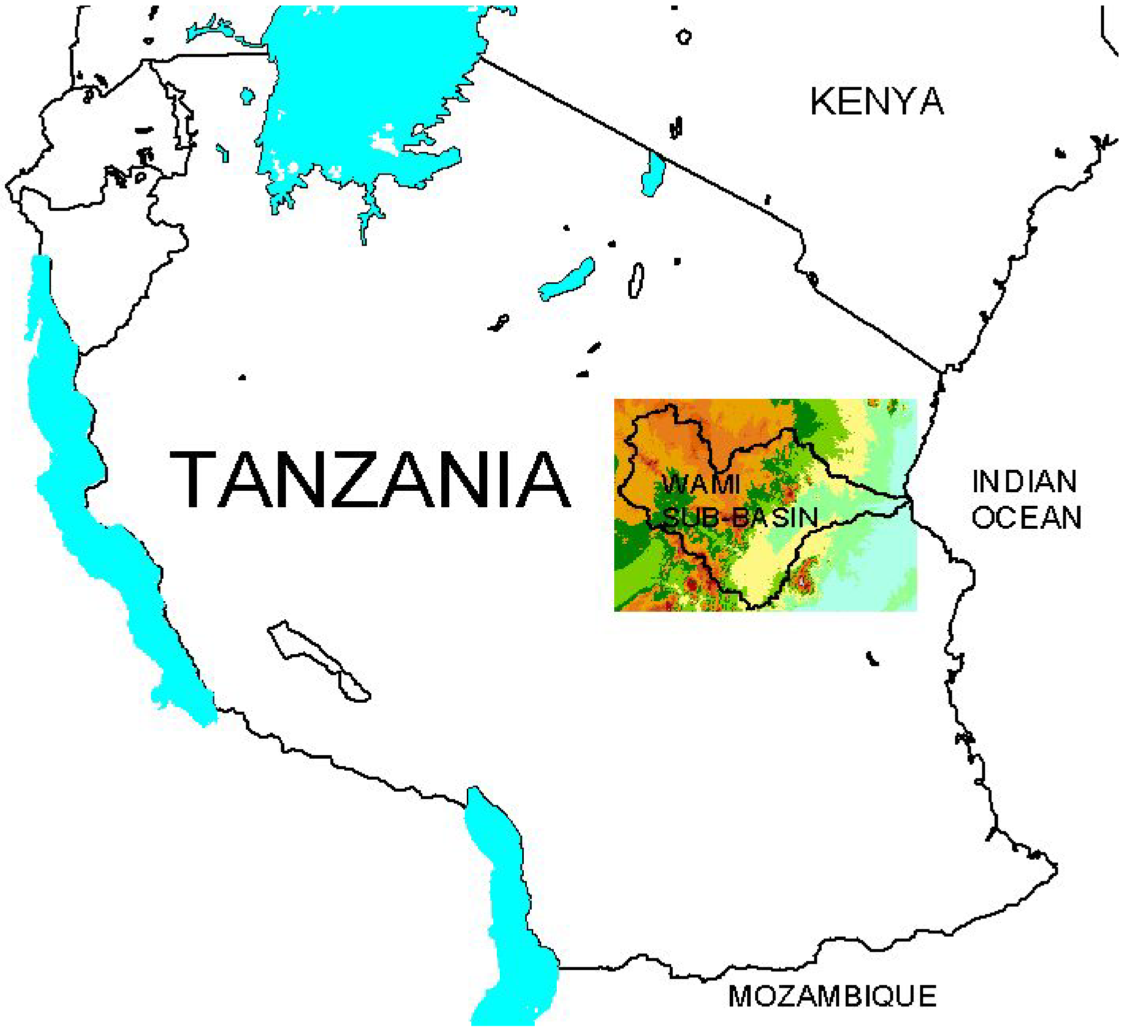

Fig.1.1: Location Map of the Study Area: (Valimba, 2007)

The Wami has its water sources in the Kaguru mountains and flows to the southeast across the Mkata plains to the Indian oceans. It covers an area of about 40,000km^2 and crosses the political boundaries of four administrative Regions; namely Dodoma, Morogoro, Tanga and Coast Regions. The Wami delta is about 90km from Dar es Salaam.

1.5.2 Climate and Hydrology

1.5.2.1 Climate

The Rainfall characteristics of Wami river basin vary both spatially and temporally. The Nguru Rubeho mountain complex receives between 800-1200 mm and the Ukaguru mountain 1000-1800mm annual rainfall. Rainfall is much less in the plains amounting 800-1000 mm near the coast reducing in amount to the North of Wami basin (Munishi, 2004).

A detailed historical analysis of seasonal rainfall patterns in the Wami river sub-basin indicates that the primary rainy season is March-May (MAM), dry season (with monthly rainfall amounts predominantly below 50mm) is June-September (JJAS), short rains in October-December (OND) and intermediate season from January-February (JF). August is the driest month in the sub-basin while the highest rainfall amounts are mainly experienced March/April (BICO, 2005). Typical seasonal rainfall patterns in the Wami-Ruvu river basin are shown in Fig 1.2 below.

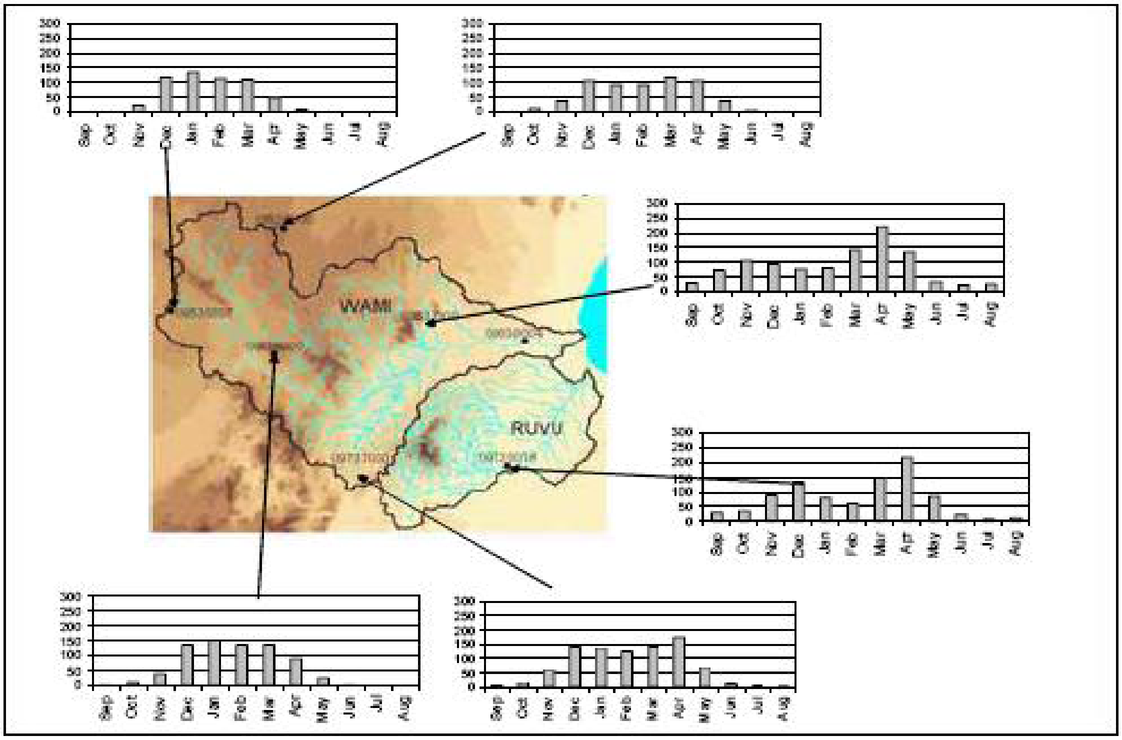

Fig. 1.2: Typical Seasonal Rainfall Patterns in the Wami-Ruvu River Basin (BICO, 2005)

1.5.2.2 Hydrology

The wami Hydrology is composed of rivers, wetlands and manmade and natural lakes. Most of the rivers in the Wami river basin are perennial although some dry up during relatively dry years. According to (Munishi, 2004) Wami river basin may be divided in to four Sub-basins:

- Kinyasungwe which drains the dry North and East of Dodoma
- The mountain areas of Ukaguru, Rubeho and Nguru mountain ranges
- The Northern semi-desert area in the Masai steppe
- The lower Wami

The main tributaries of the Wami basin river system includes the River Kinyasungwe (which drains the arid areas of Dodoma), River Mkondoa (which drains the Southern Ukaguru mountains), Rivers Lumuma and Mdukwe (which drain the Rubeho mountains), River Mkata (which drains the eastern Rubeho), Rivers Tami and Kisangata (which drain the Eastern Ukaguru mountains), River Diwale (which drains the Nguru mountains), River Lukigura draining the Nguru mountains and the main Wami.

The Wami wetland includes Tendigo and Dakawa swamps extending almost the whole length of the inland plain zone; and several manmade reservoirs including Lakes Hombolo, Ikowa and Dabalo in the upper catchment zone (Valimba, 2007). The hydrology system of Wami river basin is shown in Fig 1.3 below.

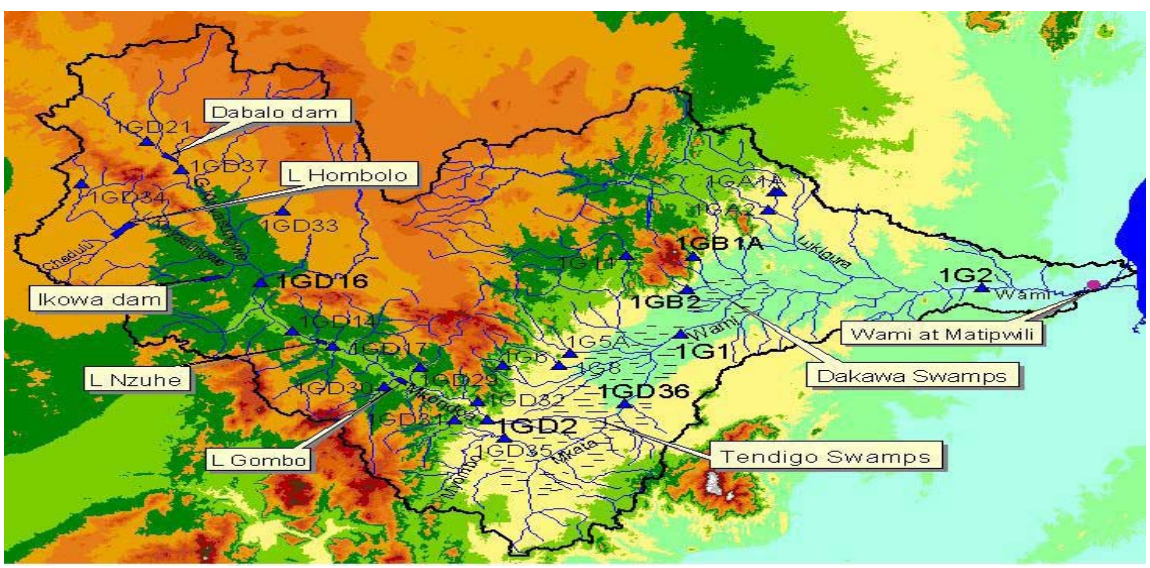

Fig.1.3: Wami Basin Hydrology System :(Valimba, 2007)

A system of 30 flow gauging stations was established in the Wami river basin in the 1950s and 1960s. The gauging stations and available records are shown in Table A-3 in Appendix A. Spatially the Wami basin area is characterized by varying topographical features as well as rainfall intensity. Accordingly the generated runoff also varies greatly in the sub basins. Runoff from the Dodoma region of the Wami and in the plains of the lower Wami is low due to high rates of evaporation in the river sub-basin and low precipitation. The Wami river basin hydrometric station near Mandera has a catchment area of about 36,400 km^2 and a mean annual flow of 62.3 Cumecs (Kalinga, 1998). Most of the flow (about 60 to 70 percent) at Mandera station (1G2) originates from a small part of the catchment on the slopes of Nguru, Ukaguru and Rubeho mountains because these areas have much higher rainfall (TCMP, 2007).Considering the temporal flow variation, the low flows in the basin occur in February-March and July-October with the lowest flows observed in October (BICO, 2005).

1.5.3 Topography

The basin consists of wide plains and large mountains. The main mountains include; the Nguru mountains West of Kilosa (altitude range 400- 2000m amsl), Rubeho mountain West of Kilosa (altitude range 500-1000m amsl) and the Ukaguru mountains to the North of the Wami river system (Altitude range 400-2000m amsl). The most noticeable plains are the Mkata-Wami, lower Wami and the Berega valley in the Wami river system (Mackie, 1998). The relief Map of Wami basin is shown in Fig.1.4 below.

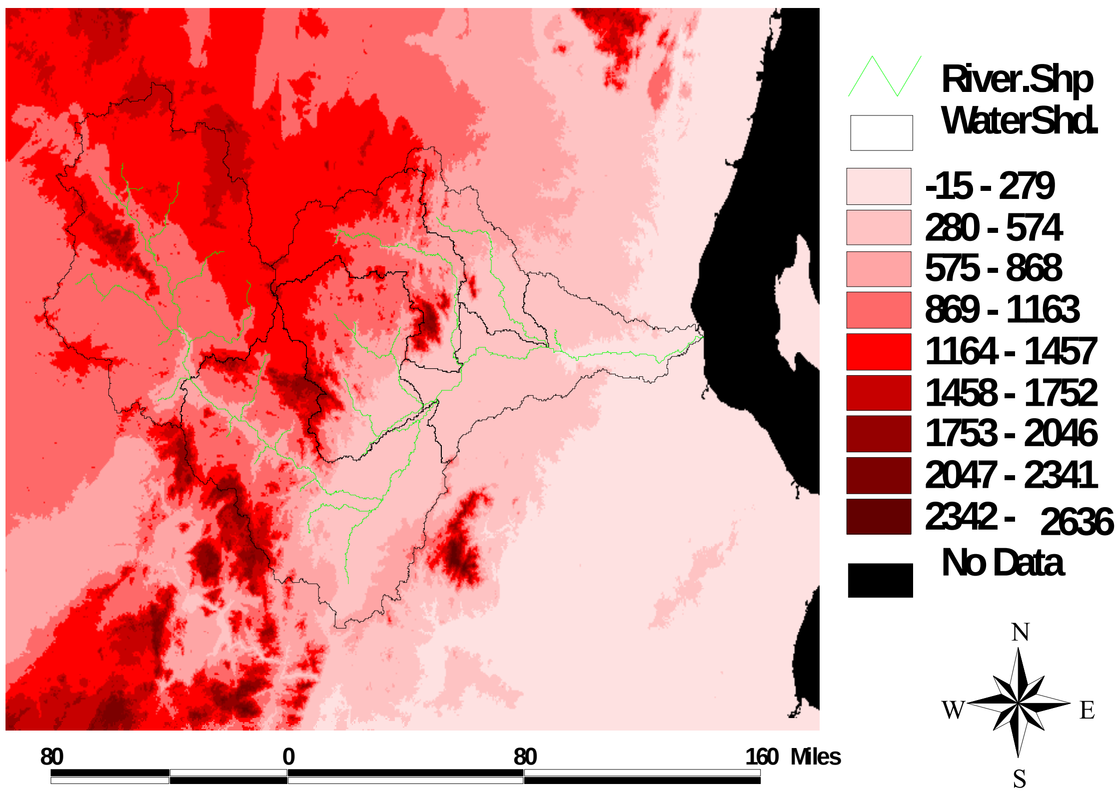

Fig.1.4: Relief Map of Wami River Basin :(USGS)

1.5.4 Geomorphology

The geomorphology of wami river basin is categorized under the geomorphological land surfaces of the Wami/Ruvu basin; which include the Gondwana African, Post African and Congo/coast land surfaces. The Gondwana land surfaces occupy a small part while the rest of geomorphological units are equally distributed over the basin (Kalinga, 1998).

1.5.5 Geology

The upper Wami river basin is mainly characterized by geological features of granitic outcrops and basement rocks. The central Wami river basin is underline by the basement complex of coarsely crystalline, metamorphic rocks of sedimentary and volcanic origin. The Nguru and Ukaguru mountains and Nguru ya Ndege are part of the Usagara system of the basement complex. The major rock formations in these areas are magmatic quartizo - feldspathic gneiss and granulite; granite-biotite gneiss; garnet-proxene hornblends; and amphibolite. The alluvial and colluvial deposits of the western section of the central plain include strata of clay, silt, sand and gravel (BRALUP, 1971).

1.5.6 Social and Economic Activity in the Basin

Outside of the major urban areas (Morogoro, Dodoma, and Kibaha), agriculture is the primary livelihood in the Wami river sub-basin (TCMP, 2007). Sugar cane, sisal and cotton are produced as cash crops in large scale agriculture. Small holder agriculture includes maize, rice, sweet potatoes and beans. Surplus food crops in small-scale agriculture are typically sold in local markets. Other rural livelihood activities include livestock keeping, bee keeping, hunting and fishing. In general, the only source of livelihood available to many in the basin is primary, i.e. a livelihood based on the direct exploitation of the basin’s natural resources. The success of these livelihoods is directly related to land and water availability.

1.6 Organization of the Dissertation

The first chapter of this work presents the general framework, motivations of this research and briefly presents the study area through the location, topography, climate, hydrology and other physical characteristics of the catchment. Chapter two covers literature review which presents hydrological modelling in general including the purpose of hydrological modelling, classification of rainfall runoff models and descriptions of the different types of rainfall -runoff models. Data collection and data processing and analysis will be discussed in chapter three and Chapter four respectively. The model application is presented in Chapter five followed by Chapter six which presents analysis, discussion of results and limitation of the study. Finally, Chapter seven concludes the study by presenting summary, conclusion and recommendation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The term modelling of hydrological systems usually means the application of mathematical and logical expressions that define quantitative relationships between flow characteristics (output) and flow-forming factors (input). This is a very general definition that covers an entire spectrum of approaches. At one extreme are the purely empirical, black-box techniques, i.e., those that make no attempt to model the internal structure and response of the catchment but that only match the input and output of the catchment system. At the other extreme are techniques involving complex systems of equations based on physical laws and theoretical concepts that govern hydrological processes- the so-called Hydrodynamical models (WMO, 1994). Between these two extremes, there are various conceptual models. These models represent a logical consideration of simple conceptual elements, e.g., linear or non-linear reservoirs and channels that simulate processes occurring in the basin. Whether black-box, conceptual, or hydrodynamical, these models yield outputs without associated probabilities of occurrence. For this reason, they are often referred to as deterministic models.

However, the term modelling of hydrological systems is sometimes considered to include stochastic modelling, where the emphasis is on reproducing the statistical characteristics of hydrological time-series. No attempt is made to model input output relationships.

2.2 Objectives of Hydrological Modelling

The primary objective of hydrological modelling is quite often to generate a long representative time series of streamflow volumes from which water supply schemes and civil structures can be designed (Hughes, 1995, Mwelwa, 2004). For efficient and dependable design decisions to be made, longer streamflow time series are required than are frequently available. Therefore flow time series have to be generated with sufficient accuracy through the use of hydrological models.

Hydrological models are therefore a useful tool to aid decision making in water resources assessments, planning and management (James, 1991; Mwelwa, 2004).Their specific applications may include: forecasting and predicting hydrologic phenomena; provision of sufficient information for engineering structural design, record extension, reservoir operation simulation, data in-filling and revision and the assessment of effects of land use changes or other catchment developments.

2.3 Types of Rainfall-Runoff Modelling

2.3.1 Stochastic and Deterministic Models

The hydrological cycle is a complex system and cannot be easily modeled by physical laws. Two approaches may be adopted to simulate the hydrological process of a catchment.

A model is termed as deterministic if the input data determines output uniquely as a function of time and not as a frequency distribution (Nash, 1982). Deterministic models have no components controlled by chance and regard hydrological processes as being chance independent. A vast majority of models are deterministic.

A model is called Stochastic if output develops in time in a probabilistic manner. Stochastic models have some components of random character and regard hydrological processes as being chance dependence, and make use of existing data and statistical principles to generate output in accordance with certain statistical patterns.

2.4 Classification of Deterministic Models

According to (WMO, 1994) Rainfall-Runoff models fall into three broad categories namely, Black box, conceptual and Hydrodynamical models. They are discussed in the following sections.

