

**The Application of the monthly time step Pitman Rainfall-Runoff
Model to the Kafue River Basin of Zambia.**

Thesis

submitted in fulfilment of the
requirements for the Degree of

Master of Science

of Rhodes University,
Grahamstown, South Africa

By

Elenestina Mutekenya Mwelwa

December 2004

DEDICATION

This thesis is dedicated to the memory of the late Chato Fackson Mwelwa, a dear husband and friend, who rejoiced with me when I got the scholarship to undertake this study, but went to be with the Lord and was not there to see the fulfilment and completion.

ACKNOWLEDGEMENTS

First and foremost, I wish to express my sincere gratitude to Professor Denis Hughes, my supervisor, for the support and the encouragement he gave me throughout the course of this study. As this study was undertaken on a semi part-time basis, I needed all the understanding and innovative suggestions I was given without which completion of this study would have been close to impossible. I also wish to thank my employers, ZESCO management for allowing me time off my busy work schedule to attend to the work on this study. In particular I wish to thank Dr. Joseph Mutale, who was my Director (ED) at the time I was processing my study permit, for taking my study permit issue personally and seeing to it that the management approval to allow me to take up this study was given.

This study would not have been possible without the financial support from the Department for International Development (DFID). I am so grateful to Dr. Jeremy Meigh of the Centre for Ecology & Hydrology, for the good coordination and facilitation of the funding in the implementation of the Southern Africa FRIEND Phase II project, under which this study was funded. In this regard, I am also thankful to the Southern African FRIEND project to have given me a chance to be the beneficiary of the regional initiative of capacity building in the application of models in the southern African region.

My work at the Institute for Water Research enabled me to meet many inspiring water resources professionals. I wish to acknowledge the privilege to have met Professor Tally Palmer who with the brief contacts she made with me just gave me the understanding that I can advance and be successful in my professional life and not lose touch with reality. I count it a blessing to have met a lady so inspiring like her. I would be failing in my task if I do not thank a good friend Juanita McLean, who ran around for me making all the preparations during the course of this study to a point that I did not even know some of the offices in the University because everything was well arranged and done on my behalf, thanks for the efficient office management skills.

As this study was undertaken in my first three years of my widowhood, it is now that I realise how much I valued every support from all my friends who took time off to send me mail or phone, I needed those shoulders to cry on and those words of encouragement to see me through. Again and again I kept wondering why a dear friend and husband would depart when I needed him most to take care of issues at home and to check on me regularly, sometimes I think it is a pure miracle from God that I made it through without Chato. For this, I give God the glory for the provisions and the favour he showed me throughout this study. Thanks Dad!

ABSTRACT

This thesis presents a discussion on the study undertaken in the application of the monthly time step Pitman rainfall-runoff model to the Kafue River basin. The study constituted one of the initial steps in the capacity building and expansion of the application of hydrologic models in the southern African region for water resources assessment, one of the core areas of the Southern African FRIEND project (Flow Regimes from International Experimental Network Data).

The research process was undertaken in four major stages, each stage working towards achieving the research objectives. The first stage was the preparation of spatial data which included the selection and delineation of sub-catchments and inclusion of spatial features required to run the Pitman model and transferring the spatial data into SPATSIM.

The second stage was the preparation of input data, mainly rainfall, streamflow, evaporation, and water abstraction data. This information was then imported into SPATSIM, which was able to assist in the further preparation of data by assessment of the input data quality, linking of observed flows and spatial interpolation of point rainfall data to average catchment rainfall in readiness for running and calibration of the model.

The third stage was the running and calibration of the Pitman model. Use was made of both the automatic calibration facility, as well as manual calibration by means of the time series graph display and analysis facility of SPATSIM. Model calibration was used to obtain the best fit and an acceptable correlation between the simulated and the observed flows and to obtain simulation parameter sets for sub-catchments and regions within the Kafue catchment.

The fourth stage was the analysis and evaluation of the model results. This included verification of results over different time periods and validation and testing of parameter transfers to other catchments. This stage also included the evaluation of SPATSIM as a tool for applying the model and as a database for the processing and storage of water resources data.

The study's output includes: A comprehensive database of hydrometeorological, physical catchment characteristics, landuse and water abstraction information for the Kafue basin; calibrated Pitman model parameters for the sub-catchments within the Kafue basin; recommendations for future work and data collection programmes for the application of the model. The study has also built capacity by facilitating training and exposure to rainfall-runoff models (specifically the Pitman model) and associated software, SPATSIM. In addition, the dissemination of the results of this study will serve as an effective way of raising awareness on the application of the Pitman model and the use of the SPATSIM software within Zambia and the region.

The overall Pitman model results were found to be satisfactory and the calibrated model is able to reproduce the observed spatial and temporal variations in streamflow characteristics in the Kafue River basin.

TABLE OF CONTENTS

	PAGE
Dedication	i
Acknowledgements	ii
Abstract.....	iv
1 INTRODUCTION.....	1
1.1 GENERAL OVERVIEW.....	1
1.2 THE FRIEND PROJECT	3
1.2.1 Southern African FRIEND.....	3
1.3 SADC WATER SECTOR INVOLVEMENT.....	5
1.3.1 Project Concept Note (PCN) 14	5
1.3.2 Terms of Reference – Study to Quantify the Surfaces Water Resources of Southern Africa (SADC).....	6
1.4 IAHS PREDICTION IN UNGAUGED BASINS (PUB).....	7
1.4.1 Objectives of the IAHS Decade of Prediction in Ungauged Basins	8
1.4.2 The PUB Targets	9
1.4.3 The Structure of PUB.....	9
1.4.4 The PUB Implementation in Southern Africa	10
1.5 AN OVERVIEW OF THE SURFACE WATER RESOURCES OF ZAMBIA.....	11
1.5.1 Rainfall.....	11
1.5.2 Water Resources Use in Zambia.....	11
2 AIMS AND OBJECTIVES	13
2.1 BACKGROUND TO THE OBJECTIVES OF THE STUDY	13
2.2 AIMS AND OBJECTIVES	14
2.2.1 Assessment of the application of the Pitman Model to the Zambian Catchments.....	14
2.2.2 Assessment of the use of SPATSIM for applying the model in a regional context	15
2.2.3 Determining suitable parameter values in a regional context.....	15
2.2.3 Building capacity in the application of rainfall-runoff models (specifically the Pitman model) within the SADC region and Zambia, in particular.....	15
2.3 THE EXPECTED OUTPUTS FROM THIS STUDY.....	16
2.3.1 Database of relevant catchment data.....	16
2.3.2 Calibrated Pitman model parameters for Kafue basin sub-catchments	16
2.3.3 Regionalised Pitman parameters for Kafue Basin	16
2.3.4 Recommendations for the future work.....	16
2.3.5 Capacity building.....	16
3 OVERVIEW OF HYDROLOGIC MODELLING	18
3.1 GENERAL ASPECTS OF HYDROLOGIC MODELS.....	18
3.2 HISTORY OF DEVELOPMENT OF HYDROLOGIC MODELLING	19
3.2.1 Prescriptive modelling development.....	20
3.2.2 Descriptive modelling development	21
3.2.3 Classification of Hydrological models.....	23
3.3 MODEL CALIBRATION AND VALIDATION	27
3.3.1 Objective functions	29
3.3.2 Optimisation procedures	30
3.3.3 Model validation.....	31

3.4	PRACTICAL USE OF MODELS FOR WATER RESOURCE ASSESSMENTS	32
3.5	INPUT DATA QUALITY AND AVAILABILITY ASPECTS	34
3.6	MODELLING WATER RESOURCES IN SOUTHERN AFRICA	35
4	METHODOLOGY	37
4.1	THE PITMAN MODEL	37
4.1.1	Rainfall distribution function	38
4.1.2	Interception function.....	38
4.1.3	Surface runoff function	40
4.1.4	Soil moisture storage and runoff function.....	41
4.1.5	Evaporation from the moisture store.....	41
4.1.6	Runoff delays and lags	41
4.1.7	Functions to represent artificial modifications to the hydrology	42
4.1.8	Main reservoir water balance model.....	42
4.1.9	Calibration procedures	43
4.1.10	Recent modifications to the Pitman model.....	46
4.2	SPATSIM – SPATIAL AND TIME SERIES INFORMATION MODELLING SOFTWARE	47
4.2.1	Structure of the SPATSIM package.....	48
4.2.2	Internal SPATSIM facilities	49
4.2.3	External SPATSIM utilities.....	55
4.3	GENERAL	63
5	STUDY AREA AND AVAILABLE DATA.....	65
5.1	THE KAFUE BASIN	65
5.1.1	Climate.....	65
5.1.2	Topography, soils and drainage.....	67
5.1.3	Geology and geomorphology	69
5.1.4	Land cover and Land use of the Kafue basin	73
5.2	RAINFALL DATA AVAILABLE	76
5.2.1	Suitability of available rainfall data for streamflow simulation.....	80
5.2.2	Distribution of rainfall within months of different rainfall amounts....	85
5.3	AVAILABILITY OF OBSERVED STREAMFLOWS	91
5.3.1	Suitability of observed streamflow data for Pitman model calibration.....	93
5.4	EVAPORATION DATA FOR THE KAFUE BASIN	100
5.5	EVAPORATION DATA FOR THE KAFUE FLATS.....	102
5.6	WATER USE INFORMATION	104
5.6.1	Natural Flood control features	104
5.6.2	Reservoirs.....	105
5.6.3	Water abstraction in the Kafue basin.....	108
6	INITIAL CONFIGURATION OF THE MODEL	111
6.1	INITIAL CONFIGURATION OF THE PITMAN MODEL FOR THE KAFUE BASIN	111
6.1.1	Lukanga Swamps.....	111
6.1.2	Itezhi-tezhi dam, Kafue Flats and Kafue Gorge dam.....	113
6.2	CALIBRATION PROCEDURES	115
6.2.1	Manual Calibration	115
6.2.2	Automatic Calibration.....	116
7	RESULTS	121
7.1	THE PITMAN MODEL PARAMETERS	122

7.1.1	Rainfall distribution factor (RDF)	122
7.1.2	Percentage area of vegetation type 2 (AFOR).....	122
7.1.3	Annual pan evaporation (PEVAP).....	123
7.1.4	The absorption rate parameters – ZMIN, ZAVE and ZMAX	124
7.1.5	Maximum storage capacity (ST)	125
7.1.6	Runoff rate at maximum storage capacity (FT).....	127
7.1.7	Power of moisture-runoff curve (POW).....	128
7.1.8	General observations.....	129
7.2	ASSESSMENT OF QUALITY OF CALIBRATION RESULTS	130
7.2.1	The coefficient of determination (R^2)	133
7.2.2	The coefficient of efficiency (CE).....	133
7.2.3	Mean monthly percentage error	134
7.3	VALIDATION OF CALIBRATION RESULTS.....	134
7.4	DISCUSSION OF SIMULATION RESULTS	135
7.4.1	Kafue River at Raglan Farm – sub-catchment A.....	135
7.4.2	Kafue River at Mpatamato – sub-catchment F.....	137
7.4.3	Lunga River at Kelongwa – sub-catchment N.....	139
7.4.4	Kafue River at Kafue Hook Bridge – sub-catchment R.....	141
7.4.5	Kafue River at Kafue Gorge Dam – sub-catchment T	143
7.4.6	Kafue Flats Floodplain storage in sub-catchment T	145
7.5	CONCLUDING REMARKS ON THE RESULTS.....	146
8	DISCUSSION AND CONCLUSIONS	149
8.1	IDENTIFIED DEFICIENCIES IN THE MODEL RESULTS	150
8.1.1	Application of the revised groundwater routines to sub-catchment A to F.	151
8.2	EVALUATION OF THE ZAMBIAN DATA FOR INPUT TO THE MODEL	154
8.2.1	Rainfall data	154
8.2.2	Annual pan evapotranspiration data.....	157
8.2.3	Observed flows	158
8.2.4	Water use data	159
8.3	EVALUATION OF MODEL RESULTS.....	160
8.4	EVALUATION OF SPATSIM AS A METHOD OF APPLYING THE MODEL AND STORING DATA.....	161
8.5	CONCLUDING REMARKS	164
9	CONCLUSIONS AND RECOMMENDATIONS.....	166
9.1	OVERALL CONCLUSIONS ON THE MODELLING EXERCISE	166
9.2	CONCLUSIONS ON THE DEVELOPMENT AND APPLICATION OF SPATSIM.....	168
9.3	RECOMMENDATIONS FOR FURTHER STUDIES IN ZAMBIA AND THE REST OF SADC.....	169
	REFERENCES.....	171

LIST OF FIGURES

	PAGE
1.1 Summary of PUB targets.....	9
3.1 Outline of classification of models	25
3.2 Graphical outline of process through which rainfall inputs are routed by through moisture accounting to produce streamflow as an output	26
4.1 Flow diagram representation of the Pitman model	39
4.2 Main window of SPATSIM.....	48
4.3 Basic data access structure in SPATSIM	49
4.4 Selection of an attribute to render from an array attribute.....	51
4.5 Specifying the scale and colour for the render	51
4.6 Rendered map showing the spatial distribution of parameter AFOR	52
4.7 Import time series data facility – step to specify data format type.....	53
4.8 Import time series data facility – step for specifying variable type and selecting data import files.....	53
4.9 Selection of sub-catchments and search radius for interpolation.....	54
4.10 Specification of the interpolation period, time step, search radius, maximum search items and data attributes to be used for interpolation.....	55
4.11 TSOFT profile containing observed and simulated flows for sub-catchments A, C, E and F.....	57
4.12 TSOFT graphical and statistical analysis facility.....	58
4.13 Baseflow analysis for observed streamflows for sub-catchment C.....	58
4.14 TSOFT X-Y scatterplot for rainfall stations, Ndola (4100) and Roan (4053)	59
4.15 TSOFT X-Y scatterplot for streamflows stations, Kafue river at Kafironda (4090) and Kafue river at Raglan Farm (4050)	59
4.16 Matching model requirements with available data from a SPATSIM database	61
4.17 The Pitman model ‘Road Map’ supplied as part of the help facilities of SPATSIM...	64
5.1 Location of the Kafue basin in the Zambezi River Basin.....	66
5.2 Kafue basin physical features and sub-catchment divisions.....	68
5.3 Geology of the Kafue basin	71
5.4 Upper Kafue basin showing landuse and landcover	75
5.5 Mpongwe block with agricultural activities	75
5.6 Land cover for the Lukanga, Itezhi-tezhi and Kafue Flats	76
5.7 Data available for all meteorological stations in Zambia	79
5.8 Kafue basin raingauges and mean annual rainfall distribution	81
5.9 X-Y scatterplot for Kasempa (3180) and St. Francis (3555).....	84
5.10 X-Y scatterplot for Ndola (4100) and Roan (4053)	84
5.11 X-Y scatterplot for Magoye (2525) and Nakambala (2402).....	85
5.12 Daily rainfall distribution (monthly rainfall of 70-100mm) tending to be closely related to an RDF of 1.28	87
5.13 Daily rainfall distribution (monthly rainfall of 150-180mm) tending to be closely related to RDF values of 0.6 and 0.8.....	87
5.14 Daily rainfall is evenly distributed (monthly rainfall of 200-280mm) and closely related to an RDF of 0.6	87
5.15 Daily rainfall distribution (monthly rainfall of 150-180mm) tending to be closely related to RDF values of 0.6 and 0.8.....	88
5.16 Daily rainfall evenly distributed (monthly rainfall of 200-280mm) tending to be closely related to an RDF of 0.6	88
5.17 Evenly distributed daily rainfall (monthly rainfall of 300-490mm) tending to be closely related to an RDF of 0.6	88
5.18 Daily rainfall distribution (monthly rainfall of 70-100mm) tending to be closely related to an RDF of 1.28	89
5.19 Daily rainfall distribution (monthly rainfall of 150-180mm) tending to be closely related to RDF values of 0.6 and 0.8.....	89

5.20	Daily rainfall distribution (monthly rainfall of 220-280mm) tending to be closely related to an RDF of 0.6	89
5.21	Daily rainfall distribution (monthly rainfall of 70-100mm) tending to be closely related to an RDF of 1.28	90
5.22	Daily rainfall distribution (monthly rainfall of 150-180mm) tending to be closely related to RDF values of 0.6 and 0.8.....	90
5.23	Daily rainfall distribution (monthly rainfall of 220-280mm) tending to be closely related to RDF values of 0.6 and 0.8.....	90
5.24	Kafue River at Kafironda (4090) against Kafue river at Raglan Farm (4050)	96
5.25	Tributary flows for Lunga at Chifumpa (4560) against Lunga at Kelongwa (4550) ...	97
5.26	Kafue River at Hook Bridge (4669) against Itezi-tezhi (460995) reservoir outflows ..	99
5.27	Flow losses to Lukanga swamps between Chilenga (4350) and Mswebi (4307)	99
5.28	Peak flow losses to Lukanga swamps	105
5.29	Domestic / Industrial water abstraction in the Kafue basin	109
5.30	Agricultural water abstractions in the Kafue basin	110
6.1	Kafue basin showing the sub-catchments used for model calibration.....	112
6.2	Diagrammatic representation of the model setup and calibration steps for sub-catchments J, L and Q	114
7.1	Geographical distribution of percentage of vegetation type 2 cover	123
7.2	Geographical distribution of annual pan evaporation	124
7.3	Geographical distribution of parameter ST	127
7.4	Geographical distribution of parameter FT	129
7.5	Graphical results of comparison between observed and simulated flows for sub-catchment A.....	136
7.6	X-Y scatterplot and statistical results of comparison between observed and simulated flows for sub-catchment A.....	137
7.7	Graphical results of comparison between observed and simulated flows for sub-catchment F.....	138
7.8	X-Y scatterplot and statistical results of comparison between observed and simulated flows for sub-catchment F	139
7.9	Graphical results of comparison between observed and simulated flows for sub-catchment N.....	140
7.10	X-Y scatterplot and statistical results of comparison between observed and simulated flows for sub-catchment F	140
7.11	Graphical results of comparison between observed and simulated flows for sub-catchment R	142
7.12	X-Y scatterplot and statistical results of comparison between observed and simulated flows for sub-catchment R.....	143
7.13	Graphical results of comparison between observed and simulated flows hydrographs for sub-catchment T	144
7.14	X-Y scatterplot and statistical results of comparison between observed and simulated flows for sub-catchment T	144
7.15	Simulated volume of the dummy reservoir representing storage on the Kafue Flats floodplain	145
8.1	Comparison of observed and simulated flows based on the original (old) version and the revised Pitman model(new)	153
8.2	Spatial distribution of the rainfall stations and mean annual rainfall distribution	156
8.3	SPATSIM and some of the linked external processes.....	162