2.4.1 Black-Box Models (System Approach)

A river basin can be regarded as a dynamic system in which lumped parameters, which are invariant over the basin, transform the input factors, precipitation and snow melt, into a hydrograph of outflow from the basin. Diagrammatically, such systems can be represented as shown in Figure 2.1, where *P(t)* is the input and *Q(t)* is the output, both functions of time *t*. The premise that the outflow hydrograph of a basin can be predicted from a sequence of precipitation and snow melt only involves the assumption that the variability of other natural inputs, such as evapotranspiration, is small or follows a known function of time (WMO, 1994). The general expression for the relationship between input *P(t)* and output *Q(t)* of a lumped-parameter, linear dynamic system may be written as:

$$a_n(t)\frac{d^nQ}{dt^n}+a_{n-1}(t)\frac{d^{n-1}Q}{dt^{n-1}}+\ldots+a_1(t)\frac{dQ}{dt}+a_0(t)Q= \\ b_n(t)\frac{d^nP}{dt^n}+b_{n-1}(t)\frac{d^{n-1}P}{dt^{n-1}}+\ldots+b_1(t)\frac{dP}{dt}+b_0(t)P \qquad (2.1)$$

Where: - the coefficients a_i and b_i are the parameters characterizing the properties of the system.

The solution to equation (2.1) for zero initial conditions gives:

$$Q(t)=\int_0^t h(t-\tau)P(\tau)d\tau \qquad (2.2)$$

Where the function *h(t,τ)* represents the response of the system at a time *t* to a single input impulse at time τ.

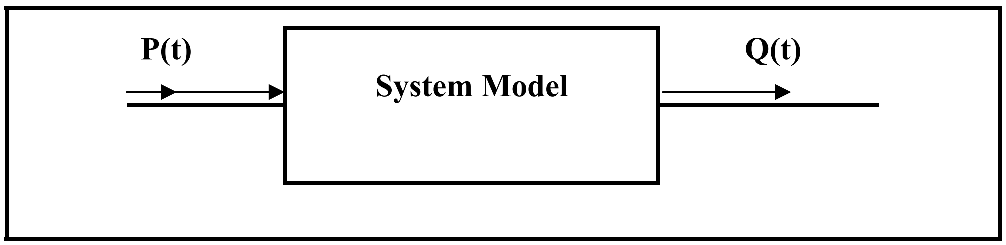

Fig 2.1- Black Box System :(WMO, 1994)

The unit Hydrograph concept and the routing techniques are examples of linear dynamic systems involving the principle of superposition. Non-linear systems are those for which the superposition principle is not satisfied. In general, the response of a non-linear, lumped-parameter system to an input can be expressed by means of an ordinary non- linear differential equation.

2.4.2. Conceptual Models

Black-box models make use of only very general concepts of the transformation of input data into the outflow hydrograph. For some purposes, such an approach is inadequate. Catchment modelling problems involving complex rainfall to runoff transformations usually do not respond well to this type of analysis, nor do many types of water-resource studies in which it is necessary to evaluate the effects of weather modification, changes in land use, and other of man's activities. As a result, an approach to modelling has been developed that involves equation structures based on various concepts of the physical processes of flow formation. These are commonly referred to as conceptual models.

Xinanjiang (China), Stanford Watershed Model (USA), Pitman (South Africa) and SMAR (Ireland) are some examples of conceptual models.

2.4.3 Hydrodynamic Models

Hydrodynamic models are based on a refined space discretization of the catchment and on numerical integration of equations of momentum and mass conservation that describe the physical processes in the basin. Such models provide a basis for full use of distributed information relevant to the physical processes in the catchment. Since hydrodynamic models are based on the physical laws governing the processes, extrapolation beyond the range of calibration may be performed more confidently than with conceptual models.

The European Hydrologic System (SHE) is an example of a hydrological model. SHE is a model with distributed parameters that has been developed from partial differential equations describing the physical processes in the basin: interception, evapotranspiration, overland and channel flow, movement of water through unsaturated and saturated zones, and snow melt.

2.4.4 Lumped and Distributed Deterministic Models

Based on the nature of the input data, deterministic models can be classified as Lumped and distributed models. A lumped model refers to a model in which the parameters do not vary spatially within the catchment. Therefore, catchment response is evaluated only at the outlet, without explicit accounting of the response of individual catchments. Typical examples of lumped parameter models are the Unit Hydrograph, HEC-1 and Tank model. A distributed model refers to a model in which the parameters are allowed to vary spatially within the catchment. This enables the calculation not only to consider the overall catchments response but also of the response of individual catchments. SHE model is an example of the distributed model.

2.5 Selection of Models

The selection of a model for a specific hydrological situation has implications in water-resources planning, development, and management. According to (WMO, 1994), some of the factors and criteria involved in the selection of a model include the following:

(*a*) The purposes and benefits of the model-output, e.g., continuous hydrograph of discharges, forecast of floods, water quality, and water-resource management;

(*b*) The climatic and physiographic characteristics of the basin;

(*c*) The lengths of the records of the various types of data;

(*d*) The quality of the data both in time and space;

(*e*) The availability and size of computers for both development and operation of the model;

(*f*) The possible need for transferring model parameters from smaller catchments to larger catchments; and

(*g*) The ability of the model to be updated on the basis of current hydrometeorological conditions.

2.6 Model Components and Model Construction

The basic catchment model components are precipitation, hydrologic Abstractions and runoff. Usually, precipitation either in the form of rainfall or snowfall is the modelling input and is the process driving the catchment model. Hydrologic abstractions are the physical processes acting to reduce total precipitation into effective precipitation and they can be determined by the catchment's properties. Runoff is the modelling output which can be distincted as catchment and stream channel runoff.

The construction of a catchment model begins with the selection of model components. Once these are chosen, they are assembled as parts of the overall model, following a logical sequence that resembles that of the natural processes. The rainfall and snowfall are considered first, followed by hydrologic abstractions, subcatchment hydrograph generation, reservoir and stream channel routing, and hydrograph combination at stream flow components.

2.7 Model Calibration

Model calibration is the process by which the values of the model parameters are identified for use in a particular application. It consists of use of rainfall-runoff data and a procedure to identify the model parameters that provide the best agreement between simulated and recorded flows. Parameters identification can be accomplished manually, by trial and error, or automatically, by using mathematical optimization techniques.

2.8 Sensitivity Analysis

Sensitivity analysis is the process by which a model is tested to establish a measure of the relative change in results caused by a corresponding change in model parameters. Sensitivity is usually analyzed by isolating the effect of a certain parameter. If a model is highly sensitive to a given parameter, small changes in the value of this parameter may cause correspondingly large changes in the model output. It is, therefore necessary to concentrate the modelling effort in to obtaining good estimates of this parameter. On the other hand, insensitive parameters can be relegated to secondary role.

2.9 Model Validation/Verification

Calibrated model parameters can result in simulations that satisfy goodness of fit criteria, but parameter values may not have any hydrological meaning. Values of model parameters will be a result of curve fitting. This is also reflected in having different sets of parameter values producing simulations which satisfy these criteria. It is necessary to test if parameter values reflect underlying hydrological processes, and are not a result of curve fitting. This is called Model validation (Klemes, 1986; Mazvimavi, 2003). There are two approaches for model validation, namely the split-sample test and Proxy-basin test (Mazvimavi, 2003). The split-sample test involves splitting the available time series into two parts. One part is used to calibrate the model, and the second part is used for testing if calibrated parameters can produce simulations which satisfy goodness-of-fit tests. This approach is suitable for catchments with long series data. Considering the proxy-basin test, calibration is done on one catchment, and the parameters are tested on a similar catchment.

2.10 Model Efficiency Criteria

The performance of the model is judged on the extent to which it satisfies its practical objective (Accuracy), on the extent to which the achieved level of accuracy persist through different samples of data (Consistency) and on the extent to which it can sustain the achieved level of accuracy when subjected to diverse applications and tests other than those used for calibrating the model (Versatility).

The correspondence of simulated and observed hydrographs is measured by a number of statistical goodness-of-fit criteria known as objective functions. There are many types of objective functions available, the choice of which to which to use is related to the modelling application. The following objective functions are able to provide a satisfactory assessment of the correspondence between observed and simulated hydrographs:

I) Index of Non-Dimensionless Residual Error (F)

A commonly used objective function is the sum of squares of differences F between the observed and the estimated discharges, with the summation taken over the whole of the calibration period, that is,

$$F = \sum_{i=1}^{N} (Q_{obs(i)} - Q_{est(i)})^2 \qquad (2.3)$$

Where:-

F is index of non-dimensionless residual error

N is the number of data points

$Q_{obs\,(i)}$ and $Q_{est\,(i)}$ are observed and estimated flows respectively

The quantity F is an index of residual error, which reflects the extent to which a model is successful in reproducing the observed discharges. It is therefore, an appropriate criterion for expressing model accuracy. However, it is not a dimensionless quantity and, while it may be used to compare various alternatives-forecasting models on the same catchment, it is not suitable for comparing the performance of a model on different catchments or with different lengths of records.

II) Model Efficiency (R^2)

Nash and Sutcliffe (1970) define the model efficiency (R^2) analogous to coefficient of determination (varies between 0 and 1) in linear regression as follows:-

$$R^2 = \frac{(F_o - F)}{F} \tag{2.4}$$

Where,

$$F_o = \sum_{i=1}^{N} (Y_{obs(i)} - Y_{mean})^2 \tag{2.5}$$

$$F = \sum_{i=1}^{N} (Y_{obs(i)} - Y_{est(i)})^2 \tag{2.6}$$

and,

$$F_{mean} = \frac{\sum_{i=1}^{N} Y_{obs(i)}}{N} \tag{2.7}$$

Where:-

F_o is the initial Variance

F is the residual Variance

N is the number of data

$Y_{obs(i)}$ is the observed discharge on day (i)

$Y_{est(i)}$ is the estimated discharge on day (i)

Y_{mean} is the average measured (observed) discharge of the calibrated period

For comparing the relative accuracies of different models (say models 1 and 2) using the same data, the R^2 criterion provides a convenient index of comparison of the corresponding sums of squares of model residual errors.

III) Index of Volumetric Fit (IVF)

The Index of Volumetric Fit (IVF) is the ratio of the total volume of the estimated flow to the total volume of observed flow and is given by:-

$$IVF = \frac{\sum_{i=1}^{N} (Q_e)_i}{\sum_{i=1}^{N} (Q_o)_i} \tag{2.8}$$

Where:-

IVF is the Index of Volumetric Fit

$(Q_e)_i$ is volume of the estimated flow

$(Q_o)_i$ is total volume of observed flow

Other types of objective functions include Coefficient of Daily Gain (DG), Percentage error in peak discharge, (% P) and Time difference between observed and simulated peaks, (TP). All of the objective functions can be calculated using untransformed discharge values or using the natural logarithm of values.

2.11 Review of Previous Studies and Findings

2.11.1 Previous Hydrological Modelling Studies in the Wami River Basin

(Kalinga,1998) has made an assessment on the application of the systems type Rainfall-runoff models to determine their adequacy for Rainfall runoff transformation and selected a model with a higher efficiency (R^2) to be used for river flow forecasting in Wami/Ruvu drainage basin.

The Rainfall-runoff models used in the study were the Seasonal Model(SM), The Multiple-Input Simple Linear Model (MISLM), The Multiple-Input Linear Perturbation Model (MILPM), The Multiple-Input Linearly Varying Gain factor Model (MILVGFM) and the Multiple-Input Linearly Varying Gain factor Perturbation Model (MILVGFPM).

All the models applied showed better results in calibration than in verification period. The efficiency (R^2) of all the models especially for the verification period was low. The Multiple-Input Linear Perturbation Model (MILPM) showed better results compared to the other models, hence it was selected to be used for flow forecasting in the basin. For further Rainfall-runoff modeling study in the basin conceptual and physically based models were recommended.

2.11.2 Previous Application of Pitman Model in the Catchments of Tanzania

The Pitman model has been widely used in the Southern Africa region. It has been used for regional studies in the Okavango basin (covering Angola, Namibia and Botswana (Hughes et al. 2006)), water resource assessment studies in the Kafue basin in Zambia (Mwelwa, 2004), for estimation of hydrologic variables and regionalization studies in Zimbabwe (Mazvimavi, 2003) and for simulation of arid climatic conditions in Namibia (Hughes and Meltzer, 1998).

One of the previous studies conducted in applying the Pitman model in the catchments of Tanzania was done by Pangani Basin flow Assessment Initiative (PBWO/IUCN, 2006) under the heading "The Hydrology of the Pangani river basin, Hydrology and system Analysis volume I"

The research was undertaken in modelling of the rainfall runoff system in the Pangani basin of Tanzania which has an approximate drainage area of about 43,600 km^2 and is comprised of five major catchments, namely the Kikuletwa and Ruvu catchments located upstream of the Nyumba ya Mungu Dam, the Mkomazi and Luengera catchments along the eastern border of the basin, and the catchment of the main stem of the Pangani in the central and southern parts of the basin. The SHELL catchment models were compiled by configuring the rainfall-runoff (Pitman) model, as well as various other sub-models that simulate water use by irrigation and other consumptive uses, stream flow reduction by forests, and reservoir water balances. The study used data record length ranges of 15 – 40 years except one catchment with data record length of six years. By adjusting the Pitman model parameters simulated historical flows were altered to achieve a favorable comparison with historical observed flows. The monthly simulated and observed flow sequences were compared by evaluating the goodness-of-fit in terms of Annual mean, Annual mean (log), Annual standard deviation, Annual standard deviation (log),Seasonal index, Coefficient of Variation and comparative graphs of monthly time series, yield-storage curves, seasonal distributions and drought sequences. 10% percent deviation in observed and simulated mean annual flows and 30% percent deviation in the annual standard deviation of observed and simulated flows were considered as target criteria suitable for compilation of the Pangani hydrology. Considering the result of the study, for about forty percent of the test catchments, all the target criteria were achieved. For the remaining sixty percent of the test catchments the targeted standard deviation limit was not attained. Even though no verification was done for the attained calibration results, the model has been applied to develop long term monthly flow sequences at a number of key points in the basin; and it has been used to provide basic hydrological information that is required to support water resource management and water allocation decisions in the basin.

2.11.3 Previous Application of SMAR Model in the Catchments of Tanzania

SMAR model has been applied in various catchments of Tanzania. In this section two previous studies carried out in Pangani and Kihansi catchments will be discussed. One of the previous studies conducted in testing the applicability of SMAR model in the catchments of Tanzania was done by (Argaw,2001) under the heading “Rainfall-Runoff

Modelling of The catchment Upstream Nyumba Ya Mungu Reservoir in Pangani River Basin Tanzania". The research was aimed at determining the rainfall-runoff modelling for catchment upstream of Nyumba Ya Mungu reservoir in Pangani basin. SMAR model together with LPM, NAM, XINANJINANG and semi distributed physically based models were applied to the catchment and comparison of the models was based on calibration done at the out lets of six sub-catchments. The record data length used ranges from five to eleven years with in the duration 1980 to 1990. The Nash-Sutcliffe (1970) Model Efficiency Index (R^2) was adopted as measures of the performances of the models. The best model efficiency result for SMAR model was R^2 of 61.16% and 77.98% during calibration and verification periods respectively at 1dd1 catchment. For the other five sub-catchments the efficiency was very low ranging R^2 of (-45.69-29.07) and (-35-22) during calibration and verification periods respectively. The results obtained for the other models in the study were also very low. By considering the model efficiency results, the study concluded that the SMAR model is not adequate to simulate the rainfall-runoff system of the catchments. According to the findings of the study, the reason that may contribute to the poor performance of the model includes highly established irrigation abstraction in the upstream of catchment of the Pangani basin and the presence of small Lake Jipe which has significant storage effect and depresses the peak flows and results in high evaporation. Finally, recommendation has been given to consider inclusion of correction for abstraction and storage effect of the lake in future studies.

The other application of SMAR model in the catchments of Tanzania was done by (P'Obong, 2007) under the heading "Rainfall-Runoff Modelling of Kihansi Catchment". The research was undertaken in modelling of the rainfall runoff system in Kihansi catchment of Tanzania which has an approximate drainage area of 581 km^2. SMAR model together with LPM and SWAT models were applied to the catchment and comparison of the models was based on calibration done at NC3, the out let of the catchment. Eight years (1997 to 2004) record length data has been used for the study. The Nash-Sutcliffe (1970) Model Efficiency Index (R^2) and Index of Volumetric Fit (IVF) were adopted as measures of the performances of the models. The model efficiencies for SMAR model were R^2 of 67.08% and 57.96% during calibration and verification periods respectively. The IVF for SMAR model were 0.97 and 0.83 during calibration and verification periods respectively. By considering the model efficiency results, the study concluded that the SMAR gave reasonable results in terms of R^2 values for rainfall runoff transformation and therefore it can be used in simulation and forecasting discharges and also as a monitoring tool for monitoring flow in the catchment.

2.12 Discussion of the Models Used in the Present Study

The present study assesses the application of two conceptual Rainfall-runoff models (Pitman and The Soil Moisture Accounting and Routing (SMAR)) in the Wami river basin of Tanzania. The Principles of the two models are described as follows:

2.12.1 Pitman Model

The Pitman model through different versions (Pitman, 1973; Hughes, 1997; Hughes and Parsons, 2005) has been the most widely used in the Southern Africa region (Kapangaziwiri, 2007). Similar to many other conceptual models, the Pitman (1973) model consists of storages linked by functions designed to represent the main hydrological processes prevailing at the basin scale.

2.12.1.1 Pitman Model Structure

Precipitation and potential evapotranspiration are the sole data inputs. The first model process starts by interception of the Precipitation input. Evaporation from intercepted water is determined from established relationships among interception storage (PI in mm), monthly rainfall and total interception loss.

The next modeled process is a splitting of the remaining rainfall input into surface runoff and absorbed rainfall. Surface runoff is defined by three parameters, AI, ZMIN and ZMAX. AI is the proportion of impervious catchment directly linked to the channel system while ZMIN and ZMAX are the minimum and maximum absorption rates in mm/month for the remaining catchment surface. The absorption rate for the catchment is assumed to follow a triangular frequency distribution.

Of the water that penetrates the soil, the balance between that which evaporates and that which reaches the channel system is determined by the potential evaporation for the month and several model parameters. Factors controlling evaporation are: PE, the potential evaporation (mm); S, the current soil moisture state (mm); ST, the total soil moisture storage capacity (mm) and R a factor that determines the rate at which evaporation decreases from potential at S= ST to zero at a storage defined by R and PE. ST and R are model parameters while PE forms part of the input data. The current value of soil moisture storage, S, is determined by satisfying the water balance of the catchment. The quantity of soil moisture that reaches the channel system is also dependent on S and ST as well as on the parameters SL, FT and POW.SL is the soil moisture state in mm below which there occurs no runoff (excluding surface runoff). FT is the runoff in mm from soil moisture at S=ST and POW is the Power of the assumed soil moisture-runoff curve.

Time delay of runoff is modeled by applying a lag, TL (months). Provision is made for separating the components of runoff in respect of time delay and the parameter GW determines the Upper limit of runoff (in mm) from soil moisture having a lag equal to GL (GL>>TL).

Pitman model simulation exercise tests the ability of the model to synthesize adequately the recorded runoff data in respect of all the test catchments and also helps to see a means of estimating the model parameters for ungauged catchments. A summary description of Pitman Model parameters is given in Table 2.1 and the Schematic diagram of the Model is shown in Fig.2.2 below.