LIST OF TABLES

	PAGE
4.1 Pitman and Reservoir model parameters	40
4.2 Example of a text file defining the data requirements of the Pitman model.....	62
5.1 Mean monthly rainfall in the Kafue basin	67
5.2 Calendar month average daily potential evapo-transpiration in the Kafue basin.....	68
5.3 Description of the geology of Kafue sub-catchments	72
5.4 Summary of Kafue sub-catchment characteristics	77
5.5 General information on available monthly rainfall data.....	80
5.6 Monthly rainfall analysis – coefficient of determination / distance between stations.....	83
5.7 Status of the hydrometric network in Zambia.....	91
5.8 Rating curves for some streamflow gauging stations in Kafue basin.....	92
5.9 General information on available monthly streamflow data.....	94
5.10 Monthly streamflow data analysis – coefficient of determination and straight map distances	95
5.11 General information on available A-pan evaporation data	101
5.12 Summary of annual open water evaporation estimates (mm) for Kafue basin	101
5.13 Mean monthly A-pan evaporation estimate for the Kafue Flats	103
5.14 Itezhi-tezhi reservoir outflow requirement	107
5.15 Summary of water abstraction data for Kafue basin	109
6.1 Release operating rules for the dummy dam representing the Kafue Flats floodplain.....	115
6.2 Initial manual calibration results for sub-catchments A, C, D, E and F	116
6.3 Automatic calibration experiment A.....	117
6.4 Fixed parameter values ranges for C.....	118
6.5 Automatic calibration experiment B	119
7.1 Calibrated Pitman model parameters for Sub-catchments A to K	131
7.2 Calibrated Pitman model parameters for Sub-catchments L to T	132
7.3 Summary of the calibration and validation results for selected sub-catchments in the Kafue river basin	135
7.4 Summary of statistical measure of goodness-of-fit between simulated and observed flows	136
8.1 Parameter changes between the original and revised versions of the Pitman model.....	153
8.2 Number of rainfall stations per sub-catchment	155
8.3 Distribution of nearest Evaporation stations for sub-catchments.....	159

1 INTRODUCTION

1.1 GENERAL OVERVIEW

The research presented in this thesis, on the application of the monthly time step Pitman rainfall-runoff model to the Zambian Catchments, constitutes one of the initial steps in the expansion of the application of hydrologic models in the southern African region for water resources assessment. The expansion of application of hydrologic models in the Southern African region is one of the core areas of Southern African FRIEND (Flow Regimes from International Experimental Network Data), which is part of the UNESCO International FRIEND programme. This research project was conceived as a result of the objective and recommendation on capacity building in the application of hydrologic models, through the provision of opportunities for collaborative work with interested individuals or organisations within the Southern African region (Hughes,1997).

The structure of this report comprises a brief discussion of the FRIEND project objectives and its contribution to water resources development in the SADC (Southern Africa Development Community) region. It also provides justification of the usefulness of water resources quantification to the Zambian water resources development needs. This is followed by an outline, in section 2, of the project objectives and the outputs and their value to the water resources assessment process. Section 3 gives an overview of hydrological models, calibration and validation procedures and the problems associated with input data. It also provides a review of the experience of the Southern African region in the use of hydrologic models in regional water resources assessment. The methodology for the study, giving a description of the Pitman model, SPATSIM (Spatial and Time Series Information Modelling software package), calibration options, spatial data preparation and data requirements of the model is presented in section 4. A description of the study area, providing the specific physical aspects of each sub-catchment that has been modelled is given in section 5. In this section, a description of the input data and its suitability for running the model is also given. The initial configuration of the Pitman model is presented in section 6. Results are presented in Section 7, while a discussion and analysis of the Zambian data, model results and application of the SPATSIM package is

given in Section 8. Conclusions and recommendations related to the overall modelling exercise, areas of further development of SPATSIM and possibilities for further studies and application of the study to Zambia and the whole Southern African region are presented in Section 9.

The research process was undertaken in four major stages, each stage working towards achieving the objectives. The first stage was the preparation of spatial data which included the selection and delineation of sub-catchments and inclusion of spatial features required to run the Pitman model. During this stage sub-catchment physical characteristics were also identified and outlined. The spatial data were then transferred into SPATSIM.

The second stage was the preparation of input data: mainly rainfall, stream flow, evaporation, and water abstraction data. This information was then imported into SPATSIM, which was able to assist in the further preparation of data such as an assessment of the input data quality through the time series graph display and analysis facility, linking of observed flows and spatial interpolation of point rainfall data to average catchment rainfall in readiness for the calibration of the model.

The third stage was the set up and calibration of the Pitman model. Use was made of both the automatic calibration facility, as well as manual calibration by means of the time series graph display and analysis facility. Model calibration was used to obtain the best fit and an acceptable correlation between the simulated and the observed flows and to obtain simulation parameter sets for sub-catchments and regions within the Kafue catchment.

The fourth stage was the analysis and evaluation of the model results. This included verification of results over different time periods and validation and testing of parameter transfers to other catchments. This stage also included the evaluation of SPATSIM as a tool for applying the model and as a database for the processing and storage of water resources data.

1.2 THE FRIEND PROJECT

This research was conceived as a result of the recommendation on the way forward for application of hydrologic models in the southern African region, a sub-programme under the Southern African FRIEND, which is part of the International FRIEND network. The FRIEND (Flow Regimes from International Experimental and Network Data) research programme is an international study in regional hydrology. Its aim is to develop a better understanding of hydrological variability and similarity across different regions through the mutual exchange of data, knowledge and techniques. Such knowledge is vital to improve practical water resource and flood design methods (UNESCO, 1997). The international FRIEND is currently a project under UNESCO's Fifth International Hydrological Programme (IHP) whose central objective is hydrology and water resources for sustainable development. From a modest beginning in 1985, with scientists from just four European countries, the project has grown considerably and now involves research institutes, universities and operational agencies from over 90 countries. There are currently seven regional FRIEND projects in operation and these are: Northern European, Alpine and Mediterranean, Hindu Kush – Himalayan, Asian Pacific, West and Central Africa, Southern Africa and Nile Basin.

1.2.1 Southern African FRIEND

The southern African FRIEND programme involves all the countries of SADC and the United Kingdom, through the Centre for Ecology and Hydrology (formerly the Institute of Hydrology) and their central involvement in the FRIEND projects of other regions. The main research participants in the Southern African FRIEND project are the University of Dar-Es-Salaam (Tanzania), the Institute for Ecology and Hydrology (UK), the SADC Water Sector and the Institute for Water Research (IWR), Rhodes University (South Africa). The geographical scope of Southern Africa FRIEND began with the eleven mainland states of SADC: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe. The Democratic

Republic of Congo joined the FRIEND project in 1998 but has yet to participate actively, while Mauritius has also participated in recent meetings.

The objectives of Southern Africa FRIEND were organised into three theme areas: Flood Research, Drought and Water Resources Assessment and Rainfall-Runoff modelling. Given the long history of the Institute for Water Research's (IWR) involvement in the development and application of rainfall-runoff models, its contribution to the rainfall-runoff theme under the FRIEND project became important. The IWR contribution to the Southern African FRIEND project was aimed at improving the experience base of the use of models in the region, with particular emphasis on identifying some of the problems associated with their application and building capacity in the field of hydrological modelling. The project had the main objective of developing procedures and guidelines for the application of appropriate deterministic catchment models within the Southern African region for a variety of water resource assessment purposes. The justification of this project was mainly that, while the topic of rainfall-runoff models has been extensively covered and models frequently used in some parts of the region, notably South Africa, there are many countries of the region where the potential of time-series modelling to solving water resource related problems has not been adequately addressed (Hughes, 1997).

Under phase 1 of the Southern African FRIEND, the IWR applied two models to a number of southern African catchments. The models were the monthly time step Pitman model and the daily time-step VTI model. The two models were packaged in the HYMAS software which allowed several models to be operated within a common suite of data preparation and analysis programs which were not only designed for simulated data, but also for carrying out a variety of hydrological and water resource assessments using observed data (Hughes, 1997). One of the objectives of the rainfall-runoff modelling sub-programme of phase 1 of the Southern African FRIEND project (1993-1996) was to assess the general applicability of a monthly and a daily time-step model to simulating the hydrology of catchments from within the whole SADC region. The monthly model selected was the Pitman model (Pitman, 1973; Pitman & Kakebeeke, 1991), which has

been applied extensively within South Africa and frequently elsewhere in the region. While it was not the express purpose of the FRIEND project to develop the model further, some limited changes were made to improve the applicability of the model to arid and semiarid catchments. (Hughes & Metzler, 1998). The main part of the research programme involved setting up, calibrating and verifying the two models on the test data sets. The programme concluded that there was a the need for further regional studies and application of the coarse time-step Pitman model and emphasised the aspect of capacity building, if the potential for the use of model in the region were to be realised and appreciated (Hughes, 1997).

1.3 SADC WATER SECTOR INVOLVEMENT

1.3.1 Project Concept Note (PCN) 14

The SADC region, through its analysis of recommendations from the SADC member country Water Sector Situation Reports, identified the need for an assessment of regional surface water resources. Therefore Project Concept Note (PCN) 14 was conceived for the purpose of producing a project proposal that would enhance surface water resources assessment in the region. PCN 14 therefore represented the first step in the efforts of the SADC Water sector to spearhead the quantification of the surface water resources of the whole of Southern Africa (SADC region) in a coordinated and unified manner as well as building capacity within the region to make site-specific water resource assessments (SADC, 1999).

In the SADC Water Sector PCN 14 the following areas of concern were highlighted:

- i) The absence of a rigorous assessment of quantity and variability (both in space and time) of the available resource as one of the several constraints to national economic and social development.
- ii) The need for improvement of the knowledge and information base for improved water resources management and inadequacies in information acquisition and sharing as a constraint to the development of transboundary water resources.

- iii) The need to produce and make accessible a SADC-wide Surface Water Resources assessment, in a manner that builds capacity in implementing institutions, promoting confidence in assessment products amongst member States.

The justification for such a project at regional level in respect of (PCN 14) was that:

- i) Assessments of the available surface water resource are fundamental to economic planning and social development. All SADC member states (except island nations) lie within international river basins; therefore assessment of the surface water resource on a regional basis is important to national water resources management and development.
- ii) To apportion and share water within international river basins, member states require a reliable quantitative assessment of water within a whole river basin in order to ensure international equity in use rather than an assessment of their national contribution alone.
- iii) Confidence amongst member states in assessment of available water within a whole river basin was identified to be more important than the assessment itself.
- iv) Regional transfers of reliable cross border flow and geographic information among riparian states is paramount, to enable riparian states to generate the necessary assessments, in an environment that has sparse data and information.
- v) A country by country basis of assessment is not sufficient to manage water in international river basins.

1.3.2 Terms of Reference – Study to Quantify the Surface Water Resources of Southern Africa (SADC)

The second step was therefore the commissioning of a team of specialists to come up with a Terms of Reference document for a study to quantify the surface water resources of Southern Africa. While the formal motivation for the compilation of the Terms of Reference was linked to PCN14, the Southern Africa FRIEND programme had also identified the need for such a study during discussions held in 1998/99 to establish the priorities for the second phase of the programme. Both PCN14 and the recommendations

of the FRIEND programme Steering Committee led to a proposal to the Water Research Commission of South Africa, which funded the project, to allow a team of specialists to compile a detailed Terms of Reference document that could be used as a basis for sourcing support from funding agencies (SADC, 2001).

In addition to PCN14 and the FRIEND Steering Committee recommendations, another driving force for the SADC region wide water assessment study is the benefit South Africa derived from the WR90 reports (Midgley *et al.*, 1994 - a regional assessment of surface water resources for South Africa, Lesotho and Swaziland). The benefits of the WR90 reports include: estimates of groundwater contributions to surface flow, environmental requirements of rivers and estuaries and impacts of streamflow reduction activities on water availability. It was perceived that the application of similar water resource assessment techniques used in South Africa would benefit the SADC region in quantifying the regional water resources.

The overall aim of the Terms of Reference document is to improve the ability of member states of SADC to make surface water resource assessments that support environmentally sustainable development through broad strategic water resource planning which is based on information and approaches that are reliable and mutually acceptable within the region. Emphasis is put on capacity building if the objective is to be met.

The study reported in this thesis was a pilot study to the proposed SADC wide study. The study focuses on the application of Pitman model to Zambian catchments and it is hoped that this application will be extended to other catchments within Zambia and the whole of the Southern African region. Unfortunately there seems to be little current progress with obtaining funding to support the broader initiative.

1.4 IAHS PREDICTION IN UNGAUGED BASINS (PUB)

IAHS is an international association for hydrological sciences established in 1922, having over 3000 members around the world. As a science association, IAHS is engaged in

various activities to enable science to serve society. Prediction in Ungauged Basins (PUB) is the most recent initiative of the IAHS. PUB arose out of free discussions by IAHS members on the internet and during a series of IAHS sponsored meetings, based on the recognition of the current needs of the world, especially of developing countries, and a scientific readiness to make a new commitment (Sivapalan, 2003).

1.4.1 Objectives of the IAHS Decade of Prediction in Ungauged Basins

The IAHS Decade on Prediction in Ungauged Basins (PUB) (2003 – 2012), is aimed at formulating and implementing appropriate science programmes to engage and energise the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged basins. The justification is that it has been found that currently, the most widely used predictive tools for water resources, water quality and natural hazards assessments are essentially data-driven, estimated from hydrometric (gauged) data. Major difficulties are encountered when applying these traditional prediction tools to river basins for which little or no hydrometric data are available. In particular, the lack of hydrometric data coupled with the effects of climatic and land use changes contribute to considerable uncertainties in hydrologic predictions and in subsequent water resources and water quality assessments. The science programmes within PUB will therefore have the following broad community objectives:

- Advance the ability of hydrologists worldwide to predict the fluxes of water and associated constituents from ungauged basins, along with estimates of the uncertainty of predictions;
- Advance the knowledge and understanding of climatic and landscape controls on hydrologic processes occurring at all scales, in order to constrain the uncertainty in hydrologic predictions;
- Demonstrate the value of data for hydrologic predictions, and provide a rational basis for future data acquisitions, including alternative data sources, by quantifying the links between data and predictive uncertainty;

- Advance the scientific foundations of hydrology, and provide a scientific basis for sustainable river basin management.
- Actively promote capacity building activities in the development of appropriate scientific knowledge and technology to areas and communities where it is needed.

1.4.2 The PUB Targets

The activities of PUB are planned to be grouped under two targets as shown in Figure 1.1. Target 1 focuses on examining and improving existing models in terms of their ability to predict in ungauged basins through appropriate measures of predictive uncertainty. Target 2 is about developing new, innovative models to capture space-time variability of hydrological processes for making predictions in ungauged basins, with a concomitant reduction of predictive uncertainty.

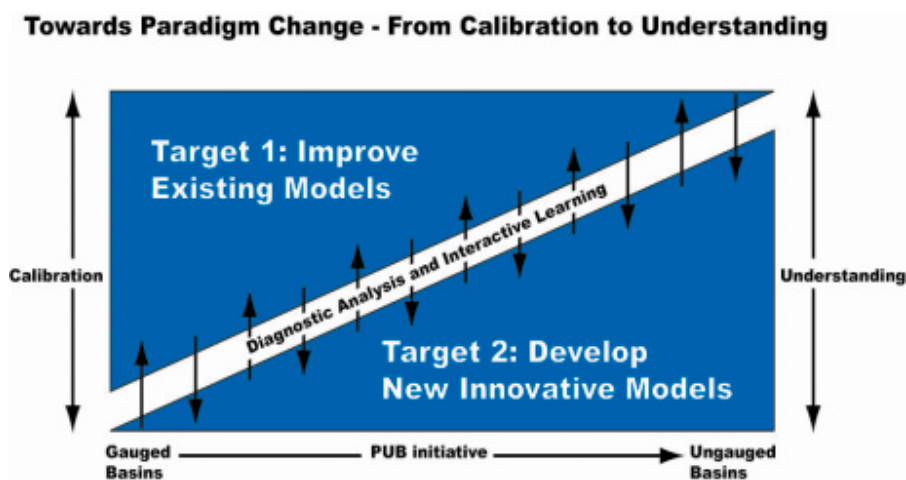


Figure 1.1 Summary of PUB targets (Source: Sivapalan, 2003, IAHS, PUB Science and Implementation Plan)

1.4.3 The Structure of PUB

The main drivers of PUB are the hydrologists, coming together in a self-organised fashion, to form affiliated PUB Working Groups. The PUB Working Groups will be

coordinated through the PUB Science Steering Group (SSG). PUB is also expected to work through partnerships with other international hydrological programmes (of which FRIEND is one example).

The SSG will proactively work towards enhanced coordination amongst the many PUB Working Groups that will be formed around the world centred on basins, problems and hydroclimatic zones. From the PUB Progress Report of September 2004, it was reported that 18 Working Groups had been formed and formally registered (IAHS Bureau Paris meeting, September 2004). There will be a PUB workshop during the April 2005 VIIth IAHS Scientific Assembly and the theme will be 'Freshwater: Sustainability within Uncertainty'.

1.4.4 The PUB Implementation in Southern Africa

In Southern Africa, the advancement of the PUB initiative was addressed at the 5th Waternet / WARFSA annual Symposium in November 2004, Windhoek, Namibia. The Southern Africa PUB Working Group was constituted (Minutes of Windhoek PUB Session, November, 2004). The main focus of the working group is:

- Understanding and reduction of predictive uncertainty through exploring the use of RADAR data for hydrological purposes in southern Africa and through capacity building by working with young researchers in producing research proposals addressing this theme
- Working Group to lobby for improvement of existing hydrometric networks through presentations to decision-makers on the importance and value of hydrological data.
- Improvement of the knowledge of effects of heterogeneity at various scales and
- Improved understanding of surface and groundwater interactions.

There are therefore many overlaps between the objectives of PUB and FRIEND and the work undertaken in the Kafue River basin for this study has the potential to contribute to the objectives of both programmes within a southern Africa context.

1.5 AN OVERVIEW OF THE SURFACE WATER RESOURCES OF ZAMBIA

1.5.1 Rainfall

Zambia is endowed with abundant water resources as it experiences a sub-humid tropical climate. The average annual rainfall and rain days in Zambia range from 657 mm and 68 days to 1402 mm and 142 days with an overall average for Zambia of 1001 mm and 97 days. Luapula Province has the highest annual rainfall of 1259 mm and 123 days on average and Southern Province has the least annual rainfall of 737 mm and 74 days on average with 90 percent of the rainfall occurring in the months from November to March and monthly averages ranging from 100 to 250 mm.

1.5.2 Water Resources Use In Zambia

Zambia's largest non-consumptive user of surface water resources is the electricity industry and over 95% of Zambia's electric energy is hydro-generated. As Zambia is endowed with abundant surface water resources, it is also blessed with a hydroelectric power potential estimated at 6 000 MW of which only about 1 625 MW have been exploited to date (less than 30% of the available potential). To conduct feasibility studies for all the remaining hydro power potential sites, reliable water assessment and quantification methodologies have to be put in place as some of the potential sites occur on ungauged catchments and some in catchments with short and/or poor streamflow records.