Table 2.1: Pitman Model Parameters: (Pitman, 1973)

Parameter	**Units**	**Pitman model parameter description**
AI	Fract.	Impervious fraction of sub-basin
PI	mm	Interception storage
ZMIN	mm month^{-1}	Minimum sub-basin absorption rate
ZMAX	mm month^{-1}	Maximum sub-basin absorption rate
ST	mm	Maximum moisture storage capacity
SL	mm	Minimum moisture storage below which no GW recharge occurs
POW	-	Power of the moisture storage-runoff equation
FT	mm month^{-1}	Runoff from moisture storage at full capacity (ST)
GW	mm month^{-1}	Maximum ground water recharge at full capacity (ST)
R	Fract.	Evaporation-moisture storage relationship parameter
TL	months	Lag of surface and soil moisture runoff
GL	months	Lag of runoff from soil moisture </= GW

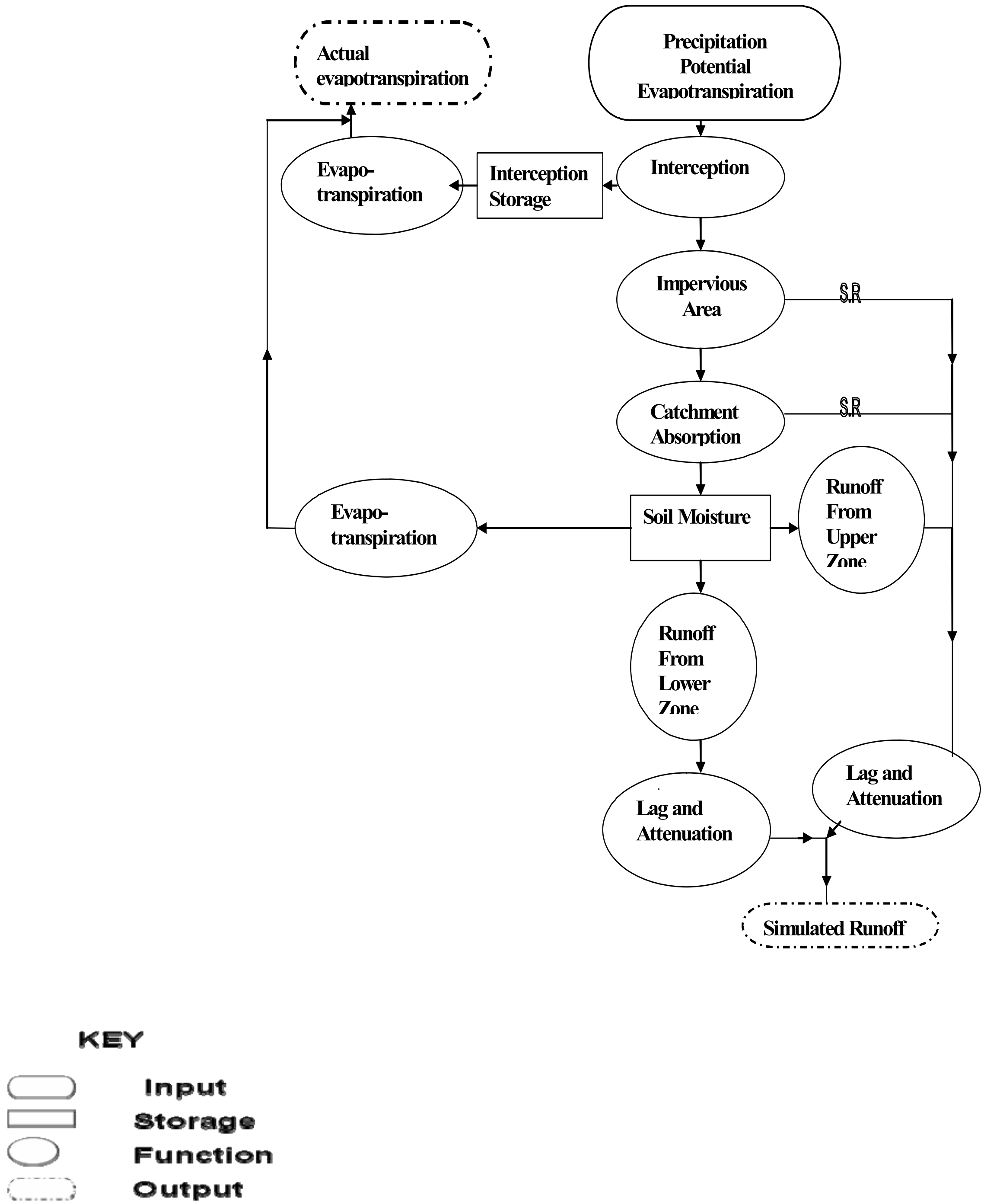

Fig.2.2: Flow Diagram to Illustrate the Structure of the Monthly Pitman Model: (Pitman, 1973)

2.12.1.2 Pitman Model Functions

The original Pitman Model used in the present study (Pitman, 1973) has six functions and twelve parameters. A summary of the details of the model functions and description of parameters are given below.

i. Rainfall Distribution Function

Each monthly rainfall is disaggregated in to a realistic sequence of shorter period precipitations. A period of ¼ month was adopted resulting in four iteration of the model operation. The distribution of the total monthly rainfall is controlled by an S-curve function that depends on total rainfall and the Rainfall distribution factor (RDF).Lower values of RDF result in a more even distribution of rainfall. In the original Pitman model the value of RDF is fixed to 1.28.

ii. Interception Function

The depth of rainfall intercepted in any month is based on an empirical relationship between the relevant interception parameter PI and rainfall depth. Interception storage contributes to satisfy the evaporation demand at the potential rate.

iii. Surface Runoff Function

Surface runoff is taken to be derived from two components, i.e, runoff from impervious areas and runoff resulting from rainfall not absorbed by the soil. The parameter AI is used to represent the proportion of the catchment that is impervious and in direct connection with the drainage system. All of the rainfall over this part of the catchment generates surface runoff and therefore the model results can be very sensitive to the value of this parameter during low rainfall depths.

Calculations of runoff resulting from rainfall not absorbed by the soil are based on a symmetrical triangular distribution of catchment absorption rates using parameters ZMIN and ZMAX to define the minimum and maximum absorption rates, respectively. For any given rainfall rate, the area under the triangle, up to the rainfall rate, effectively represents the relative proportion of the catchment that is contributing to surface runoff.

iv. Soil Moisture Storage - Runoff Function

The runoff (Q)-soil moisture (S) relationship is a simple power curve expressed in terms of the parameters SL (soil moisture content below which no runoff occurs), ST (Total soil moisture capacity), FT (Run of at maximum soil moisture state) and POW (power of Q-S curve).

The proportion of rainfall that is not intercepted or contributing to surface runoff adds to the moisture store and if the maximum value soil moisture storage (ST) is exceeded, the balance becomes part of the runoff from the upper zone or runoff from the lower zone depending of the value of GW (mm month), a parameter which separates the inter flow component from the ground water in order to lag the two components separately (Figure 2.2).

v. Evaporation -Soil Moisture Function

The catchment evaporation is determined by the current evaporation (PE), the maximum monthly evaporation (PE MAX) and a parameter R plus the soil moisture (S). R is a parameter with values ($0 < R < 1$) and is defined as the rate at which catchment evaporation diminishes as soil moisture decreases. A low value for R implies 'more effective' evaporation loss and allows evaporation to occur even at quite low levels of the moisture store. A high value of R suggests that evaporation losses cease at relatively high moisture storage levels for months with relatively low evaporative demand.

vi. Time Delay of Runoff

The runoff for any given month computed according to the processes described may be regarded as instantaneous runoff which must be subjected to time delay and attenuation as it moves laterally through the catchment. Therefore, the generated runoff from the upper and lower zones are lagged separately using parameters TL and GL, which refer to the lag parameters in the Muskingum routing equation with the weighting factor set to zero to represent reservoir-type storage attenuation. In the model allowance is made to lag the two components of the runoff by assigning different Muskingum 'K' values based on the parameters TL and GL.

2.12.1.3 Calibration Procedures

(Pitman, 1973) provides some guidelines for manually calibrating the model under different climate types. These guidelines demonstrate the effect of change in parameter values on the simulation results. The main parameters that should be involved in any manual calibration are ZMIN, ZMAX, ST, POW, FT, GW and R (Table 2.1). The majority of the other parameters should be determined *a priori*, or remain fixed during the calibration process.

In catchments with good vegetation cover, temperate to humid climates and naturally perennial flow systems the ZMIN, and ZMAX parameters are frequently not used (i.e. set to very high values beyond the range of likely monthly rainfalls). SL is normally set to zero, unless there are strong reasons for limiting runoff generation to a non-zero level of moisture storage (possibly related to deep storage that can be evaporated, but does not contribute to runoff). Setting the initial value of ST can usually be achieved by focusing on several months with very high rainfall. If these exceed the ST value, relatively high runoff peaks are usually generated which can then be compared with the observed data. Changes to ST also have substantial impacts on runoff generated during lower rainfall months, through its effect on the non-linear runoff generation equation involving parameters FT and POW. It is usually therefore necessary to adjust ST, POW and FT to try and achieve reasonable simulations across a range of different rainfall total months. Adjustments to POW and GW (and if necessary GL and TL) can be made to improve the fit to recessions into the dry season and the dry season flows. The evaporation parameter R can also have a significant impact on this aspect of the model results.

In semi-arid to arid catchments, the calibration emphasis should be placed on the ZMIN and ZMAX parameters rather than POW, FT, GW and R, while ST can be just as important.

For any program of calibration it is important to establish a set of principles that are applied across all catchments (Mwelwa, 2004). The main reason for this is that, like any model with more than a few parameters, there is a lot of parameter interaction and there is not always a unique set of values that generate a unique result. In calibrating a group of catchments, it is therefore often necessary to follow an iterative procedure whereby initial parameter sets are established for all catchments and then a 'regionalised' procedure established that allows catchments with similar known characteristics to be simulated with similar parameter values.

2.12.2 The Soil Moisture Accounting and Routing (SMAR) Model

The Soil Moisture Accounting and Routing (SMAR) Model is a development of the 'Layers' conceptual rainfall-runoff model introduced by O'Connell et al. (1970). Typical of its class, the SMAR model is a lumped conceptual rainfall-evaporation-runoff model, with quite distinct water-balance and routing components. Using a number of empirical and assumed relations which are considered to be at least physically plausible, the non-linear water balance (i.e. soil moisture accounting) component ensures satisfaction of the continuity equation, over each time-step, i.e. it preserves the balance between the rainfall, the evaporation, the generated runoff and the changes in the various elements (layers) of soil moisture storage. The routing component, on the other hand, simulates the attenuation and the diffusive effects of the catchment by routing the various generated runoff components, (which are the outputs from the water balance component), through linear time-invariant storage elements. For each time-step, the combined output of the two routing elements adopted (i.e. one for generated '*surface runoff*' and the other for generated '*groundwater runoff*') becomes the simulated (un-updated) discharge forecast produced by the SMAR model.

The version of SMAR (Version no. 2.0, March 2002) used in the present study, the schematic structure of which is sketched in figure 2.3, is that which incorporates the suggested modifications of both Khan (1986) and Liang (1992). Thus it has nine parameters (Table 2.2), five of which control the overall operation of the water-budget component, while the remaining four parameters (including a weighting parameter which determines the amount of generated '*groundwater runoff')* control the operation of the routing component.

On the model process, evaporation occurs from the top layer at the potential rate, and from the second layer, only on exhaustion of the first, at the remaining potential multiplied by a parameter C, whose value is less than unity. On exhaustion of the second layer, evaporation from the third layer occurs at the remaining potential multiplied by C^2 and so on. Thus, a constant potential evaporation applied to the basin would reduce the soil-moisture storage in a roughly exponential manner. C is a parameter to be optimized.

When the rainfall exceeds the evaporation, a fraction H' of the excess contributes to generated runoff. Of the remainder, anything exceeding a threshold value or maximum infiltration capacity Y mm $days^{-1}$ also contributes to generated runoff. Normally, the fraction H’ is taken as being proportional to the available soil-moisture content of the first five layers (H' = H x (available soil-moisture content per 125 mm of water) but if Z is less than 125 mm, then H' is given by H multiplied by the ratio of the available soil-moisture content and the storage capacity Z. Z, Y and H are a parameters to be optimized. To estimate potential evaporation the estimated pan evaporation is multiplied by a ratio T, a parameter to be optimized under the constraint that it optimizes at a reasonable value. A summary description of SMAR Model parameters is given in Table 2.2 and the Schematic diagram of the Model is shown in Fig.2.3 below.

Table 2.2: SMAR Model Parameters :(Shamseldin et al., 1999)

Parameter	Description
Z	The combined water storage depth capacity of the layers (mm)
T	A parameter (less than unity) that converts the given evaporation series to the model-estimated potential evaporation series.
C	The evaporation decay parameter, facilitating lower evaporation rates from the deeper soil moisture storage layers
H	The generated *'direct runoff'* coefficient
Y	The maximum infiltration capacity depth (mm)
n	The shape parameter of the Nash gamma function *'surface runoff'* routing element; a routing parameter
nK	The scale (lag) parameter of the Nash gamma function *'surface runoff'* routing element; a routing parameter
g	The weighting parameter, determining the amount of generated *'groundwater'* used as input to the *'groundwater'* routing element.
K_g	The storage coefficient of the *'groundwater'* (linear reservoir) routing element; a routing parameter

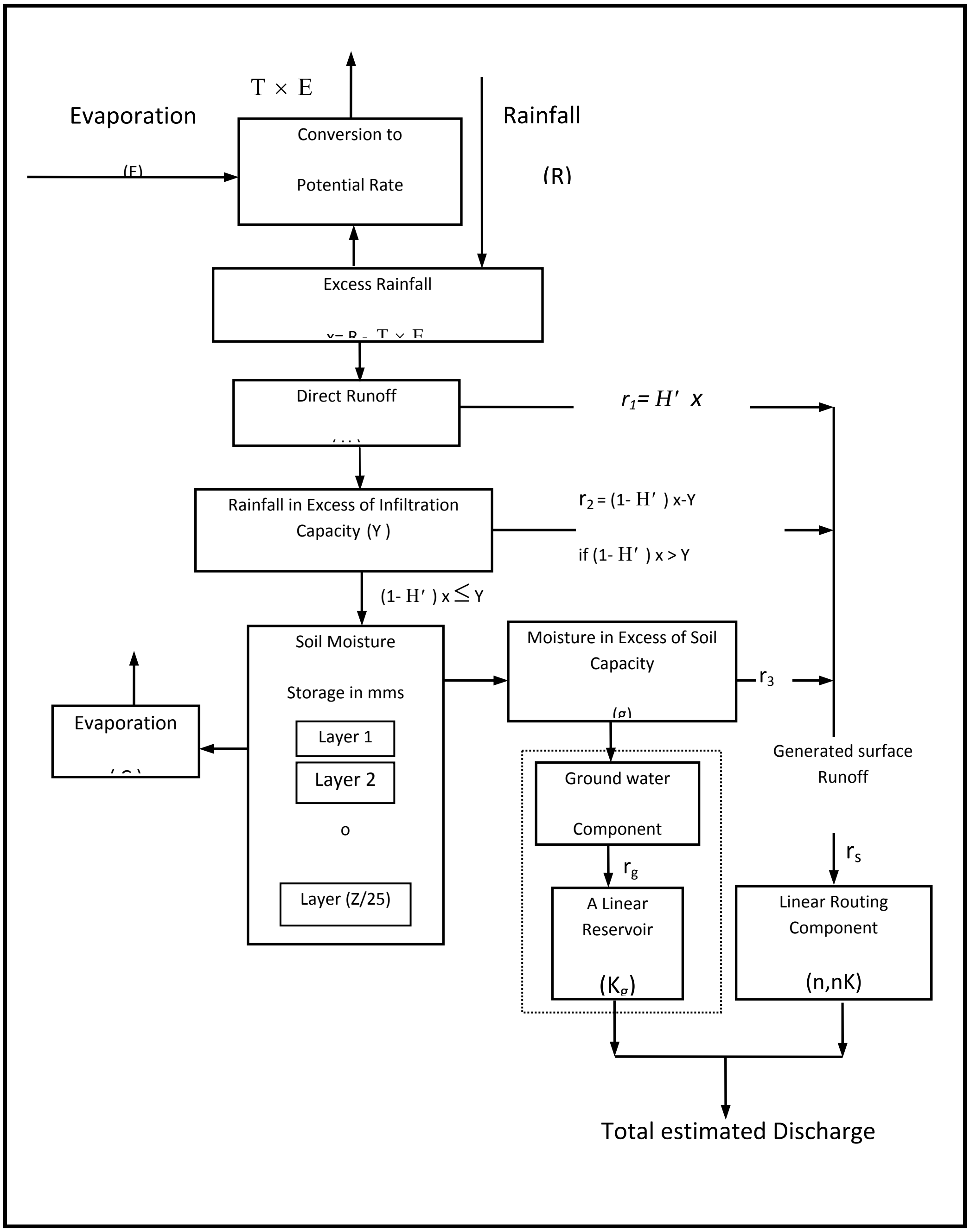

Fig. 2.3: Schematic Diagram of Liang Version of SMAR Model: (Liang, 1992)

2.12.2.1 Calibration Procedures

The SMAR Model calibration can be carried out using manual or automatic (simplex search) procedure to identify successive choices of the water balance parameters H, T, C, Y, Z, g and the routing parameters K_g ,n and *nK,* the calculation of the computed discharge y and the value of the objective function F. The search would be continued to find the values of H, T, C, Y, Z, g, K_g, n and *nK* which are realistic and which minimize the function F. We should try with various memory lengths and with various combinations of the starting values of the model parameters and check for the model efficiency R^2. The appropriate value of the memory length can be determined by observing the shape of the unit hydrograph.

All The five water balance components of the model cannot be evaluated together very effectively because the operations of several of these parameters are similar in effect in the determination of the volumes of effective rainfall. For instance, H and Y are similar in their effects and so also are the pairs C and Z, C and T and T and Z. Therefore, in any application, a model consisting of a subset of these elements must be chosen (Kachroo**,** 1992). For example, by setting H = 0, the proportional runoff component is removed from the model. By setting C = 1.0 the layers are replaced by a single storage of capacity Z, all of which is available for evaporation at the potential rate. The effect of T is removed if it is fixed at 1.0. Similarly the effect of Y is removed if it is given a fixed value exceeding the observed daily maximum rainfall during the period of record and Z becomes inoperative if it is set to a sufficiently large value.

CHAPTER THREE

DATA COLLECTION

3.1 General

The present study requires Hydro-metrological data of Wami river basin specifically daily and monthly precipitation data, daily and monthly flow data, daily and average monthly evapotranspiration data as an input. The spatial data requirements of the study include Digital Elevation Model (DEM), soil, and geology and vegetation cover data for the wami river basin.

The data collection is carriedout through contacting the responsible organizations for collecting and managing the above mentioned data, referring previous studies and searching through the Internet. Source of data, inventory of Hydro-meteorological stations and availability of data in the wami river basin is presented in the following sections.

3.2 Data Availability

3.2.1 Availability of Precipitation Data

Precipitation data was obtained from Tanzania Metrological Agency (TMA) and also available previous studies has been referred to carry out the inventory on the Meteorological stations in the basin and to identify availability of daily and monthly

Two types of time series precipitation data are collected. Monthly precipitation data is available for the whole 120 rainfall stations. Out of the 120 stations 18 stations (15% of the total) have data records with less than or equal to 9 years; 28 stations (23% of the total) have data records between 10 and 19 years; 74 stations (61.7% of the total) have data records greater than or equal to 20 years. The earliest rainfall record was done at the year 1899 at Mpwapwa research station having a record length of 109 years up to 2007. 66 stations i.e, 55% of the total established between1960 to 1979. The availability of monthly precipitation data is summarized in Tables A-1 & A-1.1 in Appendix A; and the spatial distribution of the available monthly precipitation data is shown in Fig.3.1.

Daily precipitation data is available for 17 rainfall stations. Out of the 17 stations 3 stations (17.7% of the total) have data records between 10 and 19 years; 14 stations (82.3% of the total) have data records greater than or equal to 20 years. 3 stations (17.7% of the total) have data records greater than or equal to 50 years. The availability of daily precipitation data is summarized in Tables A-2 & A-2.1 in Appendix A; and the spatial distribution of the available daily precipitation data is shown in Fig.3.2.

3.2.2 Availability of Flow Data

Flow data was obtained from Ministry of Water Resources of Tanzania (MoWRT), at Dar es Salaam, the Wami-Ruvu basin water office at Morogoro and also available previous studies has been referred to carry out the inventory on the hydrometric stations in the basin and to identify availability of flow data. According to the data inventory, there have been 30 hydrometric stations in the Wami river basin. The inventory includes available gauging stations including the station names, station code, river where the station is located, location in terms of longitude and latitude, catchment area upstream of each gauging station and the status of the gauging station.

Out of the total of the 30 stations established in the basin, 10 stations (33% of the total) have no any records, 5 stations (17% of the total) have data record length between 1 and 9 years. 6 stations (20% of the total) have data record length between 10 and 19 years.9 stations (30% of the total) have data record length 20 years and above. Almost all stations have been established in the 1950s and 1960s and all stations have been closed between 1970s and 1980s.A rehabilitation activity has been carried out from September to October 2006 making 13 stations operational enabling to collect water level data. The findings of the inventory are summarized in Tables A-3 & A-3.1 in Appendix A; and the spatial distribution of Hydrometric stations in the basin is shown in Fig-3.1.

3.2.3 Availability of Evaporation Data

Daily and monthly average Evaporation data has been collected from Tanzania Metrological Agency (TMA) at Dar es Salaam and Ministry of Water Resources of Tanzania at Dar es Salaam. The availability of evaporation data is summarized in Table A-4 in Appendix A; and the spatial distribution of the available evaporation data is shown in Fig 3.1.

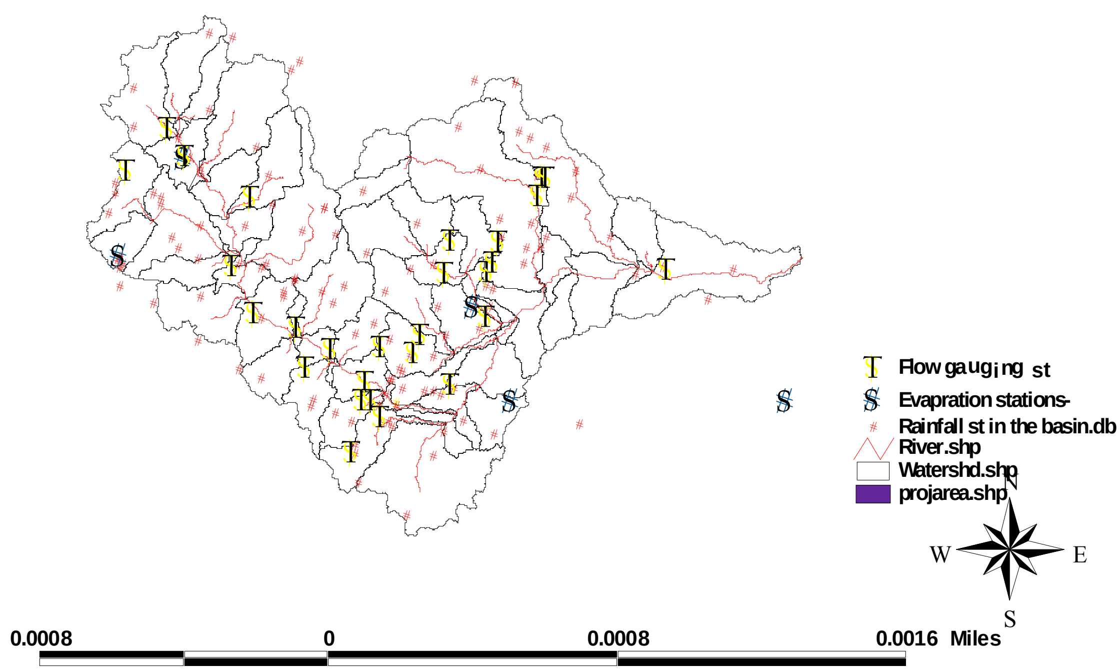

Fig 3.1: Spatial Distribution of Hydrometeorological Stations in and near Wami Basin
Data source: (TMA, MoWRT)

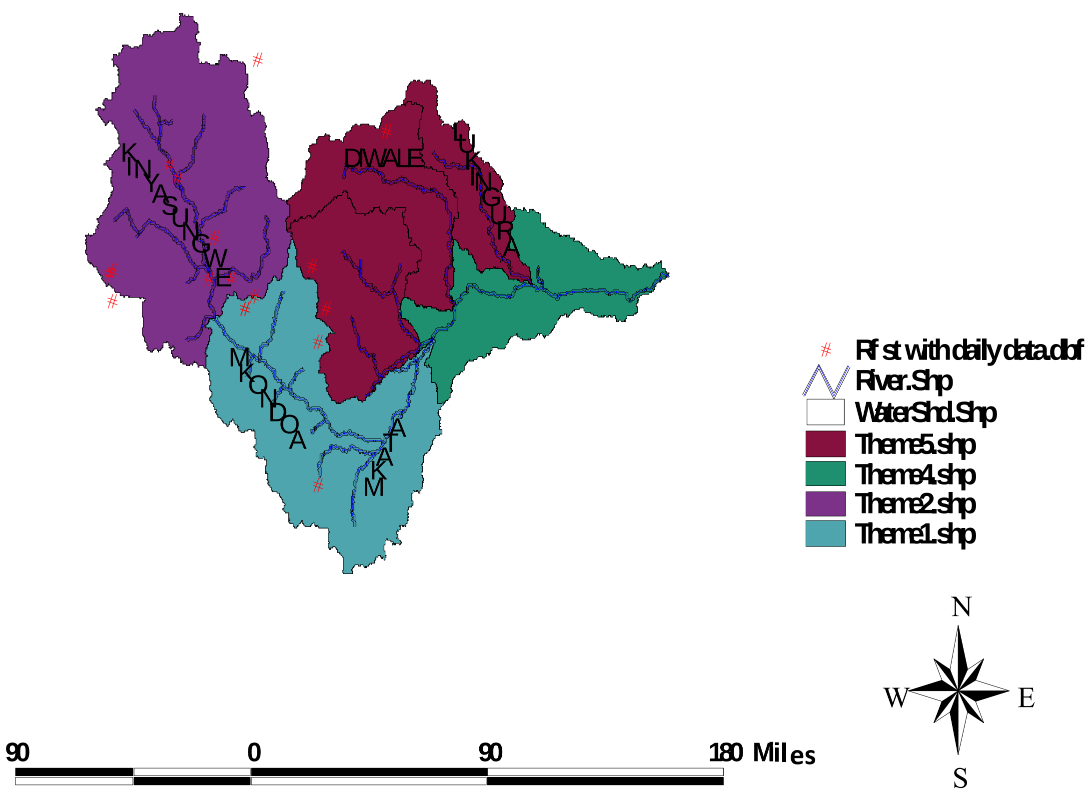

Fig.3.2 Main Sub-catchments of Wami Basin with Available Daily Rainfall Data
Data source: (TMA)

3.2.4 Availability of Water Abstraction Data

According to ongoing Environmental flow study in the Wami river basin (Valimba, 2007) and data obtained from Wami-Ruvu basin Water Office, Surface Water abstractions in Wami river basin lie in two categories; water abstraction from dams and direct-from-river abstraction.

i) Water Abstraction from Dams

The First category of surface water abstraction in the Wami river basin is water abstraction from dams. This is widely practiced in Kinyasungwe upper catchment of wami river basin. The available information about the Dams in the Basin is summarized in Table A-5 in Appendix A.

ii) **Direct-from-River Abstraction**

The second category of surface water abstraction in the Wami river basin is direct-from-river abstraction. According to (Valimba, 2007) about 99 abstractions from various rivers and 14 from springs in the sub-basin have been given water rights. Despite the lack of coordinates of exact locations of almost all abstraction points, the rivers which they abstract water are known. The total licensed water abstractions in major rivers in wami river basin are summarized in Table A- 6 in Appendix A.

3.2.5 Availability of Spatial Data

Digital Elevation Model (DEM) data set for Africa and watershed delineation data set for Africa were obtained from United States Geological Survey (USGS) through the Internet accessed on Jan 5, 2008. Vegetation cover data set for Tanzania was obtained from FAO Africover website accessed on March 3, 2008. Soil and Geological information on Wami basin obtained from Atlas of Tanzania. Digital Elevation Model (DEM) data set together with watershed delineation data will be used to delineate the catchment. The vegetation cover, the soil and geological data and information will be used to define sub-catchment characteristics and model parameter relationship.

CHAPTER FOUR

DATA PROCESSING AND ANALYSIS

4.1 Introduction

Data processing entails transforming the raw data into forms that enable ready manipulation. The raw data has been checked for its quality and continuity, and input data measuring stations with appropriate time range of analysis were selected for the proposed study. Hydrological analysis has been also performed to obtain spatial and temporal information about certain variables. The data processing and analysis process in the present study includes the following main activities:-

i) Data quality checking
ii) Data selection
iii) Data reconstruction
iv) Spatial interpolation
v) Data preparation for model input

4.2 Data Quality Checking

This includes screening the outliers and identifying missing values. After screening the data, all the missing values and all the outliers were removed and replaced by -9.9.

4.3 Data Selection

Observation of the acquired river flow and rainfall data reveal that the data from the different gauging stations vary both in record length and quality (in terms of Missing values). Data selection includes selection of time range and selection of stations.

The following procedure is used to select data for the present study:-

I) Selection of continuous and reasonably long data record time range common for the three input data, i.e., Precipitation, Flow and Evaporation by observing the continuity of the available data.

II) Selection of stations which have data for the selected time range

II) Further screening of the selected stations for data continuity with percentage missing value less than 15%.

IV) Assigning of Rainfall and evaporation stations for each stream gauging sub-catchment by considering the spatial distribution of the stations.

Based on the above data selection procedure, six (6) gauging stations, fourteen (14) Rainfall stations and one (1) Evaporation station are selected with a time range of eight years. The percentage missing values for the Rainfall and flow data in the selected time range are shown in Table 4.1 and Table 4.2 respectively. The data selection output has been summarized in Table 4.3 and the selected hydrometeorological stations are shown in Fig.4.1

Table 4.1: Percentage Missing Values of Rainfall Records in the Selected Time Range of Analysis

No.	Station	Selected Time			No. of Points	% Missing
		From	To	Years		
1	9536000	1/1/1974	31/12/1981	8	2922	21.97
2	9536004	1/1/1974	31/12/1981	8	2922	0.00
3	9537009	1/1/1974	31/12/1981	8	2922	52.12
4	9636029	1/1/1974	31/12/1981	8	2922	0.00
5	9636027	1/1/1974	31/12/1981	8	2922	12.53
6	9636026	1/1/1974	31/12/1981	8	2922	15.57
7	9636018	1/1/1974	31/12/1981	8	2922	0.03
8	9636013	1/1/1974	31/12/1981	8	2922	1.10
9	9636008	1/1/1974	31/12/1981	8	2922	0.03
10	9636006	1/1/1974	31/12/1981	8	2922	74.98
11	9635014	1/1/1974	31/12/1981	8	2922	0.07
12	9635012	1/1/1974	31/12/1981	8	2922	0.03
13	9635001	1/1/1974	31/12/1981	8	2922	0.00
14	9736007	1/1/1974	31/12/1981	8	2922	0.17

Table 4.2: Percentage Missing Values of Flow Records in the Selected Time Range of Analysis

No.	Station	Selected Time			No. Points	% Missing
		From	To	Years		
1	1G1	1/1/1974	31/12/1981	8	2922	5.0
2	1G2	1/1/1974	31/12/1981	8	2922	13.2
3	1G5A	1/1/1974	31/12/1981	8	2922	9.0
4	1GD29	1/1/1974	31/12/1981	8	2922	1.9
5	1GD31	1/1/1974	31/12/1981	8	2922	2.8
6	1GD2	1/1/1974	31/12/1981	8	2922	14.1
7	1GD16	1/1/1974	31/12/1981	8	2922	82.8

Table 4.3 Data Selection Summary

Sno	Station	River	Location	Lat.	Long.	Selected Time Range (Years)	No. of Years	No. of Data(Days)		
								Total	Calibr.	Verifi.
1	1G2	Wami	Mandera	-6.23	38.40	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)
2	1G1	Wami	Dakawa	-6.45	37.53	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)
3	1GD2	Mkondoa	Kilosa	-6.83	36.98	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)
4	1G5A	Tami	Msowero	-6.53	37.21	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)
5	1GD29	Mkondoa	Mbarahwe	-6.60	36.78	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)
6	1GD31	Mdukwe	Mdukwe	-6.83	36.93	(1974-1981)	8	2922	1948	974
								(1/1/74-31/12/81)	(1/1/74-2/5/79)	(3/5/79-31/12/81)

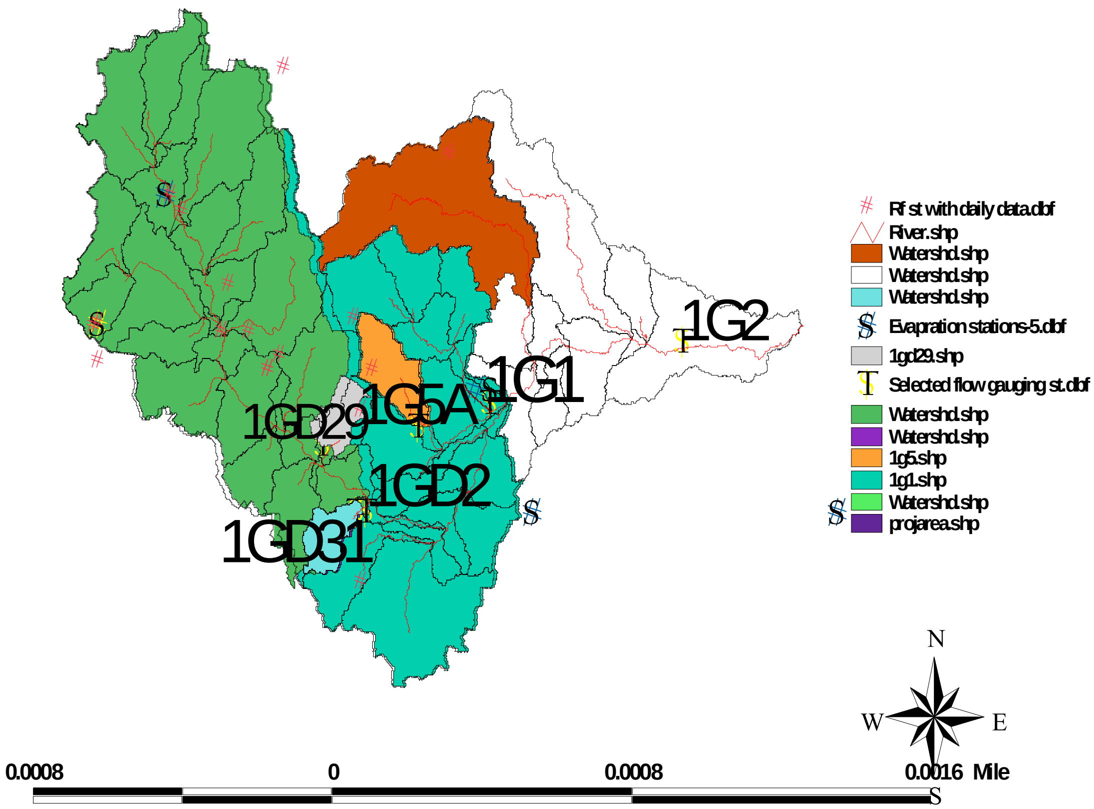

Fig.4.1: Hydrometric Stations Selected for Modeling

Data source: (MoWRT, TMA)

4.4 Data Reconstruction

The main task of the data reconstruction stage is to fill the missing values of the input data. The methods applied to fill the input data are discussed below.

4.4.1 Rainfall Data Reconstruction

Filling of the missing values of the rain fall data has been done by FORTRAN program using inverse distance square method expressed as-

$$P_A = \frac{\sum_{i=1}^{n} \frac{P_i}{Di^2}}{\sum_{i=1}^{n} \frac{1}{Di^2}} \tag{4.1}$$

Where:-

P_A is the estimated rainfall at station A

P_i is the observed rainfall at station i and, D_i is the distance between the point to be estimated and the other neighboring stations.

4.4.2 Flow Data Reconstruction

The missing values of the flow data in the selected time range has been filled by a FORTRAN program using Seasonal Mean method expressed as:-

$$\hat{y} = \frac{1}{N} \sum_{r=1}^{N} y_{d,r} \tag{4.2}$$

Where:- $\hat{y}$ is the estimated seasonal mean value

$y_{d,\,r}$ is the observed discharge on date d in year r, and N is the number of years.

4.4.3 Evaporation Data Reconstruction

Due to the limitation in the availability of daily evaporation data correlation with neighboring stations could not be used to fill the missing values. Therefore, the missing values were filled by seasonal mean method.

4.5 Spatial Interpolation of the Rainfall Data

The spatial interpolation of the rainfall data includes transforming the point rainfall data into areal average rainfall for each sub catchment of the stream gauging station. This has been performed by a FORTRAN program using arithmetic mean method expressed as:-

$$\overline{P} = \frac{1}{N} \sum_{i=1}^{N} P_i^j \tag{4.3}$$

Where

$\overline{P}$ is the areal rainfall

P_i^j is the rainfall depth on day j and in gauge i within and near the basin and

N- is the total number of rain gauging stations within and near the basin

4.6 Data Formatting for Model Input

Model input data preparation has been done Using FORTRAN program and EXCEL spread sheet. The daily rainfall and flow data were formatted using UCG format for SMAR and PITMAN models input. Daily evaporation data have been formatted using UCG format for SMAR model and mean monthly series evaporation data prepared in excel Format for PITMAN model. The Pitman model has been configured using FORTRAN Program.

CHAPTER FIVE

MODEL APPLICATION

5.1 Application of Pitman Model

The monthly time step rainfall-runoff Pitman conceptual model (its description presented in chapter 2) was applied at six selected stream gauging stations in the Wami river basin of Tanzania (Fig 4.1). The selected stations for the present study are 1G2-Wami at Mandera, 1G1- Wami at Dakawa, 1GD2- Mkondoa at Kilosa, 1G5A -Tami at Msowero, 1GD29 –Mkondoa at Mbarahwe and 1GD31-Mdukwe at Mdukwe. The inputs to the model were average catchment rainfall and potential evaporation on monthly series basis. The calibration period for the model was 5.3 years (from 1/1/74 to 2/5/79), and verification period was 2.7 years (from 3/5/79 to 31/12/81).

The calibration process has been carriedout using manual calibration method. By adjusting the Pitman model parameters, simulated historical flows are altered to achieve a favorable comparison with historical observed flows.

5.1.1 Criteria for Testing Accuracy of Simulated Runoff for Pitman Model

According to (Pitman, 1973) the purpose for which a sequence of runoff data is simulated should be borne in mind when selecting criteria for accepting or rejection. This model has been developed specifically to synthesize runoff in a form in suitable as input to models that simulate the performance of water resources systems or to such other models as are designed to aid studies of the long-term water balance. The characteristics of river flow behavior that are perhaps of greatest significance in such studies are

i. Long-term average yield of the catchment
ii. Seasonal distribution of flow
iii. Reliability of flow

The average yield is usually referred to as the Mean Annual Runoff (MAR) and it is expressed in suitable volumetric units. By comparing the logs of this parameter, an assessment of the accuracy with which low to medium flows are simulated, can be made. Seasonal distribution can be conveniently illustrated by stating the average runoff in each calendar month expressed as a percentage of the annual runoff. Seasonal totals of runoff generally follow the lognormal distribution, and the standard deviation of such a distribution is convenient measures of the reliability of runoff. Based on the above discussion, (Pitman, 1973) recommends that a simulated runoff record that is a good estimate of the observed record would be expected to display close agreement between its MAR, monthly distribution and standard deviation of logarithms of annual runoff totals and those of the actual record. Concerning the average error of estimation (Pitman, 1973) has obtained average error 0.016 units, 6% and 4% for the Mean (log), standard deviation and MAR respectively, and he recommends that errors of about twice of those given above may be taken as being acceptable.

Based on recommendations of (Pitman, 1973) and experiences of other previous Pitman model simulation exercises (Mazvimavi, 2003; PBWO/IUCN, 2006); the present study considers a simulation to be acceptable if simulated monthly flows satisfy the following conditions:

i. The difference between the mean of observed and that of simulated monthly flows is within the +/-10% range.
ii. The difference between the standard deviation of observed flows and that of simulated flows is within the +/-15
iii. Model efficiency (R^2) >0.70
iv. An acceptable agreement between hydrographs of observed and simulated flows based on visual inspection

5.2 Application of SMAR Model

The Soil Moisture Accounting and Routing (SMAR) Lumped conceptual model is one of the two models which have been applied in the Wami river basin in the present study. The data requirements for SMAR model are pan evaporation, mean areal rainfall and observed discharge on daily basis. The six selected stream gauging stations; and the calibration and verification periods previously used in modelling flows using the Pitman model were maintained. The parameters of the models cannot, in general, be determined directly from physical catchment characteristics, and hence the parameter values must be estimated by calibration against observed data. During model calibration parameters were adjusted to create a good fit between the simulated and the observed hydrographs by checking the efficiency of the model. Calibration was performed by automatic optimization using simplex search method. The starting values were chosen by trial and error method.

5.2.1 Criteria for Testing Accuracy of Simulated Runoff for SMAR Model

The selected measure of model errors used for this study are the sum of squares of the discharge forecast errors and the corresponding index of volumetric fit (i.e. the ratio of the total volume of the estimated discharge hydrograph to that of the corresponding observed hydrograph).

The following target criteria were considered to evaluate the calibration output:-

(i) Good behavior of the simulated hydrograph compared to the observed hydrograph:-

- Model efficiency (R^2) -Greater than or equal to 70%

(ii) Water balance agreement between simulated and observed stream flows:-

- Index of Volumetric Fit (IVF) –closer to 1.00

iii) Good simulation of low flows and good simulation of high flows

CHAPTER SIX

ANALYSIS AND DISCUSSION OF THE RESULTS

6.1 Discussion of the Results of Pitman Model

6.1.1 Flow Gauging Station 1G2 (Wami at Mandera)

Wami-Mandera flow gauging station 1G2 is located at $6^{o}13'48''$S and $38^{o}24'00''$ E, and it covers a catchment area of about 36,450 km^2. It is the last station to measure the flow of Wami river before it drains to the Indian Ocean. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 1641.04Mm^3 and 707 mm respectively.

During calibration of 1G2 gauging station, both the soil moisture runoff parameters (POW,ST & FT) and infiltration parameters (ZMIN & ZMAX) have been found important. The calibration results of transformed mean annual runoff and the annual standard deviation show a deviation of 0.46 % and 90.71% respectively, indicating a good fit of low and medium flows and a poor fit of seasonal flow distribution and reliability. During calibration and verification of the model, it was observed that, the model efficiency (R^2) was 66.02% and -371.60% respectively indicating a fairly good calibration coupled with worst verification result. The possible reasons for the poor verification result are discussed in section 6.3. The calibration data and results of the calibration process are summarized in Tables 6.1- 6.3 and Fig. 6.1 and 6.2 below.