The Zambian Government is currently encouraging private participation in the energy industry and therefore has given the mandate to ZESCO Limited (Electricity Power Company in Zambia) to carry out feasibility studies and prioritise the hydroelectric projects for investment. In this regard, vital water resource information is required for decision making. As the most feasible project sites occur on the Kafue River basin, ZESCO, in its quest to get more information on the status of the Kafue Basin environment, commissioned the Kafue Basin Integrated Environmental Impact

Assessment study that would help generate the data and information on which decisions for future developments in the Kafue River basin would be based. It is with this background in mind, that this study decided to concentrate the application of the Pitman model on the Kafue basin. The results would be of immediate use in the process of developing the Kafue Basin Hydroelectric Power Project phases, which would include development of the Kafue Gorge Lower power station (600 MW), development of the Itezhi-tezhi hydroelectric power station (120 MW) and fine tuning and synchronising of reservoir regulation to meet the needs of the three power stations.

The highest consumptive user of water, with a high potential for expansion, is the agricultural sector. The importance of this is highlighted by the food shortages that have occurred in Zambia in the last few years. Because of droughts and floods, a new look at the expansion of irrigation has been taken, to examine the possibilities of growing irrigated winter crops, to supplement the rain fed summer crops. The irrigation potential can only be successfully tapped with the availability of long-term quantitative data of both surface and ground water resources.

2 AIMS AND OBJECTIVES

2.1 BACKGROUND TO THE OBJECTIVES OF THE STUDY

The study was conceived as a result of the objective and recommendation of the Southern Africa FRIEND Project on capacity building for the application of hydrologic models, through the provision of opportunities for collaborative work with interested individuals or organisations within the region (Hughes, 1997). This is also in line with the recommendation from the SADC Water Sector PCN 14, which highlights the need for the regional application of rainfall-runoff models to facilitate regional water resources assessment.

This study on the application of the Pitman model to the Zambian catchments is viewed therefore as a pilot project contributing to the proposed long-term SADC wide study, which is considered to be of critical importance to the sustainable economic development of the region.

One of the motivations for the long-term assessment study is the range of benefits that South Africa has derived from the WR90 reports and database (Midgley *et al.*, 1994 - A regional assessment of surface water resources for South Africa, Lesotho and Swaziland). While designed largely to support strategic level water resource availability assessments and the preliminary design of abstraction schemes, additional benefits have included the estimation of groundwater contributions to surface flow, environmental requirements of rivers and estuaries and the impacts of streamflow reduction activities on water availability. It was perceived that the application of similar water resource assessment techniques used in South Africa would benefit the SADC region in quantifying regional water resources. The basis for the WR90 streamflow database is the application of the Pitman (1973) monthly rainfall-runoff model and the generation of simulated natural flow for 1946 quaternary catchments using regionalised model parameters based on calibration against naturalised observed streamflows.

In designing the work programme for Phase II of the SA FRIEND project, it was recognised that a contribution to the larger long-term study would have the best potential benefits to the region. Given the limited resources available to the FRIEND project, three focus areas were identified as being of value and achievable in the time frame of Phase II and one of the areas of focus was to undertake a regional application of the Pitman model in Zambia, designed to assess the model and associated software tools capabilities, identify problems related to data availability and to build capacity in the use of the model.

2.2 AIMS AND OBJECTIVES

The project has the following specific objectives:

- Assessment of the application of the Pitman model to Zambian catchments.
- Assessment of the use of SPATSIM (a database and model application software package) for applying the model in a regional context.
- Determining suitable parameter values in a regional context.
- Building capacity in the application of the rainfall-runoff models (specifically the Pitman model) within the SADC region and Zambia, in particular.

2.2.1 Assessment of the application of the Pitman model to the Zambian catchments.

It is planned to apply the Pitman model to the Kafue basin of Zambia, building on the initial work that was undertaken in phase I of the Southern Africa FRIEND programme (Hughes, 1997) on other Zambian catchments; also to undertake an assessment of the suitability of the Pitman model as a tool for water resource assessment for the Zambia hydrological system.

2.2.2 Assessment of the use of SPATSIM for applying the model in a regional context.

SPATSIM is a software package designed as a database, data analysis and modelling system, specifically for hydrological and water resource applications (Hughes, 2002). It has been developed at the Institute for Water Research using the Delphi programming language with links to Paradox database tables and uses ESRI MapObjects to provide the spatial data display and analysis facilities (see Section 4 for detailed description). This study provided an opportunity for assessing its applicability in the regional context.

2.2.3 Determining suitable parameter values in a regional context

The Pitman model application can be used to determine suitable model parameter values that not only provide the best fit, but also can be related to the sub-catchment differences in the Kafue basin as a way of assessing the successful application of the model.

2.2.4 Building capacity in the application of the rainfall-runoff models (specifically the Pitman model) within the SADC region and Zambia, in particular.

Rainfall-runoff models were identified as potentially useful tools that could contribute to the regional assessment of water resource availability. However, it was also recognised that several problems exist which include:

- lack of experience within the region in the use of such tools.
- lack of access to the software required to apply models.
- lack of a common understanding of the benefits of different models and their results.

This study offered an ideal opportunity to initiate efforts in capacity building through facilitating training and exposure to rainfall-runoff models (specifically the Pitman model) and associated software (SPATSIM) within the SADC region, in advance of a more structured training programme for the long-term PCN 14 project.

2.3 THE EXPECTED OUTPUTS FROM THIS STUDY

2.3.1 Database of relevant catchment data

A comprehensive database of hydrometeorological, physical catchment characteristics, landuse and water abstraction information for the Kafue basin in Zambia and an assessment of the adequacy of these data for modelling purposes.

2.3.2 Calibrated Pitman model parameters for Kafue basin sub-catchments

Calibrated Pitman model parameters for the sub-catchments within the Kafue basin and an assessment of the success of the application of the model. The results would provide a good basis for further national scale applications of the Pitman model

2.3.3 Regionalised Pitman parameters for Kafue Basin

The project is designed to generate a set of regionalised Pitman model parameters for the Kafue basin, as well as guidelines for their application.

2.3.4 Recommendations for future work

The Pitman model application will be used to identify issues that need further attention. Recommendation for future work and data collection programmes will be made based on the model application experience.

2.3.5 Capacity building

This study offered an ideal opportunity to initiate efforts in capacity building through facilitating training and exposure to rainfall-runoff models (specifically the Pitman model) and associated software, SPATSIM. The expected output is an adequately trained practitioner, who may subsequently assist in building capacity in other water resource

staff. The dissemination of the results of this study will serve as an effective way of raising awareness on the application of the Pitman model and the use of the SPATSIM software within Zambia but also in the southern African region.

3 OVERVIEW OF HYDROLOGIC MODELLING

This Section presents a discussion of the general aspects of hydrologic modelling and their practical application for water resource assessment in a southern Africa context. It further discusses some of the issues related to both manual and automatic model calibration, input data problems and their impact on model results. Finally, the experience of the use of hydrological and water resource estimation models in Southern Africa is reviewed.

3.1 GENERAL ASPECTS OF HYDROLOGIC MODELS

A hydrological model may be defined as a set of mathematical relations describing the various components of the hydrological cycle, with the aim of simulating the end result of the hydrological cycle, which is runoff. In the hydrological cycle, the transformation of input (rainfall) into output (runoff) involves a number of interrelated processes. In hydrological models, attempts are made to duplicate this transformation of rainfall into runoff (Pitman, 1973), albeit with varying degrees of simplification and generality.

The assumptions underlying modelling approaches should be consistent with hydrological reality and predictions should not be made outside the observed range of system behavior. The true value of any hydrological model is said to be in its ability to be applied to find solutions to real water resource problems. The practical value of any model must be evaluated in the context, not only of its theoretical base in hydrology, but also from the point of view of the degree to which its data requirements are consistent with the information that is readily available (Hughes, 1997). Several hydrological model specialists have demonstrated that the quantity and quality of the input data is often the limiting factor in successful model simulations (Hughes and Beater, 1989; Sorooshian, 1991).

To limit the model to acceptable complexity, only the principal components and relationships in the hydrological cycle are normally selected. Therefore, Pitman (1973)

describes the chief goal of hydrologic simulation as the provision of a skeleton of the absolute knowledge. The model would be said to be physically relevant if an improved understanding of the hydrologic cycle and its processes is achieved (Pitman, 1973).

According to Pitman (1973), a practical hydrologic model should meet the following requirements:

- Represent to an acceptable degree of accuracy, the hydrologic regimes of a wide variety of catchments
- It should be easily applied with existing hydrologic data to different catchments.
- The model should be physically relevant so that, in addition to streamflow, estimates of other useful components such as actual evaporation or soil moisture state can be made.

3.2 HISTORY OF DEVELOPMENT OF HYDROLOGIC MODELLING

The science and art of modelling is said to have developed in response to the research community's perceived opportunities for advancing the state of knowledge in the subject, and the engineering community's need for predictive hydrological tools (O'Connell, 1991). This is with the background that the relationship between rainfall and runoff has been one of the central themes of hydrological research for many years (Ward, 1984). The advancement in hydrological modelling can therefore be viewed from two standpoints. The first is one that seeks to contribute to a better understanding of the catchment hydrological response in an effort to find answers as to why catchments respond as they do. This is the 'why driven research' relating to Penman's 'what happens to the rain' assertion (Penman, 1961). This type of modelling is referred to as the descriptive approach. The second is the engineering standpoint, which is concerned with how to make engineering predictions with a demand for hydrological predictions of an acceptable accuracy to be generated by whatever means available. This modelling approach, is referred to as prescriptive modelling and is primarily driven from the point of the engineering quest for making better hydrologic predictions for use in engineering planning and design (O'Connell, 1991).