Table 6.1: Summary of Calibration Data for Sub-catchment 1G2

PARAMETER	TOTAL
Catchment Area (km^2)	36,450
Catchment MAP(mm)	707
Observed MAR(Mm^3/year)	1641.04

Note: - Annual statistics apply to the calibration period of (1974-1978)

Table 6.2: Pitman Model Parameters for Sub-catchment 1G2

PITMAN MODEL PARAMETERS											
POW	**SL**	**ST**	**FT**	**GW**	**AI**	**ZMIN**	**ZMAX**	**PI**	**TL**	**GL**	**R**
3	0	500	40	0	0	100	500	8	0.25	0	0

Table 6.3: Calibration and Verification Statistics for Sub-catchment 1G2

Sub-catchment 1G2		**OBSERVED FLOW**	**SIMULATED FLOW**	**DIFFERENCE (%)**
Mean Annual Runoff (Mm^3)	Calibration	1641.04	1633.45	0.46
	Verification	1097.37	2945.56	-168.42
Mean Annual Runoff(log)	Calibration	3.22	3.21	0.06
	Verification	3.04	3.47	-14.10
Annual Standard Deviation(log)	Calib. & Verifi.	3.06	0.28	90.71
Model Efficiency(R^2) (%)	Calibration		Verification	
	66.02		-371.60	

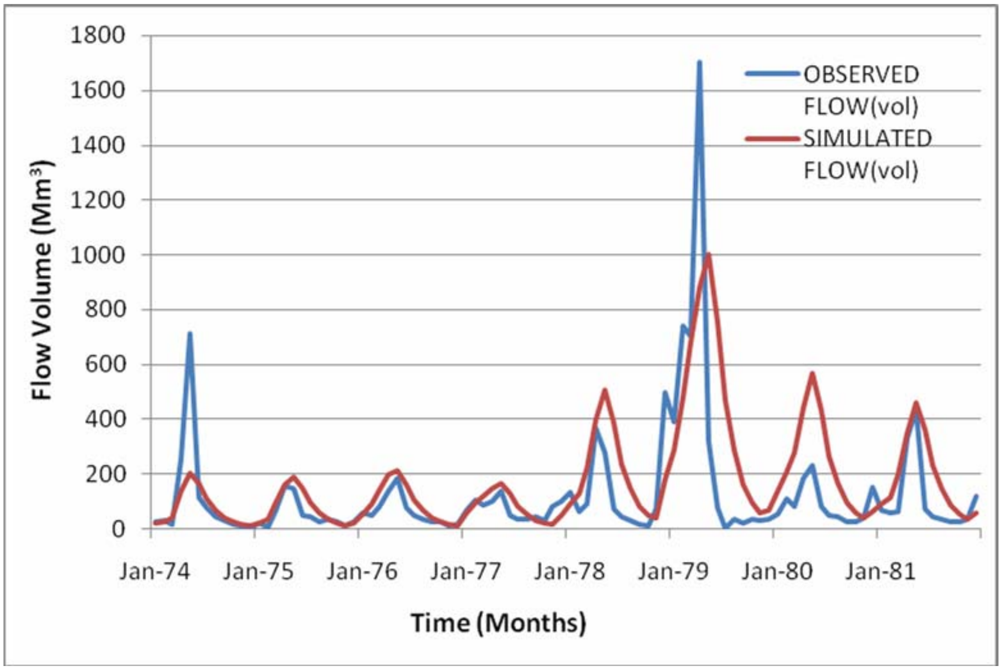

Fig. 6.1: Comparison of Observed and Simulated Flows at Sub-catchment 1G2

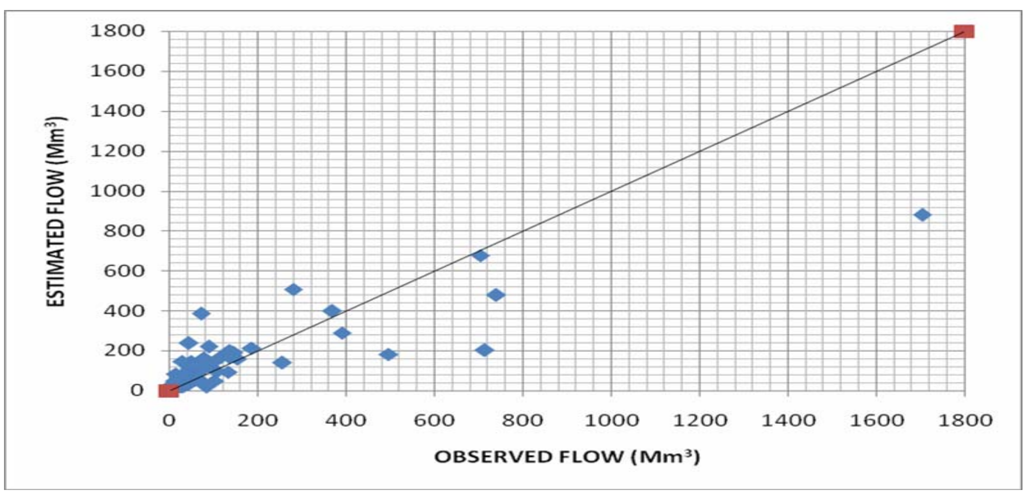

Fig. 6.2: X-Y Scatter Plot of Observed and Simulated Flows for Sub-catchment 1G2

6.1.2 Flow Gauging Station 1G1 (Wami at Dakawa)

Wami Dakawa hydrometric station 1G1 is located at 6°25’48’’S and 37°31’48’’ E at Dakawa and it covers a catchment area of about 28,488 km^2. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 668.20Mm^3 and 707 mm respectively.

Examination of Tables 6.5 & 6.6 below shows low soil moisture storage characteristics of 1G1 catchment. During calibration process, the soil moisture runoff parameters (ST, FT, & POW), the infiltration parameters (ZMIN & ZMAX) together with the ground Water recharge parameter (GW) and the interception Parameter (PI) have been found to have significance influence for the runoff characteristics of the catchment. From the statistical data and the hydrograph, it can be observed that the model simulation for low and medium flow is generally good. The calibration data and results of the calibration process are summarized in Tables 6.4- 6.6 and in Fig. 6.3 below.

Table 6.4: Summary of Calibration Data for Sub-catchment 1G1

PARAMETER	TOTAL
Catchment Area (km^2)	28,488
Catchment MAP(mm)	707
Observed MAR(Mm^3/year)	668.20

Note: - Annual statistics apply to the calibration period of (1974-1978)

Table 6.5: Pitman Model Parameters for Sub-catchment 1G1

PITMAN MODEL PARAMETERS											
POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3	0	400	70	15	0	40	300	13	0.1	0.25	0.1

Table 6.6: Calibration and Verification Statistics for Sub-catchment 1G1

Sub- catchment 1G1		OBSERVED FLOW	SIMULATED FLOW	DIFFERENCE (%)
Mean Annual Runoff (Mm^3)	Calibration	668.20	693.63	-3.81
	Verification	762.52	1086.73	-42.52
Mean Annual Runoff(log)	Calibration	2.82	2.84	-0.57
	Verification	2.88	3.04	-5.34
Annual Standard Deviation(log)	Calib. & Verif.	2.80	0.28	90.03
Model Efficiency(R^2) (%)	Calibration		Verification	
	77.37		36.76	

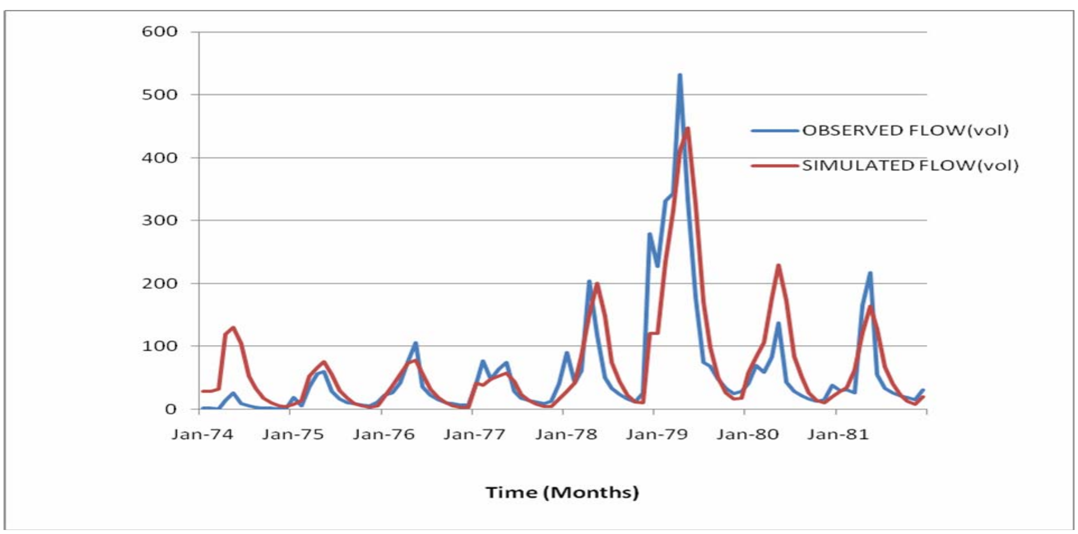

Fig. 6.3: Comparison of Observed and Simulated Flows at Sub-catchment 1G1

6.1.3 Flow Gauging Station 1GD2 (Mkondoa at Kilosa)

The Mkondoa river hydrometric station 1GD2 is located at $6^{o}49'48''S$ and $37^{o}00'00''$ E near the Mkondoa Bridge at Kilosa. The river originates from Kondoa Irangi in Dodoma, draining the Ukaguru Mountains and forms a tributary to the Wami river. It covers a catchment area of about 17,560 km^2. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 322.85Mm^3 and 707 mm respectively.

Results of Pitman model calibration at 1GD2 gauging station show Poor calibration and verification results. The possible reasons for poor calibration and verification result are discussed in section 6.3. The calibration data and results of the calibration process are summarized in Tables 6.7- 6.9 and in Fig. 6.4 below.

Table 6.7: Summary of Calibration Data for Sub-catchment 1GD2

PARAMETER	TOTAL
Catchment Area (km^2)	17560
Catchment MAP (mm)	707
Observed MAR (Mm^3/year)	322.85

Note: - Annual statistics apply to the calibration period of 1974-1978

Table 6.8: Pitman Model Parameters for Sub-catchment 1GD2

PITMAN MODEL PARAMETERS											
POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3	0	700	40	0	0	15	400	12	0.3	0	0.6

Table 6.9: Calibration and Verification Statistics for Sub-catchment 1GD2

Sub-catchment 1GD2		OBSERVED FLOW	SIMULATED FLOW	DIFFERENCE (%)
Mean Annual Runoff (Mm^3)	Calibration	322.85	323.32	-0.15
	Verification	323.96	610.80	-88.54
Mean Annual Runoff(log)	Calibration	2.51	2.51	0.00
	Verification	2.51	2.79	-10.97
Annual Standard Deviation (log)	Calib. & Verfi.	2.30	0.24	89.76
Model Efficiency(R^2) (%)	Calibration		Verification	
	63.08		-252.99	

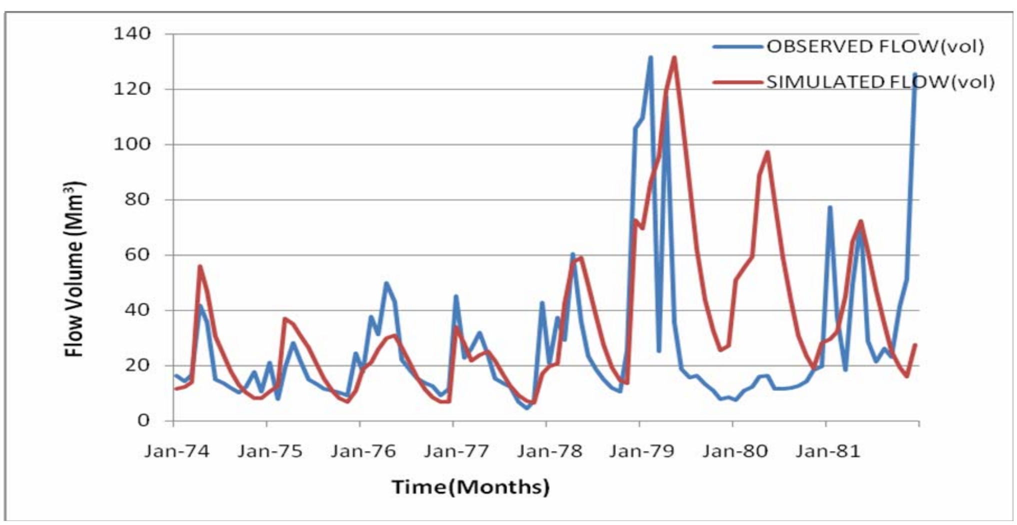

Fig. 6.4: Comparison of Observed and Simulated Flows at Sub-catchment 1GD2

6.1.4 Flow Gauging Station 1G5A (Tami at Msowero)

The river Tami/Msowero hydrometric station 1G5A is located at 6°31'12''S and 37°12'36'' E at Msowero. The river drains the Ukaguru mountains range and it covers a catchment area of about 907 km^2. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 151.17Mm^3 and 1016 mm respectively.

Pitman Model parameters POW,ST,FT, and PI have been calibrated for Sub-catchment 1G5A.The calibration results show mean annual flows of 151.17 and 157.76 Mm^3 for observed and estimated flow respectively with a deviation of -4.36 %. The calibration results of the transformed mean annual runoff values and the annual standard deviation also show a deviation of -0.85% and 91.95% respectively. During calibration and verification of the model, it was observed that, the model efficiency (R^2) were 56.40% and 50.65% respectively. From the hydrograph, it can be observed that both the calibration and verification simulation are poor. The calibration data and results of the calibration process are summarized in Tables 6.10- 6.12 and in Fig. 6.5 below.

Table 6.10: Summary of Calibration Data for Sub-catchment 1G5A

PARAMETER	TOTAL
Catchment Area (km^2)	907
Catchment MAP(mm)	1016
Observed MAR(Mm^3/year)	151.17

Note: - Annual statistics apply to the calibration period of 1974-1978

Table 6.11: Pitman Model Parameters for Sub-catchment 1G5A

PITMAN MODEL PARAMETERS											
POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2	0	500	30	0	0.1	400	1000	13	0.1	0	0

Table 6.12: Calibration and Verification Statistics for Sub-catchment 1G5A

Sub-catchment 1G5A		OBSERVED FLOW	SIMULATED FLOW	DIFFERENCE (%)
Mean Annual Runoff (Mm^3)	Calibration	151.17	157.76	-4.36
	Verification	105.49	140.51	-33.19
Mean Annual Runoff(log)	Calibration	2.18	2.20	-0.85
	Verification	2.02	2.15	-6.15
Annual Standard Deviation (log)	Calib. & Verfi.	2.03	0.16	91.95
Model Efficiency(R^2) (%)	Calibration		Verification	
	56.40		50.65	

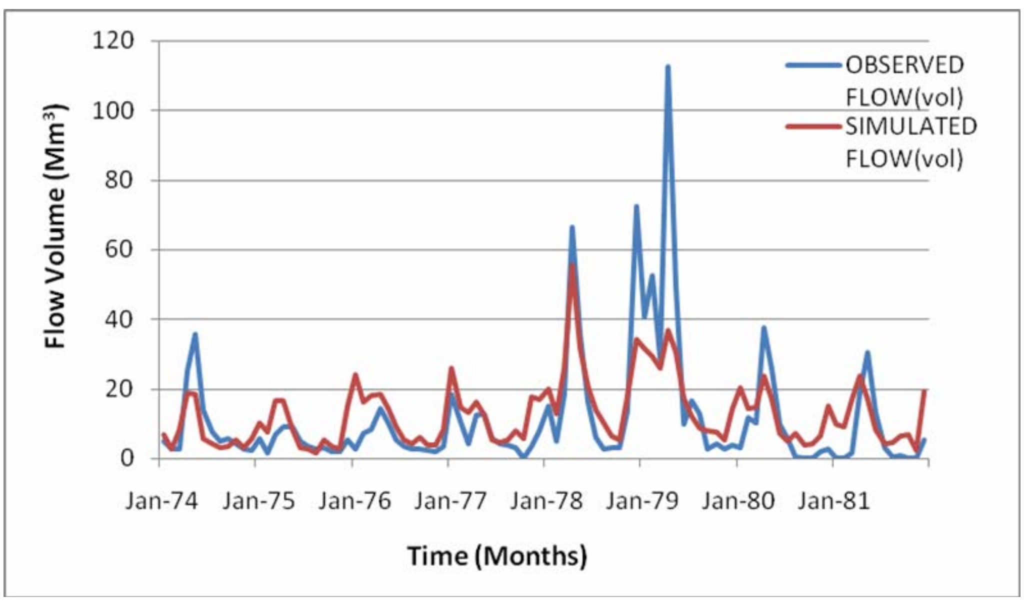

Fig. 6.5: Comparison of Observed and Simulated Flows at Sub-catchment 1G5A

6.1.5 Flow Gauging Station 1GD29 (Mkondoa at Mbarahwe)

The Mkondoa river hydrometric station 1GD29 is located at 6^o36'00''S and 36^o46'48'' E at Mbarahwe and it covers a catchment area of about 475 km^2. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 81.76 Mm^3 and 1275 mm respectively.

At 1GD29 gauging station, it has been tried to calibrate parameters POW, ST, FT, and PI. The calibration results show mean annual flows of 81.76 and 78.53 Mm^3 for observed and estimated flow respectively with a deviation of 3.94 %. During calibration and verification of the model, it was observed that, the model efficiency (R^2) were 55.48% and 11.93% respectively. From the hydrograph, it can be observed that both the calibration and verification simulation are poor. The calibration data and results of the calibration process are summarized in Tables 6.13- 6.15 and in Fig. 6.6 below.

Table 6.13: Summary of Calibration Data for Sub-catchment 1GD29

PARAMETER	TOTAL
Catchment Area (km^2)	475
Catchment MAP(mm)	1275
Observed MAR(Mm^3/year)	81.76

Note: - Annual statistics apply to the calibration period of 1974-1978

Table 6.14: Pitman Model Parameters for Sub-catchment 1GD29

PITMAN MODEL PARAMETERS											
POW	**SL**	**ST**	**FT**	**GW**	**AI**	**ZMIN**	**ZMAX**	**PI**	**TL**	**GL**	**R**
3	0	1800	300	0	0.02	500	1000	15	0.1	0	0.5

Table 6.15: Calibration and Verification Statistics for Sub-catchment 1GD29

Sub-catchment 1GD29		**OBSERVED FLOW**	**SIMULATED FLOW**	**DIFFERENCE (%)**
Mean Annual Runoff (Mm^3)	Calibration	81.76	78.53	3.94
	Verification	94.47	147.72	-56.36
Mean Annual Runoff(log)	Calibration	1.91	1.90	0.91
	Verification	1.98	2.17	-9.83
Annual Standard Deviation (log)	Calib. & Verfi.	1.71	0.22	87.33
Model Efficiency(R^2)	Calibration		Verification	
(%)	55.48		11.93	

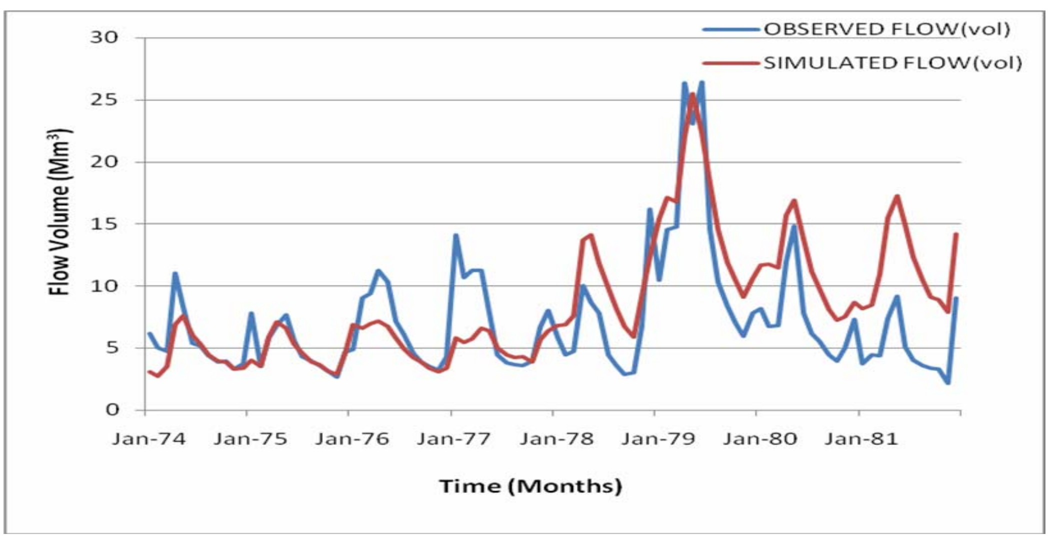

Fig. 6.6: Comparison of Observed and Simulated Flows at Sub-catchment 1GD29

6.1.6 Flow Gauging Station 1GD31 (Mdukwe at Mdukwe)

The Mdukwe river hydrometric station 1GD31 is located at 6^{o}49’48’’S and 36^{o}55’48’’ E at Mdukwe and it covers a catchment area of about 430 km^2. The mean annual flow and the mean annual precipitation of the catchment in the calibration period are 143.11Mm^3 and 1021 mm respectively.

Parameters POW, ST, FT, ZMAX, GW and PI have been found important for calibrating 1GD31flow gauging station. The calibration results show mean annual flows of 143.11 and 143.42 Mm^3 for observed and estimated flow respectively with a deviation of 1.15 %. The calibration results of the transformed mean annual runoff values and the annual standard deviation also show a deviation of -0.04% and 90.68% respectively. During calibration and verification of the model, it was observed that, the model efficiency (R^2) were 51.38% and 14.70% respectively. From the hydrograph, it can be observed that both the calibration and verification simulation are not satisfactory. The calibration data and results of the calibration process are summarized in Tables 6.16- 6.18 and in Fig. 6.7 and 6.8 below.

Table 6.16: Summary of Calibration Data for Sub-catchment 1GD31

PARAMETER	TOTAL
Catchment Area (km^2)	430
Catchment MAP(mm)	1021
Observed MAR(Mm^3/year)	143.11

Note: - Annual statistics apply to the calibration period of 1974-1978

Table 6.17: Pitman Model Parameters for Sub-catchment 1GD31

PITMAN MODEL PARAMETERS											
POW	**SL**	**ST**	**FT**	**GW**	**AI**	**ZMIN**	**ZMAX**	**PI**	**TL**	**GL**	**R**
1	0	550	30	10	0	300	650	6	1	3	0.8

Table 6.18: Calibration and Verification Statistics for Sub-catchment 1GD31

Sub-catchment 1GD31		OBSERVED FLOW	SIMULATED FLOW	DIFFERENCE (%)
Mean Annual Runoff (Mm^3)	Calibration	143.11	143.42	-0.22
	Verification	151.44	156.99	-3.66
Mean Annual Runoff(log)	Calibration	2.16	2.16	-0.04
	Verification	2.18	2.20	-0.72
Annual Standard Deviation (log)	Calib. & Verfi.	2.03	0.19	90.68
Model Efficiency(R^2) **(%)**	Calibration		Verification	
	51.38		14.70	

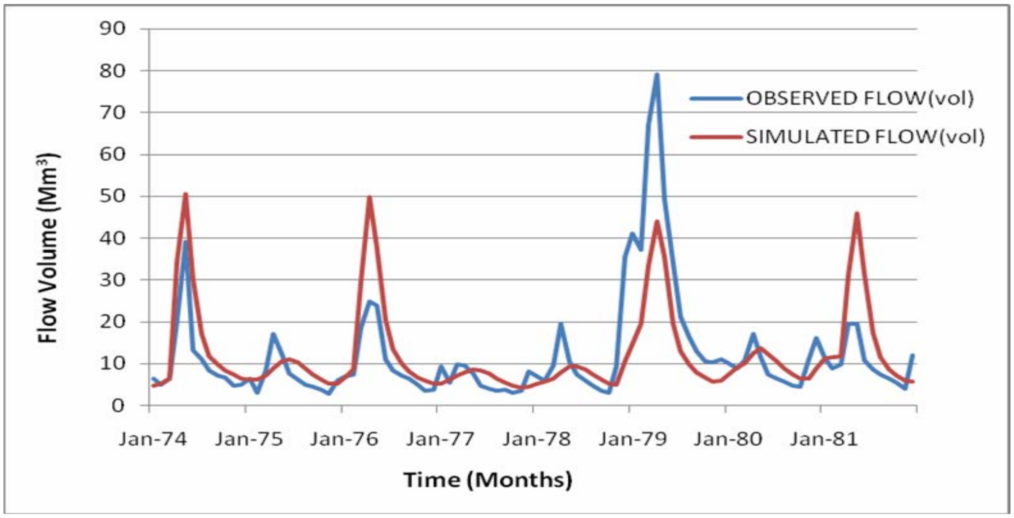

Fig. 6.7: Comparison of Observed and Simulated Flows at Sub-catchment 1GD31

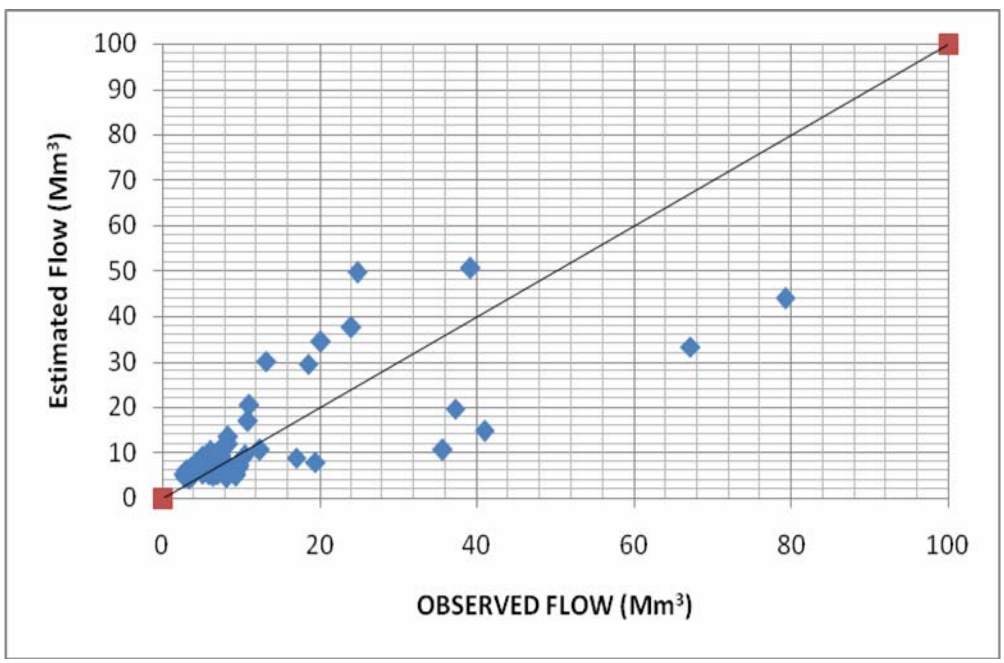

Fig. 6.8: X-Y Scatter Plot of Observed and Simulated Flows for Sub-catchment 1GD31

6.2 Discussion of the Results of SMAR Model

6.2.1 Flow Gauging Station 1G2 (Wami at Mandera)

The SMAR model calibration results at 1G2 gauging station show mean daily flows of 52.23 and 42.94 cumecs for observed and estimated flow respectively. For 1G2 sub-catchment, optimization of CH combination gave the model efficiency R^2 equal to 79.89% and 9.58% for calibration and verification respectively. The model recorded IVF of 0.70 for calibration and 0.54 for verification. From the hydrograph, it can be observed that the simulation of the low flow is fairly satisfactory. The optimized parameters and results of the calibration statistics are summarized in Tables 6.19 & 6.20 and in Fig. 6.9 & 6.10 below.

Table 6.19: Optimized SMAR Model Parameters for Sub-catchment 1G2

SMAR MODEL PARAMETERS								
C	**Z**	**Y**	**H**	**T**	**G**	**N**	**NK**	**KG**
1	365.88	96.76	0.26	0.72	0.25	3.4	10	94.99

Table 6.20: SMAR Model Calibration Statistics for Sub-catchment 1G2

Sub-catchment	**Calibration**		**Verification**	
	R^2	**IVF**	**R^2**	**IVF**
1G2	79.89	0.70	9.58	0.543

Warm-up period=85 days, Memory length = 30 days

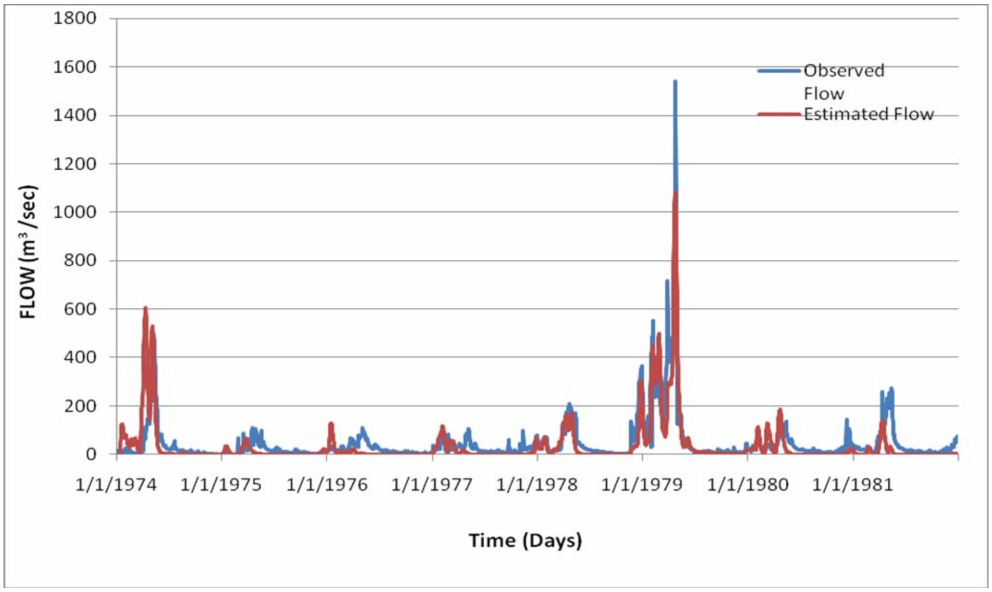

Fig.6.9: Comparison of Observed and Simulated Flows at Sub-catchment 1G2

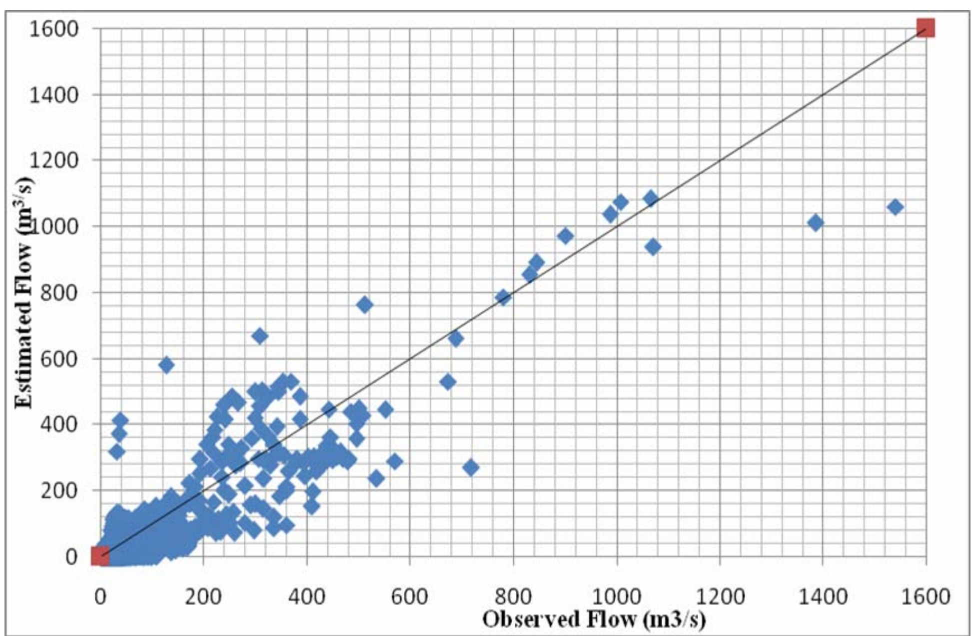

Fig. 6.10: X-Y Scatter Plot of Observed and Simulated Flows for Sub-catchment 1G2

6.2.2 Flow Gauging Station 1G1 (Wami at Dakawa)

The SMAR model calibration results at 1G1 gauging station show mean daily flows of 21.33 and 21.70 cumecs for observed and estimated flow respectively. For 1G1 sub-catchment, optimization of ZH combination gave the model efficiency R^2 equal to 73.14% and 58.16% for calibration and verification respectively. The model recorded IVF of 1.019 for calibration and 0.991 for verification. From the hydrograph, it can be observed that the simulation of the low flow is fairly satisfactory. The optimized parameters and results of the calibration statistics are summarized in Tables 6.21 & 6.22 and in Fig. 6.11 below.

Table 6.21: Optimized SMAR Model Parameters for Sub-catchment 1G1

SMAR MODEL PARAMETERS								
C	**Z**	**Y**	**H**	**T**	**G**	**N**	**NK**	**KG**
1	58.44	129.11	0.8	0.45	0.97	5.81	198.42	82.71

Warm-up period=60 days, Memory length = 28 days

Table 6.22: SMAR Model Calibration Statistics for Sub-catchment 1G1

Sub-catchment	Calibration		Verification	
	R^2	IVF	R^2	IVF
1G1	73.14	1.019	58.16	0.991

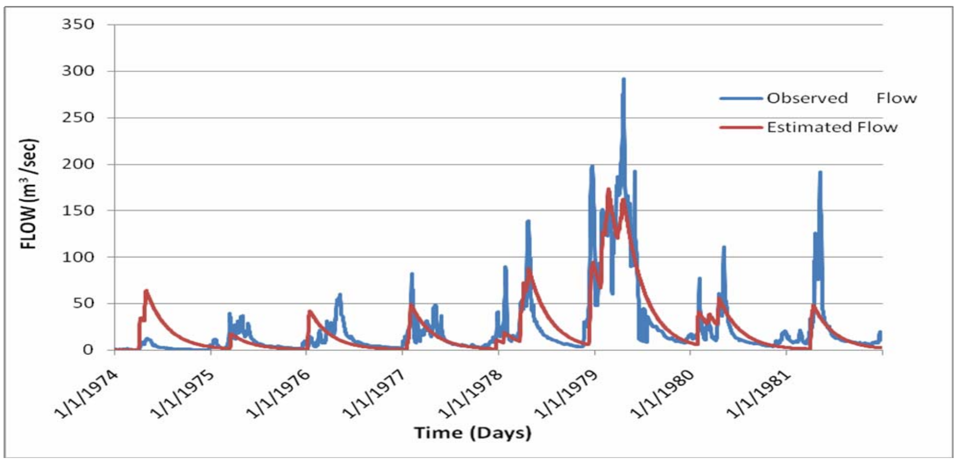

Fig. 6.11: Comparison of Observed and Simulated Flows at Sub-catchment 1G1

6.2.3 Flow Gauging Station 1GD2 (Mkondoa at Kilosa)

The SMAR model calibration results at 1GD2 gauging station show mean daily flows of 10.24 cumecs for both observed and estimated flows. For 1GD2 sub-catchment, optimization of ZT combination gave the model efficiency R^2 equal to 47.72% and -217.14% for calibration and verification respectively. The model recorded IVF of 1.01 for calibration and 2.32 for verification. From the hydrograph, it can be observed that the simulation of the low flow during calibration period relatively good, however the verification result is worst. The optimized parameters and results of the calibration statistics are summarized in Tables 6.23 & 6.24 and in Fig. 6.12 below.

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Table 6.23: Optimized SMAR Model Parameters for Sub-catchment 1GD2

SMAR MODEL PARAMETERS								
C	**Z**	**Y**	**H**	**T**	**G**	**N**	**NK**	**KG**
0.61	222.6	205.45	0.49	0.36	0.49	1.0	316.36	1588.80

Warm-up period=60 days, Memory length = 8 days

Table 6.24: SMAR Model Calibration Statistics for Sub-catchment 1GD2

Sub-catchment	**Calibration**		**Verification**	
	R^2	**IVF**	**R^2**	**IVF**
1GD2	47.72	1.01	-217.14	2.32

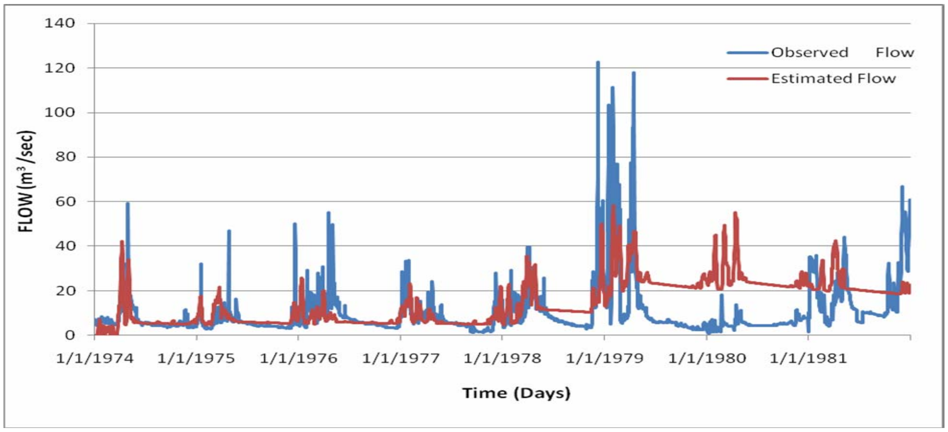

Fig. 6:12: Comparison of Observed and Simulated Flows at Sub-catchment 1GD2

6.2.4 Flow Gauging Station 1G5A (Tami at Msowero)

The SMAR model calibration results at 1G5A gauging station show mean daily flows of 4.81 and 3.89 cumecs for observed and estimated flows respectively. For 1G5A sub-catchment, optimization of ZH combination gave the model efficiency R^2 equal to 71.43% and 51.69% for calibration and verification respectively. The model recorded IVF of 0.865 for calibration and 0.558 for verification. From the hydrograph, it can be observed that the simulation of the low flow during calibration period relatively good, however the simulation could not capture high flows in both calibration and verification periods. The optimized parameters and results of the calibration statistics are summarized in Tables 6.25 & 6.26 and in Fig. 6.13 below.

Table 6.25: Optimized SMAR Model Parameters for Sub-catchment 1G5A

SMAR MODEL PARAMETERS								
C	Z	Y	H	T	G	N	NK	KG
0.94	625	96.66	0.33	0.72	2.86	1.02	8.8	461.53

Warm-up period=60 days, Memory length = 30 days

Table 6.26: SMAR Model Calibration Statistics for Sub-catchment 1G5A

Sub-catchment	Calibration		Verification	
	R^2	IVF	R^2	IVF
1G5A	71.43	0.865	51.69	0.558

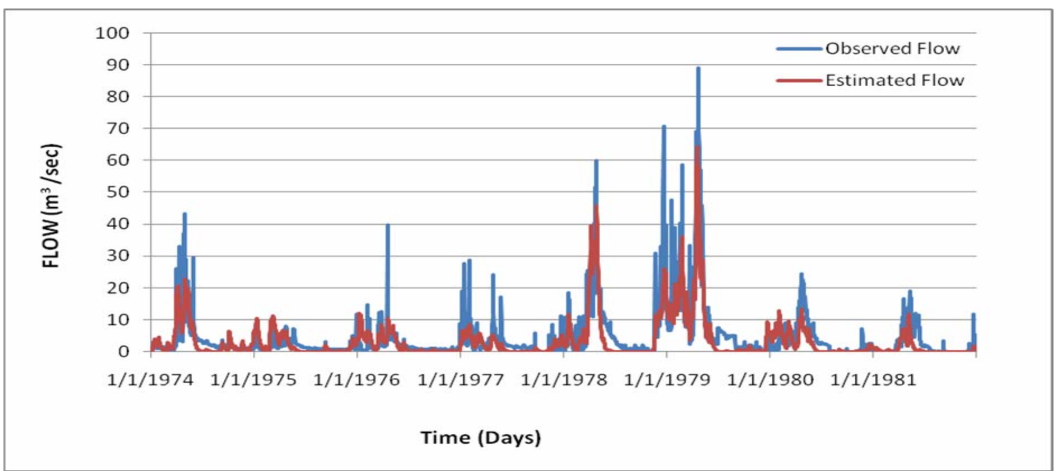

Fig. 6.13: Comparison of Observed and Simulated Flows at Sub-catchment 1G5A

6.2.5 Flow Gauging Station 1GD29 (Mkondoa at Mbarahwe)

The SMAR model calibration results at 1GD29 gauging station show mean daily flows of 2.60 and 2.52 cumecs for observed and estimated flows respectively. For 1GD29 sub-catchment, optimization of CY combination gave the model efficiency R^2 equal to 45.94% and 42.69% for calibration and verification respectively. The model recorded IVF of 0.993 for calibration and 1.08 for verification. From the hydrograph, it can be observed that the simulation of the low flow during calibration period relatively good, however the simulation could not capture high flows both in calibration and verification periods. The optimized parameters and results of the calibration statistics are summarized in Tables 6.27 & 6.28 and in Fig. 6.14 & Fig.6.15 below.