3.2.1 Prescriptive modelling development

Systems Engineering approach to modelling

The origins of the systems engineering approach to modelling can be traced from the desire to solve engineering problems, notably reservoir spillway design, land drainage system design, and urban sewer systems design (Todini, 1988; O’Connell, 1991). This quest gave rise to the development of the Unit Hydrograph (UH), which was based on prepositions that were believed to be dubious. Despite this criticism, the prepositions based on the UH opened a way through research hydrologists in the 1960s to the development of conceptual models. The research led to the development of the Instantaneous Unit Hydrograph (IUH), which could be expressed in terms of a few parameters, which could in principal be related to catchment characteristics (Nash, 1960). Stimulated by technological developments in data sensing and transmission techniques and in associated computer hardware and software, hydrologists have turned their attention increasingly to the opportunities for employing rainfall-runoff models as practical water resources estimation and management tools for flood warning, reservoir management, water detention areas management, diversion canal management, irrigation and water distribution canals management and sewer networks management (O’Connell, 1991.)

The Explicit Soil Moisture Accounting (ESMA) approach to modelling

The acronym (ESMA) is said to have been coined by Todini and Wallis (1977) to describe a generation of rainfall runoff models, which emerged in the early 1960’s. Linsley (1982), in an overview of rainfall-runoff model development, traces the origins of these models to various studies of the component processes of the hydrological cycle and flood routing. Most of the development in this approach can be traced to the Stanford Watershed Model (SWM) developed in 1960 which was relatively simple and used daily rainfall, a simple infiltration function, and a Unit Hydrograph and recession function to produce the mean daily flow hydrograph (Crawford and Linsley, 1962; Fleming, 1975).

The SWM underwent further development in the quest to model total catchment response rather than storm runoff and in an effort to represent the behaviour of various component processes within the hydrological cycle through storage and routing processes. An overall mass balance between inputs, outputs and storage changes was maintained at all times (O'Connell, 1991). The term 'physically-based' was coined in the context of the SWM model to refer to parameters which could be evaluated from maps, surveys, or existing hydrometeorological records (Fleming, 1975; O'Connell, 1991). The advent of the SWM model approach is said to have given rise to a proliferation of similar ESMA models of varying degrees of complexity. Most of the models that have been developed and used in the southern Africa region are of this type (Pitman, 1973; Roberts, 1978; Gorgens, 1983; Hughes and Sami, 1994; Schulze, 1994).

It is under the ESMA approach that the problem of matching model output to observed streamflow was seen as requiring special attention, particularly since model calibration at that time was a somewhat subjective process carried out through the interpretation of results of successive model runs, a process best carried out by the developer of the model. This then led to extensive studies of optimisation techniques, which brought a recognition that parameter estimation could be achieved through an optimisation procedure that minimises (or maximises) an objective function (Sorooshian and Gupta, 1983). With the advent of interactive computer graphics in the early 1980s, prospects for making manual calibration procedures easier and more efficient were improved with the possibility of using both manual and automatic parameter estimation within an interactive graphics framework (Klatt and Schultz, 1981). Subsequently, advances in computer technology (both computing power and graphics capabilities) have removed many of the earlier restrictions on calibration approaches (Hughes et al., 2000; Madsen, 2000; Eckhardt and Arnold, 2001).

3.2.2 Descriptive modelling development

The motivation behind descriptive modelling is deemed to be the quest for a better understanding of the behaviour of hydrological systems. The discussion here will be

centred on developments which have a bearing on the evolution of physically based distributed models of basin scale hydrology.

Hillslope hydrology and runoff production mechanisms

The origin of the scientific debate on how runoff occurs can be traced to Horton's (1933) work on the role of infiltration in the hydrological cycle. Horton's theory assumes that runoff is generated where and when rainfall intensity exceeds the rate at which water enters the soil. However, over the years, research on hillslopes have shown that Hortonian overland flow is a relatively rare occurrence in the field and that there are other physical mechanisms needed to explain runoff production. This led to the emergence of the study of hillslope hydrology and the introduction of the concept of subsurface flow through the work of Hewlett (Hewlett and Hibbert, 1967) and others. The concept of variable source areas within the catchment, which would have different time lags of overland flow contribution to the storm hydrograph was also introduced (Dunne, 1978). In a review of field studies associated with the hillslope flow process and evidence for runoff production mechanisms carried out by Dunne, 1978, a conclusion was made that water could reach stream channels by several routes and that the processes that deliver storm flow, and the volumes and timing of their contributions, vary with topography, soil properties, vegetation, land use and rainfall characteristics (Dunne, 1978; Ward, 1984). This development therefore heightened interest in the subject of spatial variability and scale which were considered to be the key to evolving a sound basis for modelling runoff production at catchment scales (Beven et al., 1988)

Physically-Based Distributed modelling at the catchment scale

The development of physically-based distributed modelling was seen by some as the only approach that would lead to the application of catchment-scale distributed models to real world problems, such as the environmental impacts of man's activities in catchments (Schulze, 2000). A major step in this category was the development of the Système Hydrologique Européen (SHE) model (Abbot et al., 1986a, b). The motivation for the

development of SHE came from the perception that conventional rainfall-runoff models were inappropriate to many pressing hydrological problems, notably those related to the impact of man's activities on the flow, water quality and sediment transport of river basins. A physically based distributed modelling system such as SHE appeared to provide the appropriate framework for predicting such impacts. SHE was developed as a comprehensive modelling system with a flexible system structure that allows new versions of the component models to be easily integrated and which provides a continuous upward development path for the system as opposed to the one-off empirical modelling philosophy (Abbot et al., 1986a; Abbot et al., 1986b; O'Connell, 1991).

While the concepts associated with the promotion of physically-based modelling approaches are clearly sound, the reality of applying such models in practice is a different matter. Beven (1989) highlighted the problem of transferring physics-based equations, developed at very small scales, to the typical modelling scale of a catchment (see also Blöschl and Sivalapan, 1995). This debate continues today (Hughes, 2005), although there has been a shift away from the structure of the models and more towards the assimilation of data into hydrological models of different types (Kovar and Nachtnebel, 1993; McLaughlin, 1995; Wagener et al., 2003).

3.2.3 Classification of Hydrological models

In the recent past, hydrological modelling techniques have increased in popularity resulting in the proliferation of many different models (Beven, 2001). Some of the models are intended for specific applications, while others are more general in their area of applicability and range from very simple to highly complex (Beater, 1989).

Hydrological models have traditionally been broadly classified into two categories; stochastic and deterministic (Clarke, 1973; Fleming, 1975). Stochastic models recognise chance dependence of hydrological processes and make use of existing data and statistical principals to generate output in accordance with certain statistical patterns. In contrast, deterministic models regard hydrological processes as being chance

independent. This suggests that there are definite physical laws which govern the processes that transform rainfall to river flow in a catchment. Deterministic models also assert the fact that a catchment is not a random assembly of different parts, but a geomorphological system with catchment characteristics which may vary spatially and temporally, but in a known way (Pitman, 1973; Beater, 1989).

Figure 3.1 provides an outline of one possible model classification system. However even the distinction between stochastic and deterministic can become blurred and there are instances where according to water resources design needs, a requirement would arise where both stochastic and deterministic modelling approaches are used in what is known as quasi-stochastic models (Pitman, 1973; Moore, 1985). In some instances a stochastic model may be used to lengthen rainfall records and a deterministic model may be used to predict runoff from the generated rainfall (Bonne, 1970; Herald, 1989; Beater, 1989). Another distinguishing factor between deterministic and stochastic simulation lies in the length of data that can be generated. For deterministic simulations, the length of data to be generated depends on the length of observed precipitation data, while in stochastic simulations, data can be generated for any length of period.

The first level of distinction frequently used for deterministic models is the level of hydrological process detail that is included in the model. Empirical (or so-called Black Box) models tend to ignore process detail, in favour of simple rainfall-runoff transformation equations with very few parameters (Perrin et al., 2003). Physically-based models, on the other hand, are attempts to include as much detail as possible, partly through a requirement that parameter values should be measurable from field observations. Conceptual models are frequently seen as a compromise solution, where the essential structure of the hydrological cycle is represented in the model, but in a simplified way.

Conceptual models are models in which some understanding of hydrological processes is included in the model formulation, with the catchment being perceived as consisting of

one or more moisture storages through which rainfall inputs are routed by a process of moisture accounting to produce streamflow, as illustrated in Figure 3.2.

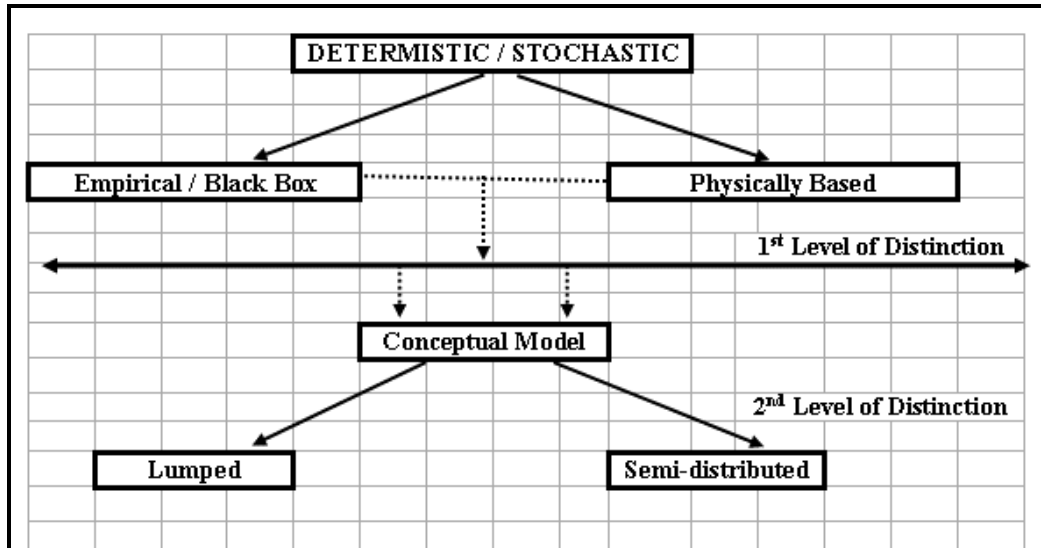


Figure 3.1 Outline of classification of models.

The distinction between simple lumped models and distributed models is related to the amount of spatial detail that is allowed for in a model and is frequently reflected in the calibration procedure adopted to determine the appropriate parameter values. Lumped models are based on a single set of parameter values for the whole catchment area and rely primarily on the comparison between observed and simulated outflows to calibrate the parameters. On the other hand, distributed models divide the catchment into a number of sub-units (grids, slope elements, etc.) and parameter values are frequently estimated from measured catchment and/or climate characteristics. Calibration is therefore often based on scaling the *a priori* established parameter values for groups of similar sub-units. These can therefore prove to be very complicated with a large number of parameters, especially when there is a lack of physical catchment information.

An alternative approach is represented by semi-distributed models which attempt to bridge the gap between the simple lumped models and the complex distributed models (Beven and O'Connell, 1982; Beven, 1991). Semi-distributed models take into account

the spatial heterogeneity of parameters over a catchment, but retain the more simple structure of the less data intensive lumped models. The perceived advantages are that both model parameters and input climate variables can be represented in a more realistic, spatially distributed manner. The success of adding spatial complexity is largely dependent upon the availability of reliable and appropriate spatially distributed information (Hughes, 2005).

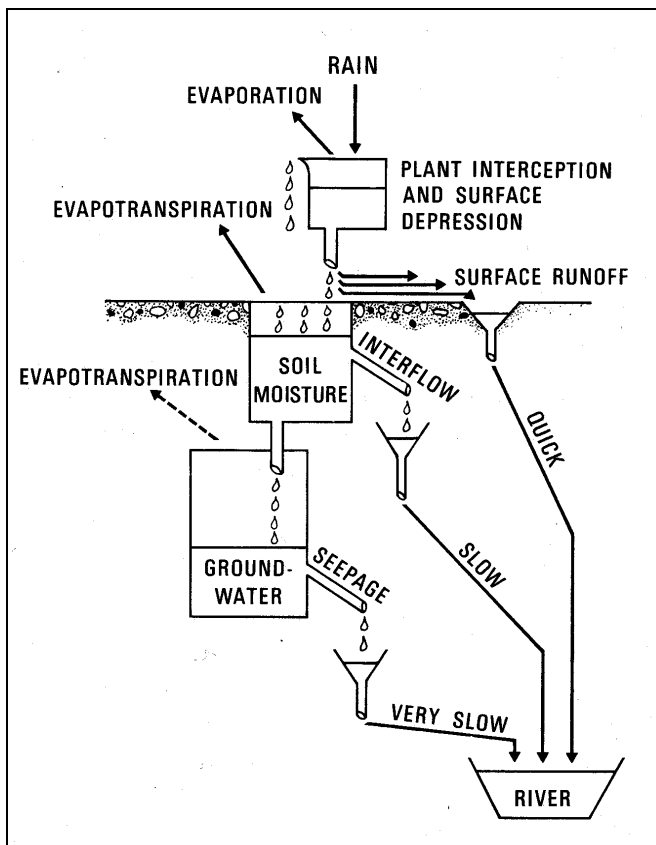


Figure 3.2 Graphical outline of processes through which rainfall inputs are routed by through moisture accounting to produce streamflow as an output (Beater, 1989)

Another distinction in models is based on the time-step used in the modelling process. The time step could vary from course intervals of monthly, weekly, daily, hourly to very fine intervals of five minutes or less (Hughes, 2005). Some models also use variable time

intervals (Hughes, 1992), in order to minimize run time and designed to simulate process activity in smaller time-steps during rapidly changing hydrological events, such as periods of peak rainfall.

3.3 MODEL CALIBRATION AND VALIDATION

It was during the emergence of the ESMA approach that the problem of matching model output to observed streamflow was seen by some research hydrologists as requiring special attention, because at that time model calibration was a somewhat subjective process carried out through the interpretation of the results of successive model runs. One of the first optimisation procedures was proposed by Dawdy and O'Donnel (1965). Subsequently, there have been many contributions to the hydrological literature on the subject of model fitting, calibration processes, objective functions and parameter identifiability (Sorooshian and Gupta, 1983; Görgens, 1983; Ndiritu and Daniell, 1999, 2001; Beven, 2001; Wagener et al., 2003)

Model calibration, which refers to the process of estimating model parameters is said to be the first stage in the evaluation of the model performance. That is the models' ability to reproduce runoff hydrographs is determined through calibration. The main purpose of the model calibration is to obtain a parameter set for a catchment which gives the best possible fit between the simulated and observed hydrographs for the calibration period (Ndiritu and Daniel, 1999). It is fundamentally an iterative process involving the following steps:

- The simulation using an initial parameter set from a search space to obtain the model performance.
- The determination of a parameter set that is likely to perform better than used in the previous simulation and simulation using the new parameter set.
- The repetition of the second step until a satisfactory performance is obtained, or further improvements are negligible.

This calibration procedure may include parameter sensitivity analysis which provides information about the degree and pattern of interaction between parameters as well as the sensitivity of fitting statistics to changes in parameter values (Beater, 1989).

A number of approaches exist which may be adopted to calibrate rainfall-runoff models, these include: the *a priori* approach (Chapman, 1975) where model parameters are inferred from measurable catchment or storm characteristic; goodness-of-fit approach (Pitman, 1976), where model parameters are inferred by a quest to find parameters which will ensure close correspondence between specific characteristics of a hydrologic time series and their observed equivalent; and the third calibration approach involves estimating parameters by use of both *a priori* and goodness-of-fit methods (Gorgens, 1983), where a number of parameters are physically based and may be estimated from catchment characteristics. In the later approach, the parameter values can then be fine-tuned by goodness-of-fit calibration methods (either manual or automatic).

The latter point serves to illustrate that the system of calibration is not necessarily independent of the type of model being applied. For example, any *a priori* quantification of parameter values assumes some knowledge of the relationships between parameters and measurable catchment or climatic characteristics. The developers of the ACRU model (Schulze, 1994; 2000) argue that the successful application of models in ungauged basins relies upon *a priori* quantification, as there is no possibility of calibration. However, there are different approaches to *a priori* quantification. Schulze (2000) argues that it should be based on physical relationships between parameter values and catchment characteristics, while others have argued that it is possible to develop empirical relationships through regional calibration against observed data (Hughes, 1985; Meigh et al., 1999). The empirical relationships can then be used to estimate parameter values at ungauged sites. The regionalised parameter values of the Pitman model for the whole of South Africa (Midgley et al., 1994) were developed through the classification of catchments into hydrological zones and the regionalisation of parameter sets derived from model calibration for sample catchments where observed data were available. No strict relationships between the characteristics of the zones and the parameter sets were

developed and the process was somewhat subjective. However, the resulting simulated time series of natural flow data have been used in South Africa for water resource planning purposes for over 10 years.

3.3.1 Objective functions

The correspondence of simulated and observed hydrographs is measured by a number of statistical goodness-of-fit criteria known as objective functions (Rosenbrock, 1960; Gorgens, 1983; Ndiritu and Daniel, 1999) There are many types of objective functions available, the choice of 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:

- Coefficient of efficiency, also referred to as the Nash-Sutcliffe criterion after Nash and Sutcliffe, 1970 (CE) – dimensionless measure of the one to one fit;

$$CE = 1 - \frac{\sum (Obs. - Sim.)}{\sum (Obs. - ObsMean)}$$

- Coefficient of determination, (R^2) – the correlation coefficient squared;

$$R^2 = \frac{\sum \{(Obs. - ObsMean)(Sim. - SimMean)\}}{n.S_o.S_s}$$

Where: S_o is the standard deviation of observed data

S_s is the standard deviation of simulated data

- Percentage error in total runoff volume, (%V)
- Percentage error in peak discharge, (%P)
- Time difference between observed and simulated peaks, (TP).

The coefficient of efficiency is sensitive to systematic errors such as the general over- or under-prediction between observed and simulated hydrographs, whereas the coefficient

of determination is not (Nash and Sutcliffe, 1970). Large differences between these coefficients is an indication of systematic errors. While high percentage errors in peak (%P) and volume (%V) can also indicate systematic errors. Low percentage errors in peak (%P) and volume (%V) can be associated with low coefficient values, unless a large time difference between the observed and simulated peak discharge occurs, in which case the coefficient values can be quite low. All of the objective functions can be calculated using untransformed discharge values or using the natural logarithm of values. Logarithmic transformation removes the bias towards the high values (Dobson, 1983).

3.3.2 Optimisation procedures

The iterative steps of model calibration could be undertaken manually or automatically using an optimisation method or procedure. Effective automatic methods are preferred by some as they reduce subjectivity (Ndiritu and Daniel, 1999). However, where the modeller is adequately experienced with a given model, manual calibration could suffice (Ndiritu and Daniel, 1999). The use of optimisation techniques will allow the model to be calibrated satisfactorily for the range of catchments it is intended to represent such that there is knowledge on how the parameters are varying between catchments. Optimisation procedures therefore enhance the ability of the modeller to assess the predictive power of the model (Klemeš, 1986).