Table 6.27: Optimized SMAR Model Parameters for Sub-catchment 1GD29

SMAR MODEL PARAMETERS								
C	**Z**	**Y**	**H**	**T**	**G**	**N**	**NK**	**KG**
0.72	212.74	10	9.52	0.1	0.23	1.0	264.93	134.83

Warm-up period=60 days, Memory length = 10 days

Table 6.28: SMAR Model Calibration Statistics for Sub-catchment 1GD29

Sub-catchment	Calibration		Verification	
	R^2	IVF	R^2	IVF
1GD29	45.94	0.993	42.69	1.08

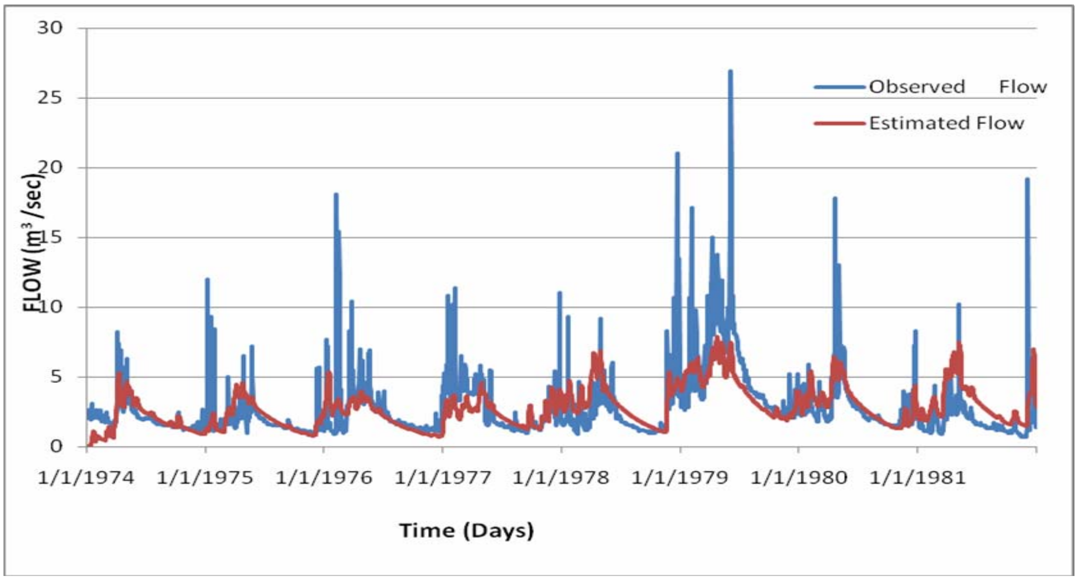

Fig. 6.14: Comparison of Observed and Simulated Flows at Sub-catchment 1GD29

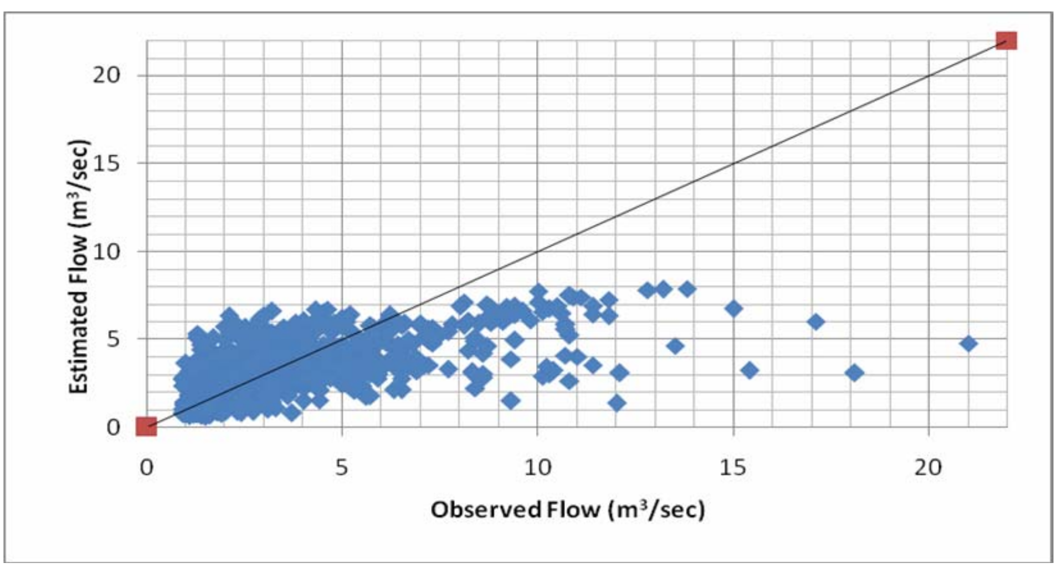

Fig. 6.15: X-Y Scatter Plot of Observed and Simulated Flows for Sub-catchment 1GD29

6.2.6 Flow Gauging Station 1GD31 (Mdukwe at Mdukwe)

The SMAR model calibration results at 1GD31 gauging station show mean daily flows of 4.56 and 4.35 cumecs for observed and estimated flows respectively. For 1GD31 sub-catchment, optimization of CZ combination gave the model efficiency R^2 equal to 49.47% and 15.93% for calibration and verification respectively. The model recorded IVF of 0.952 for calibration and 0.926 for verification. From the hydrograph, it can be observed that the simulation of the low flow during calibration period relatively good, however the simulation could not capture high flows in both calibration and verification periods. The optimized parameters and results of the calibration statistics are summarized in Tables 6.29 & 6.30 and in Fig. 6.16 below.

Table 6.29: Optimized SMAR Model Parameters for Sub-catchment 1GD31

SMAR MODEL PARAMETERS								
C	**Z**	**Y**	**H**	**T**	**G**	**N**	**NK**	**KG**
0.27	213.63	15.42	4.08	0.3	1.0	1	340.35	68.68

Warm-up period=60 days, Memory length = 17 days

Table 6.30: SMAR Model Calibration Statistics for Sub-catchment 1GD31

Sub-catchment	**Calibration**		**Verification**	
	R^2	**IVF**	**R^2**	**IVF**
1GD31	49.47	0.952	15.93	0.926

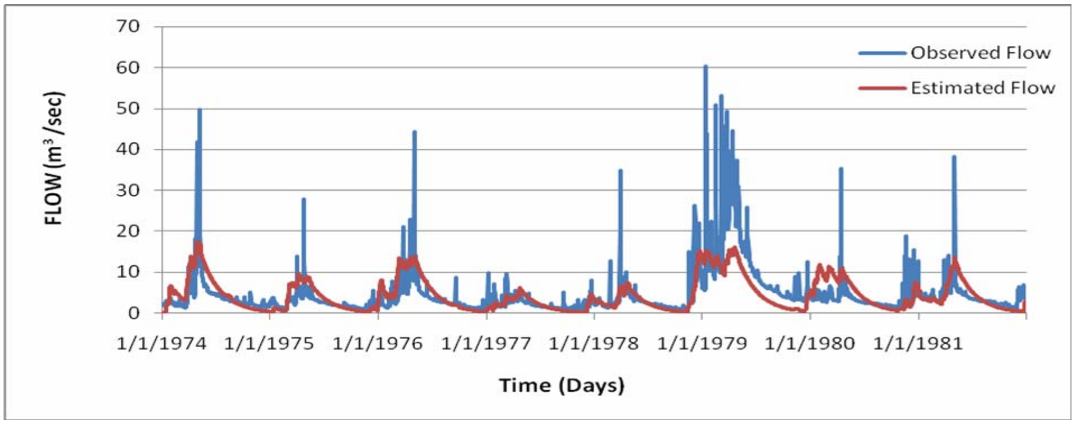

Fig. 6.16: Comparison of Observed and Simulated Flows at Sub-catchment 1GD31

6.3 Factors Contributing to Low Performance of the Applied Models

Application of the two test models described in sections 6.1 & 6.2 demonstrated that the performance efficiencies of the models are unsatisfactory. The low Model performance and deficiencies that have been observed in the simulation may be related to:

6.3.1The Complex Wetland System of the Basin

The Wami basin includes Tendigo and Dakawa swamps extending almost the whole length of the inland plain zone; several manmade reservoirs including Lakes Hombolo, Ikowa and Dabalo in the upper catchment zone. Moreover several water abstraction points have been licensed. These all have effect in seasonal flow volume and variability which might be the cause to the models' inability to satisfactorily represent the real hydrological processes. The effect of the swamps and water abstractions in the catchments has been demonstrated with the help of rainfall versus runoff plots.

6.3.1.1 Effect of the wetland System at 1G1 and 1G2 Flow Gauging Stations

The Tendigo and Dakawa swamps extend almost the whole length of the inland plain zone. The Flow gauging station 1G1 is found downstream of the Tendigo swamp and it is most likely affected by the storage effect of the swamp. The flow gauging station 1G2 is located downstream of both Tendigo and Dakawa swamps it is under the influence of the two swamps. Observation of rainfall versus runoff plot for catchment 1G2 shows that the stream flow shows very little change with the presence of abundant rainfall. Most of the time, the stream flow pattern is constant not affected by the rainfall amount indicating the presence of abstraction or storage upstream of the flow gauging station. The Rainfall-runoff plot for sub-catchment 1G2 is shown in Fig.6.17 below.

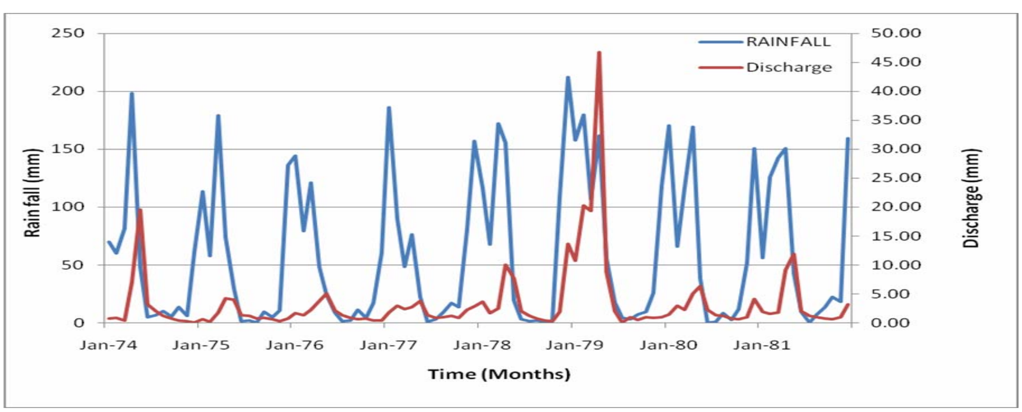

Fig.6.17: Plot of Rainfall versus Runoff for Sub-catchment 1G2

6.3.1.2 Effect of the Reservoirs at 1GD2 Flow Gauging Station

The upper catchment zone of the wami basin is mainly characterized by several manmade reservoirs including Lakes Hombolo, Ikowa and Dabalo and water abstraction (Appendix A- Tables 5 & 6).Flow gauging station 1GD2 is located downstream of the reservoirs and water abstraction sites. Therefore, the flow character at 1GD2 station is under the influence of the operation of the reservoirs and the pattern of abstraction. However, investigation of the reasons for model simulation failure at 1GD2 station shows that the simulation is dominantly influenced by the poor quality of the input data (section 6.3.2.2 below).

6.3.1.3 Effect of Water Abstractions

According to the findings of data collection (Appendix A- Table A-6) about 99 abstractions from various rivers and 14 from springs in the sub-basin have been given water rights. The effect of water abstraction on the flow pattern of the river can be magnified if the catchment area is small. The flow gauging station at 1GD31 (catchment area 430km^2 is most probably under the influence of the upstream abstraction site at Lumuma (Appendix A- Table A-6).Observation of the rainfall versus runoff plot for 1GD31 shows that part of the rainfall was lost due to abstraction upstream before it appears as runoff in the gauging station .This can be justified by the more or less constant flow pattern regardless of rainfall variability. Fig.6.18 below shows the Rainfall-runoff pattern of sub-catchment 1GD31.

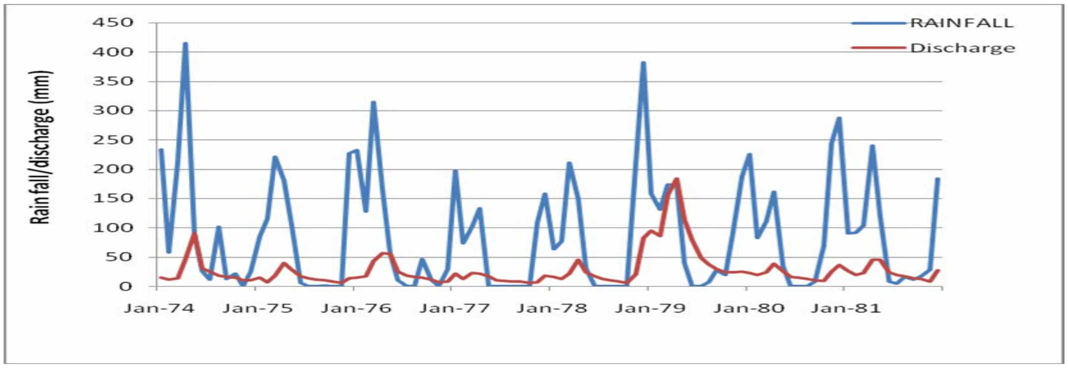

Fig.6.18: Plot of Rainfall versus Runoff for Sub-catchment 1GD31

6.3.2 The Quality of Input Data

6.3.2.1 Poor Spatial Distribution of Input Data

The main challenge faced the present study is lack of daily precipitation and evaporation data. The spatial distribution of rainfall and evaporation stations used in the study is most likely representative of the upper Wami catchment and the lower Wami is represented poorly. The upper wami catchment is characterized by arid climate. Use of input data dominantly from the upper arid catchment can result in under-estimation of annual precipitation and over estimation of evaporation on other non–arid sub-catchments of the basin contributing to failure of the model in simulating the observed flow. The humid sub-catchments 1G5A, 1GD29 and 1GD31 are most likely under the influence of overestimated evaporation resulting in low simulated flow.

6.3.2.2 Low Quality of Input Data

The quality of the input data (in terms of missing values) at some stations was not good. Hydrological models are so sensitive to the quality of the measured input data; this may have negative impact on the performance of the model in simulating the actual hydrological phenomena. Flow gauging station 1G2 with missing value of 37.4% of the verification period and flow gauging station 1GD2 with missing value of 22.7% of the verification period (Fig.6.1 & 6.4) have shown very poor verification results. Fig.6.19 below shows the missing values of the flow data as possible reason for simulation failure at Station-1GD2.

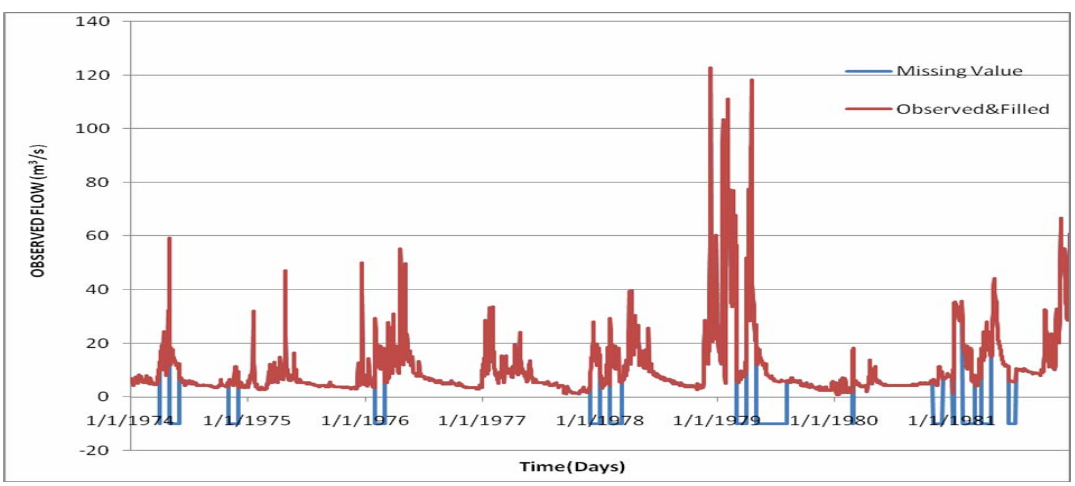

Fig. 6.19: Observation of Missing Data as Illustration for Flow Simulation Failure-Station1GD2

6.4 Comparison of Findings of the Present and Previous Studies

As it has been discussed in section 2.10 of this report, previous hydrological modelling study has been carried out in the Wami river basin (Kalinga, A.1998). The study was performed on Wami Mandera (1G2) and Wami Dakawa (1G1) flow gauging stations. The system type rainfall-runoff models used in the study were the Seasonal Model (SM), The Multiple-Input Simple Linear Model (MISLM), The Multiple-Input Linear Perturbation Model (MILPM), The Multiple-Input Linearly Varying Gain factor Model (MILVGFM) and the Multiple-Input Linearly Varying Gain factor Perturbation Model (MILVGFPM).The record length adopted was six years from 1973 to 1978, where four years of data were used for calibration and two years of it for verification.

In order to evaluate the performance of system type and conceptual models for rainfall- runoff system of Wami river basin, comparison has been made between the results of the SMAR conceptual model and the system type rainfall-runoff models used in the previous study. The efficiency (R^2) has been used for comparison purposes and the result has been summarized in Table 6.31 below.

Examination of Table 6.31 shows that at Wami Dakawa- flow gauging station 1G1, The SMAR Model with R^2 values 73.14 & 58.16 for calibration and verification respectively, shows better results for both the period of calibration and verification compared to all other Models considered. At Wami Mandera- flow gauging station 1G2, The Multiple Input-LPM Model with a record of maximum efficiency (R^2) for calibration and medium value of (R^2) for verification, it shows better results compared to all other models considered. SMAR recorded good calibration result next to the Multiple Input-LPM Model, but its verification record is one of the least two records. General observation of the calibration and the verification result shows that both the system and conceptual rainfall-runoff models exhibit better results in calibration than in verification period.

Table 6.31: Comparison of the Results of the SMAR Model with the Corresponding Results of System Type Models Applied in the Previous Study

No.	Sub-Catchment		Model Efficiency (R^2)					
			SMAR	SM	MISLM	MILPM	MILVGFM	MILVGFPM
1	Wami-Dakawa (1G1)	Calibration	73.14	46.12	41.08	65.77	42.77	64.52
		Verification	58.16	7.63	5.65	18.62	3.26	-13.68
2	Wami-Mandera (1G2)	Calibration	79.89	51.23	77.75	81.64	55.52	62.95
		Verification	9.58	5.03	32.13	33.66	43.28	54.35

CHAPTER SEVEN

SUMMARY, CONCLUSION AND RECOMMENDATION

7.1 Summary

The monthly time step rainfall-runoff Pitman model and the Soil Moisture Accounting and Routing (SMAR) model were applied in the Wami river basin. A summary of the model efficiency results obtained is presented in Tables 7.1 & 7.2 below.

The Pitman model gave acceptable range of % deviation for transformed mean annual runoff (mean annual log), indicating a fairly satisfactory simulation of low and medium flow both in calibration and verification but the other criterion i.e., the % deviation in MAR and annual standard deviation of the observed and simulated series and efficiency (R^2) show low performance specially in the verification period.

The SMAR efficiency (R^2) results fall in a range of (45.94%-79.89) and (-217.14%-58.16%) for calibration and verification respectively, indicating fairly satisfactory calibration results followed by low verification results. The water balance in terms of IVF values for both calibration and verification period has been found fairly satisfactory for most of the test sub-catchments.

Table 7.1: Summary of Pitman Model Calibration and Verification Statistics

Sub-catchment		1G2	1G1	1GD2	1G5A	1GD29	1GD31
Efficiency Criteria		**(%) DIFFERENCE**					
Mean Annual Runoff (Mm^3)	Calibration	0.46	-3.81	-0.15	-4.36	3.94	-0.22
	Verification	-168.42	-42.52	-88.54	-33.19	-56.36	-3.66
Mean Annual Runoff(log)	Calibration	0.06	-0.57	-0.03	-0.85	0.91	-0.04
	Verification	-14.10	-5.34	-10.97	-6.15	-9.83	-0.72
Annual Standard Deviation (log)	Calibration	90.71	90.03	89.76	91.95	87.33	90.68
Efficiency Criteria		**Model Efficiency (R^2) (%)**					
Calibration		66.02	77.37	63.08	56.40	55.48	51.38
Verification		-371.60	36.76	-252.99	50.65	11.93	14.70

Table 7.2: Summary of SMAR Model Calibration and Verification Statistics

Sub-catchment	Calibration Efficiency		Verification Efficiency	
	R^2 (%)	**IVF**	**R^2 (%)**	**IVF**
1G2	79.89	0.70	9.58	0.543
1G1	73.14	1.019	58.16	0.991
1GD2	47.72	1.01	-217.14	2.32
1G5A	71.43	0.865	51.69	0.558
1GD29	45.94	0.993	42.69	1.08
1GD31	49.47	0.952	15.93	0.926

7.2 Conclusion

The application of the two conceptual models (Pitman and SMAR) in Wami river basin in the present study have shown better performance of the two test models in calibration than in verification period. Some satisfactory calibration results have been observed, however, most of the verification results are low resulting in low overall performance of both Models. The low Model performance and deficiencies that have been observed in the simulation may be related to low quality of input data (in terms of missing value and poor spatial distribution) and the complex nature of wetland system of the basin and water abstractions which can affect the seasonal flow volume and variability and might be the cause to the models' inability to satisfactorily represent the real hydrological processes.

The low overall model performance obtained by applying the two conceptual models demonstrated that the models are not adequate to simulate the rainfall-runoff system of Wami river basin. The findings of the present study entail to other more detail studies of the Wami hydrology with improved input data quality and better understanding of the complex nature of the basin.

7.3 Recommendation

Selection of a best performing model for the rainfall-run of system of a catchment is a process that requires development of alternative scenarios employed to test the applicability of different types of Models. The previous study on Rainfall-runoff modelling in the Wami-Ruvu basin (Kalinga, 1998), has obtained low performance results of system analysis models for the rainfall-runoff system of Wami river basin. The present study has tested the applicability of two lumped conceptual models in the same study area and similar results are obtained like that of the previous study.

The complex nature of Wami basin hydrology which comprises a number of vegetated swamps and natural and manmade reservoirs needs more detail studies. Considering the great spatial variation of the hydrologic characteristics and variation in flow contribution of sub-catchments physically based semi-distributed Rainfall-runoff models accompanied with other sub-models that simulate water use by irrigation and other consumptive uses, and reservoir water balances should be tested for further Rainfall-runoff modelling studies in the Wami river basin. Moreover, Further Rainfall-runoff modelling studies in the Wami river basin should look for ways for improved data quality and availability.

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APPENDIX A

Table A-1: Rainfall Stations in and near Wami Basin with Available Monthly Record :(TMA)

SNO	WMO_CODE	NAME	LAT	LONG	ALT (m)	Available Record		
						From	To	Length
1	09636000	MPWAPWA RESEARCH STATION	-6.33	36.50	1037	1899	2007	109
2	09637018	MHONDA MISSION	-6.13	37.58	488	1904	2006	103
3	09637000	MOROGORO AGRICULTURE	-6.08	37.67	579	1905	1996	92
4	09635001	DODOMA AIRPORT	-6.17	35.77	1120	1911	2007	97
5	09637001	KILOSA AGRICULTURE	-6.83	37.00	491	1912	2007	96
6	09635002	DODOMA RESERVOIR I	-6.22	35.77	1143	1931	1986	56
7	09536007	NJOGE UJAMAA VILLAGE	-5.95	36.68	1219	1931	1975	45
8	09636002	BUIGIRI MISSION	-6.13	36.03	1066	1931	1966	36
9	09635003	MVUMI MISSION	-6.38	35.92	1066	1931	1945	15
10	09637003	BEREGA MISSION HOSPITAL	-6.20	37.17	853	1932	2006	75
11	09638004	MANDERA MISSION	-6.22	38.38	213	1933	2003	71
12	09636001	MPWAPWA SCHOOL	-6.35	36.50	1010	1933	1981	49
13	09536000	KIBAYA	-5.28	36.57	1457	1934	2000	67
14	09636004	KIBAKWE MISSION	-6.72	36.40		1935	2004	70
15	09637009	KIMAMBA RAILWAY STATION	-6.78	37.13	458	1935	1976	42
16	09636003	KONGWA MISSION	-6.22	36.40	1066	1935	1965	31
17	09637010	MASKATI	-6.08	37.47	1829	1936	1995	60
18	09637013	SCUTARI SISAL ESTATE	-6.78	37.17	457	1938	2007	70
19	09637014	USAGARA (MARIOS) ESTATE	-6.80	37.20	442	1938	2007	70
20	09638012	KWARUHOMBO PRIMARY SCH.	-6.08	38.13	457	1938	2007	70
21	09636006	KIBORIANI (MARTI)	-6.28	36.55	1783	1938	1996	59
22	09637021	MVOMERO CCM	-6.32	37.43	487	1938	1996	59
23	09637016	KILOSA SISAL ESTATE	-6.85	37.00	457	1938	1995	58
24	09637019	MSOWERO GINNERY	-6.53	37.22	1066	1938	1990	53
25	09635005	DODOMA GEOLOGICAL OFFICE	-6.18	35.77	1128	1938	1984	47
26	09638018	UTONDWE SALT WORKS	-6.25	38.25	6	1943	2007	65
27	09537000	TALAMAI	-5.37	37.35	1311	1943	1982	40
28	09637036	MBOGO-CHANZI PR. SCHOOL	-6.20	37.57	487	1945	1994	50
29	09635008	DODOMA RESERVOIR II	-6.20	35.78	1170	1945	1971	27
30	09636008	VIANZE DAIRY	-6.33	36.50	1067	1947	1997	51
31	09636050	KIYEGEYA MAJI	-6.52	36.82	991	1950	1997	48
32	09537001	MGERA PRIMARY SCHOOL	-5.38	37.53	1006	1951	1990	40
33	09637038	KISANGATA SISAL ESTATE	-6.62	37.17	457	1952	2007	56
34	09637042	MTIBWA SUGAR ESTATE	-6.13	37.65	457	1952	2007	56
35	09636013	KONGWA P.R.S	-6.03	36.33	914	1953	2007	55
36	09637047	HOBWE	-6.98	37.57	742	1954	2007	54
37	09537003	TAMOTA SETTLEMENT	-5.60	37.55	716	1954	1971	18
38	09537002	KWEKIVU SCHOOL	-5.77	37.38	853	1955	1964	10
39	09636018	UKAGURU FOREST STATION	-6.33	36.95	1676	1956	2007	52
40	09637051	MLALI	-6.97	37.33	594	1956	2007	52
41	09537004	KWADUNDWA	-5.67	37.67	853	1959	1978	20
42	09736007	ULAYA	-7.07	36.90	610	1960	2007	48
43	09636020	KINYASUNGWE	-6.20	36.30	914	1961	2007	47
44	09637032	ILONGA AGROMET	-6.77	37.03	502	1961	2007	47
45	09637056	WAMI PRISON FARM	-6.40	37.47	579	1961	2007	47
46	09535006	ZANKA PRIMARY SCHOOL	-5.88	35.75	1133	1961	2004	44
47	09535005	HOMBOLO PRIMARY SCHOOL	-5.88	35.92	1097	1961	1977	17
48	09637055	MADOTO	-6.73	37.08	518	1961	1977	17
49	09637030	UPONERA ESTATE	-6.93	37.82	426	1961	1961	1
50	09535007	MAKUTUPORA MAJI	-5.97	35.72	1080	1962	2007	46
51	09635012	DODOMA MAJI	-6.18	35.75	1133	1962	2007	46
52	09635014	MATAMBULU DAM	-6.30	35.77	1067	1962	1995	34
53	09536003	KIBAYA MAJI	-5.32	36.53		1962	1993	32
54	09536004	DABALO DAM	-5.78	36.13	1524	1962	1989	28
55	09737030	KIKOBOGA MIKUMI	-7.35	37.15	549	1963	1997	35
56	09637061	MVUMI VILLAGE	-6.62	37.17	487	1963	1995	33
57	09535009	MBUYUNI	-5.40	35.83	1219	1963	1986	24
58	09638035	WAMI RAILWAY STATION	-6.23	38.72		1964	1997	34
59	09535011	HOMBOLO LEPROSY CENTRE	-5.93	35.95	1036	1964	1988	25
60	09536005	ZOISA PRIMARY SCHOOL	-5.67	36.38	914	1964	1977	14
61	09637067	RUDEWA SISAL ESTATE	-6.70	37.13	442	1966	2007	42

SNO	WMO_CODE	NAME	LAT	LONG	ALT (m)	Available Record		
						From	To	Length
62	09637065	MSIMBA SEED FARM	-6.73	37.07	487	1966	2005	40
63	09636025	MYOMBO ESTATE	-6.92	36.97		1966	1996	31
64	09637066	KIVUNGU SISAL ESTATE	-6.93	37.03		1966	1989	24
65	09637043	MAGOLE ESTATE	-6.40	37.30	457	1966	1986	21
66	09637064	CHANJULU ESTATE	-6.80	37.05		1966	1984	19
67	09636048	NGALAMILO MAJI	-6.88	36.73	975	1969	1982	14
68	09636047	MDUKWI JUU	-6.92	36.80	853	1969	1980	12
69	09637075	KILANGALI RICE SEED FARM	-6.95	37.08	457	1970	2007	38
70	09637073	MAGUBIKE VILLAGE	-6.23	37.17	1310	1970	1995	26
71	09636027	NONGWE PRIMARY SCHOOL	-6.47	36.90	1880	1970	1993	24
72	09636026	GAIRO	-6.15	36.87	1786	1970	1989	20
73	09636049	LUFUSI MAJI	-6.85	36.62	1143	1971	2004	34
74	09636022	BUIGIRI DAM	-6.18	36.12	1067	1971	1994	24
75	09636029	KONGWA ADMIN.OFFICE	-6.20	36.42	914	1972	2007	36
76	09636031	MLALI VILLAGE	-6.30	36.77	1524	1972	1999	28
77	09636034	CHAMKOROMA PR.SCHOOL	-6.33	36.67		1972	1996	25
78	09536011	NJOGE PRIMARY SCHOOL	-5.95	36.68		1972	1986	15
79	09636035	GULWE RAILWAYS	-6.45	36.40		1972	1985	14
80	09636041	MIMA PRIMARY SCHOOL	-6.55	36.12		1972	1983	12
81	09536010	CHANDAMA DISPENSARY	-5.15	36.17		1972	1981	10
82	09636032	MSETA VILLAGE	-6.38	36.72	1524	1972	1980	9
83	09636033	PANDAMBILI	-6.07	36.73	1219	1972	1980	9
84	09636037	CHILOMWA PR. SCHOOL	-6.03	36.13		1972	1979	8
85	09536009	MKOKA VILLAGE	-5.80	36.43	1219	1972	1972	1
86	09636038	MTANANA PRIMARY SCHOOL	-6.05	36.58		1972	1972	1
87	09536013	SONGAMBELE UJAMAA VILL.	-5.93	36.45	1200	1973	1986	14
88	09636030	SAGARA	-6.27	36.55	1219	1973	1986	14
89	09636043	IGANDU DISPENSARY	-6.35	36.13	950	1973	1982	10
90	09535019	HOMBOLO AGROMET	-5.90	35.95	640	1974	2007	34
91	09637078	LUKENGE MTIBWA SUGAR LTD	-6.00	37.60	395	1974	2007	34
92	09536017	IKAMBO MET.STATION	-5.72	36.08		1974	2001	28
93	09535020	ZANKA VILLAGE	-5.83	35.75	1153	1974	1995	22
94	09536014	IZAVA VILLAGE	-5.50	36.17		1974	1988	15
95	09636045	CHAMWINO VILLAGE	-6.08	36.00	1036	1974	1987	14
96	09637079	KILOSA NATURAL RESOURCES	-6.85	37.02	670	1975	2003	29
97	09535021	CHENENE PRIMARY SCHOOL	-5.58	35.83	1194	1975	1997	23
98	09637083	KIGURUKIRO VILLAGE	-6.30	37.53		1975	1991	17
99	09637080	MELELA VILLAGE	-6.92	37.42	50	1975	1985	11
100	09537005	KILINDI	-5.63	37.60		1976	1989	14
101	09537009	SONGE PRIMARY SCHOOL	-5.58	37.28	1150	1976	1989	14
102	09537008	MZIHA PRIMARY SCHOOL	-5.90	37.78	450	1976	1985	10
103	09636046	WOTTA	-6.68	36.30		1976	1977	2
104	09638042	KIWANGWA PRIMARY SCHOOL	-6.37	38.60		1977	1983	7
105	09736015	MUHENDA TCA FARM	-7.20	36.92		1978	1986	9
106	09637085	KILOSA AGR. SEC. SCHOOL	-6.68	37.12		1979	1996	18
107	09536002	ITISO PRIMARY SCHOOL	-5.63	36.03	1219	1979	1994	16
108	09537006	KIMBE	-5.80	37.63		1980	1989	10
109	09537012	NEGERO PRIMARY SCHOOL	-5.78	37.80		1980	1987	8
110	09637089	MKATA RANCH	-6.77	37.38		1981	1998	18
111	09637086	LUHINDO-DAKAWA I	-6.50	37.50	360	1981	1989	9
112	09637090	KANGA PRIMARY SCHOOL	-6.02	37.75		1981	1988	8
113	09536016	KITETO	-5.87	36.85		1981	1987	7
114	09637088	MAKUYU VILLAGE	-6.02	37.20		1981	1982	2
115	09737041	DOMA PRIMARY SCHOOL	-7.08	37.28		1982	2004	23
116	09637091	DAKAWA RICE FARMS II	-6.40	37.55	396	1982	1999	18
117	09536015	MRIJO CHINI PR SCHOOL	-5.17	36.27		1982	1988	7
118	09736018	ULAYA ESTATE	-7.03	36.90		1982	1988	7
119	09637087	UNONE PRIMARY SCHOOL	-6.55	37.07		1982	1987	6
120	09636036	LUMUMA PRIMARY SCHOOL	-6.82	36.63		1988	1988	1

Table A-1.1: Ranges of Availability of Monthly Precipitation Data

Record length(yrs)	1-9	10-19	≥20	≥50
Qty	18	28	74	27
percentage	15.00	23.33	61.67	22.50

Table A-2: Availability of Daily Precipitation Data :(TMA)

S.NO.	WMO_CODE	NAME	LAT	LONG	ALT (m)	From	To	Length(yrs)
1	09536000	KIBAYA	-5.28	36.57	1457	1934	1992	59
2	09536004	DABALO DAM	-5.78	36.13	1524	1962	1991	30
3	09536017	IKAMBO MET.STATION	-5.72	36.08		1977	1990	14
4	09537009	SONGE PRIMARY SCHOOL	-5.58	37.28	1150	1976	1994	19
5	09635001	DODOMA AIRPORT	-6.17	35.77	1120	1932	1995	64
6	09635012	DODOMA MAJI	-6.18	35.75	1133	1961	1990	30
7	09635014	MATAMBULU DAM	-6.30	35.77	1067	1962	1995	34
8	09636000	MPWAPWA RESEARCH STATION	-6.33	36.50	1037	1925	1961	37
9	09636006	KIBORIANI (MARTI)	-6.28	36.55	1783	1938	1994	57
10	09636008	VIANZE DAIRY	-6.33	36.50	1067	1947	1995	49
11	09636013	KONGWA P.R.S	-6.03	36.33	914	1953	1995	43
12	09636018	UKAGURU FOREST STATION	-6.33	36.95	1676	1956	1995	40
13	09636020	KINYASUNGWE	-6.20	36.30	914	1960	1979	20
14	09636026	GAIRO	-6.15	36.87	1786	1970	1989	20
15	09636027	NONGWE PRIMARY SCHOOL	-6.47	36.90	1880	1970	1993	24
16	09636029	KONGWA ADMIN.OFFICE	-6.20	36.42	914	1972	1990	19
17	09736007	ULAYA	-7.07	36.90	610	1960	1989	30

Table A-2.1: Ranges of Availability of Daily Precipitation Data

Record length(yrs)	10-19	≥20	T0tal	≥50
Qty(stations)	3	14	17	3
percentage	18	82	100	18

Table A-3: Hydrometric Stations in the Wami River Basin :(MoWRT, Valimba, 2007)

Sno.	Station	River	Location	Lat	Long	Area (km²)	Status (Feb,2008)
1	1G1	Wami	Dakawa	-6.4478	37.5334	28,488.0	Operational – rehab in Sep 2006
2	1G2	Wami	Mandera	-6.2333	38.4000	36,450.0	Operational – rehab in Dec 2007
3	1G8	Wami	Rudewa	-6.6167	37.1833	63.2	Non-Operational
4	1G5A	Tami	Msowero	-6.5314	37.2141		Operational – rehab in Oct 2006
5	1G6	Kisangata	Mvumi	-6.5887	37.0229	140.3	Operational – rehab in Oct 2006
6	1G11	Chogoali	Difulu Village	-6.1000	37.3600		Non-Operational
7	1GA1A	Lukigura	Kimamba Rd. Br.	-5.8140	37.8011	1,060.0	Operational – rehab in Sep 2006
8	1GA1	Lukigura	Kwamvemo	-5.8153	37.8167	206.6	Non-Operational
9	1GA2	Mziha	Mziha (Kimamba)	-5.8959	37.7817	178.0	Operational – rehab in Sep 2006
10	1GB1A	Diwale	Ngomeni	-6.1044	37.5903	3,290.0	Operational – rehab in Oct 2006
11	1GB2	Mkindu	Mkindu	-6.2472	37.5389	90.7	Non-Operational
12	1GD2	Mkondoa	Kilosa	-6.8318	36.9781	17,560.0	Operational – rehab in Oct 2006
13	1GD29	Mkondoa	Mbarahwe	-6.5958	36.7833	475.3	Non-Operational
14	1GD32	Mkondoa	Railway Bridge	-6.7500	36.9500		Non-Operational
15	1GD17	Kinyasungwe	Godegode	-6.5000	36.6200	12,500.0	Non-Operational
16	1GD14	Kinyasungwe	Gulwe	-6.4333	36.4167	11,103.0	Non-Operational
17	1GD16	Kinyasungwe	Kongwa/Dodoma	-6.2177	36.3103	9,570.0	Operational – rehab in Sep 2006
18	1GD37	Kinyasungwe	Ikombo	-5.7160	36.0849	930.0	Operational – rehab in Sep 2006
19	1GD21	Kinyasungwe	Itiso	-5.5900	36.0000	900.0	Operational – rehab in Sep 2006
20	1GD34	Kinyasungwe	Mayamaya	-5.7800	35.8000		Non-Operational
21	1GD30	Lumuma	Kilimalulu	-6.6833	36.6667	502.0	Non-Operational
22	1GD31	Mdukwe	Mdukwe	-6.8311	36.9333	460.0	Non-Operational
23	1GD33	Masena	Ibumila	-5.9000	36.4000	240.0	Non-Operational
24	1GD35	Myombo	Kivungu	-6.9097	37.0242		Operational – rehab in Oct 2006
25	1GD36	Mkata	Mkata	-6.7592	37.3613		Operational – rehab in Oct 2006
26	1GB3	Chazi	Chazi	-6.2000	37.5667		Non-Operational
27	1G10	Mkundi	Matale	-6.2500	37.3333	0.0	Non-Operational
28	1GD6	Miyombo	Ulaya	-7.0667	36.8833	0.0	Non-Operational
29	1GD5	Mkombola	Lukando			0.0	Non-Operational
30	1G4	Mkundi	Mkundi				Non-Operational

Table A-3.1: Ranges of Availability of Flow Data

Record length(yrs)	**No- record**	**1-9**	**10-19**	**≥20**	**Total**
Qty (stations)	10	5	6	9	30
Percentage (%)	33	17	20	30	100

Table A- 4: Summary of Available Monthly Evaporation Data :(TMA, MoWRT)

S.no.	STID	STN_NAME	LAT.	LONG.	Length of Record		No. of years
					From	To	
1	9536017	Ikambo Met.Stn	-5.72	36.08	1974	1982	8
2	9637056	Wami Prison Farm	-6.40	37.47	1983	1991	9
3	9635001	Dodoma Airport	-6.17	35.77	1973	2007	23
4	9637076	Morogoro Met.Stn	-6.83	37.65	1970	2007	37
5	9638027	Kibaha Agromet	-6.83	38.97	2002	2007	5

Table A-5: List of Dams in Wami River Basin: (Valimba, 2007)

SNo.	Reservoir	River/stream	Lat	Long	Capacity (m^3)
1	Ikowa	Majenjeule	-6.17	36.20	3,107,000
2	Dabalo	Gt Kinyasungwe	-5.78	36.13	
3	Hombolo	Lt Kinyasungwe	-6.80	39.28	
4	Imagi	Imagi stream	-6.20	35.73	174,000
5	Msalatu	Msalatu stream	-6.20	35.75	388,000

Table A-6: Summary of Available Surface Water Abstractions in the Main Rivers of Wami Basin :(Valimba, 2007)

Zone	Major river	Amount (l/s)
Kinyasungwe	Little Kinyasungwe	1,088.30
	Great Kinyasungwe	
	Kinyasungwe	1,421.30
Mkondoa	Mkondoa	661.20
	Lumuma	2,645.00
Mkata	Mkata	54.10
	Myombo	3,839.10
Diwale	Chazi	27.80
	Dizungwi	90.70
	Divue	0.28
	Diwale	1,784.20
Wami	Kisangata	699.90
	Wami Dakawa	5,243.10
	Wami Mandera	3,280.00
	Wami Matipwili	116.00