Manual optimisation generally involves modifying one or more parameter value and observing the effect on the fitting criteria between the observed and the simulated values and then repeating the exercise (Gorgens, 1983). However manual optimisation is time consuming and can be confusing particularly if there is a high degree of interaction between parameters (Eckhardt and Arnold, 2001; Madsen, 2000). The success of a manual calibration is said to depend heavily on the experience of the modeller and their knowledge of the model components and parameter interactions (Eckhardt and Arnold 2001).

Automatic optimisation means that parameters are evaluated using an automatic optimising technique (Rosenbrock, 1960; Ibbitt and O'Donnell, 1971; James, 1972; Gupta and Sorooshian, 1985; Yapo et al., 1995; Ndiritu and Daniel, 1999). This procedure lessens reliance on the subjective judgement of the modeller and calibration can be significantly faster. According to Ndiritu and Daniel (1999), due to parameter correlations, it is often found that a unique global optimum parameter set does not exist and therefore recommend that the detection of parameter correlations should become an integral component of parameter identification and that an adequate level of optimisation should detect parameter correlations precisely. Since only one objective function can be used in some automatic optimisers, it may be necessary to carry out manual adjustments to parameter values to fine tune the model to achieve a better overall correspondence based on several criteria.

Eckhardt and Arnold (2001) suggest that since the high number of parameters in distributed models make special demands on the optimization process, there is need to develop a strategy of imposing constraints on parameters to limit the number of independently calibrated values.

In automatic optimization, calibration based on a single performance measure is often inadequate to properly identify the successful simulation of all the important characteristics of the system that are reflected in the observations (Madsen, 2000). This then has led to the development of automatic calibration strategies with the use of multi-objective functions (Madsen, 2000). These are known to be quite complicated but may be a step in the right direction to enhance the usefulness of automatic optimization routines.

3.3.3 Model validation

There is some confusion in the literature between model validation and verification and they have frequently been used to describe the same thing. There are essentially two checks that are needed in the application of hydrological models. The first is that the model algorithms and the way these are represented in the computer code are correct and

accurate (Stedinger and Taylor, 1982). This may include an assessment of whether the model is achieving a water balance (i.e. no water is being lost in the model). For the purposes of this document, this process is referred to as ‘model’ validation or verification.

Once the calibration of a model is completed, it becomes necessary to check that the calibrated parameter values can be used satisfactorily to simulate events, or climatic conditions, other than those used for the calibration (Sorooshian, 1983; Pirt and Bramley, 1985). This is referred to in this document as ‘parameter’ validation or verification, as it is the calibrated parameter set that is being assessed, rather than the model structure.

Another level of validation is to check perceived associations between model parameters and physical catchment characteristics. If these associations can be established and are then applied to different data sets from the calibrated catchments, then parameter validation would involve the assessment of the success of the transfer of the parameter relations to other catchments. This is vital to demonstrate whether the model can be used successfully to simulate flows in ungauged catchments.

3.4 PRACTICAL USE OF MODELS FOR WATER RESOURCE ASSESSMENTS

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). Sufficient knowledge of streamflow is necessary to aid in the efficient design and construction of bridges, conduits, dams, flood control structures, irrigation schemes, multipurpose water supply schemes, transboundary water transfers and any water resources related infrastructure such as hydroelectric power stations. 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.

Many water resources problems are best tackled by testing the simulated performance of alternative designs in relation to representative sequences of hydrological input in the system. For the purpose of simulation, usually a hydrograph covering a period of 50 years of monthly river flows is required at each key point of interest in the system. Getting this length of 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. Rainfall-runoff modelling often provides a solution because precipitation records normally extend back much further than flow records. This is due to the relative ease of making precipitation measurements as compared to setting up a discharge measuring station. Raingauges are easy to install with a much greater flexibility of choice of site which can be conveniently located near a centre of human activity thus facilitating operation and maintenance. River gauging stations on the other hand, must be located at hydraulically acceptable sites which are often remotely located, with gauge plates often being susceptible to damage or lack of maintenance. Gauging stations also require calibration through the establishment of rating curves which may require many years to adequately cover the range of stage variations. These requirements, added to the fact that resources in terms of both human and material costs are limited, has led to the situation where there are fewer river gauging stations with relatively shorter records while precipitation stations are numerous and have longer records (Shawinigan, 1993):

Hydrological models are therefore a useful tool to aid decision making in water resources assessments, planning and management (James, 1991). 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.

3.5 INPUT DATA QUALITY AND AVAILABILITY ASPECTS

One of the prerequisites of any modelling procedure is an assessment of the data that are available to set up and calibrate the model. No model results can be better than the quality of the available data and it becomes important to appreciate the limitations that the quality of available data places on the reliability of the model results (Hughes et. al., 2003; Paturel et.al., 1994). The availability of good quality data is vital for effective calibration. A model would not be optimised adequately in the absence of good quality input data with associated observed flows for calibrations. Hughes and Beater (1989) identified the amount of information available for defining the input data and quantifying model parameter values as one of the important factors in the choice of which model to apply. This is especially true of parts of the southern African region, where warfare and economic limitations of the present and past have largely precluded the collection of spatially and temporally representative water resource information (Hughes, 1997).

No model can be applied successfully when rainfall data used for input are not adequately representative of the true catchment inputs. This lack of representativeness may apply to mean or median annual depths, or may relate to shorter-term inputs and their spatial variability (Wilson et al., 1979) and may further relate to extended periods of missing data (Hughes, 1997). It is the inadequacy of raingauge networks that has led to the trend of looking for alternative sources for this information such as radar facilities (Obled et al., 1994; Mazvimavi, 2003) and satellite derived rainfall information. Deficiencies in input data for modelling has also led international organizations such as IAHS to spearhead the trend in developing tools to help overcome the problems and to improve predictions in ungauged basins (PUB). The investigation of such options is one of the objectives of the IAHS, PUB programme (Sivapalan, 2003).

A number of Modellers (such as Dawdy and Bergman, 1969; Beven and Hornberger, 1982; Krajewski et al., 1991) have concluded in their studies and experiments that time- and space-varying rainfall inputs can influence the timing and magnitude of simulated

responses. Sorooshian et al. (1983) further pointed out that rather than length of input data, it is the quality of information contained in the data which is important.

The lack of data was identified as a common feature in most SADC countries by the SADC Water Sector PCN 14. All of the SADC member State Water Sector Situation Reports submitted to the SADC Regional Strategic Action Plan (RSAP) called for improved surface water resources assessment at either sub-national, national, river basin or regional scales (SADC PCN 14). The PCN 14 identified that the absence of a rigorous assessment of the bulk and variability (in time and space) of the available resources is one of the several constraints to national economic and social development (SADC, 1999; 2001).

The current development of remote sensing and advanced ground-truth measurement devices have been acknowledged as one aspect that will help solve the problem of a lack of reliable data which has had a negative impact in the development of hydrologic models (Sorooshian, 1991). This has also contributed to the development of grid-based approaches to water resources assessment tools (Meigh et al., 1999; Gumbrecht, 2000; Tate et al., 2000)

3.6 MODELLING WATER RESOURCES IN SOUTHERN AFRICA

The growing population and ever increasing demand placed on the water resources in the Southern African region, has brought a realisation among water resource experts that water resources are finite and therefore need to be managed more rigorously than before. This management cannot be effectively done without the objective assessment of the available water resources by use of empirical methods of hydrologic models (Chibanga, 2002). However it has been recognized by Hughes et al. (2003) that there is a lack of experience within the region in the use of such tools, as well as inadequate access to software required to apply models. The need for water resources assessment was identified as needing attention in the SADC countries. This was identified by the SADC Water Sector PCN 14 (SADC, 1999; 2001).

It has been noted that the positive experience of the use of models in a South African context (Hughes, 2005) clearly demonstrate the practical value of models for water resource planning and decision making. Hughes (1997) affirms that there is great potential for extensive application of models in the Southern African region where many of the water resource problems are similar. It is hoped that the initiative of application of models will continue into the future and gain momentum as more hydrologists within the region perceive the benefits of modelling approaches and become adept in their application (Hughes, 1997).

Apart from the widely applied Pitman model (Hughes, 1997), a number of other initiatives related to water resource assessments have been applied. One example is drought assessment using ARIDA (Assessment of the Regional Impact of Drought in Africa), which is based on the combination of rainfall-runoff models and a grid-based assessment using GWAVA – global water availability assessment tool for fresh water availability and demand at the global scale (Meigh et al., 1999; Tate et al., 2000)

In addition to models serving specifically as useful tools for design purposes, the Southern African Development Community (SADC) through the Water Sector Coordination Centre identified the use of models as key to the water resources assessment of the regional basins (SADC, 2001). Following this identification, the FRIEND project commissioned a project through the Institute for Water Research whose objective was to develop procedures and guidelines for the application of appropriate deterministic catchment models within the SADC Region for a variety of water resource assessment purposes (Hughes, 1997).

4 METHODOLOGY

This section describes the methodology used in the application of the Pitman model to the Kafue basin of Zambia. This includes a description of the Pitman model and the modifications made to the original model in response to the different modelling needs under the FRIEND project and includes a description of the data required. The SPATSIM software package is also described giving details of the facilities within the package to facilitate data management and preparation for modelling. Descriptions are also provided of the manual and automatic model parameter calibration options and parameter transfer approaches.

4.1 THE PITMAN MODEL

The Pitman model was developed in 1973 (Pitman, 1973) and has become one of the most widely used monthly time-step rainfall-runoff models within Southern Africa. The basic form of the model has been preserved through all the subsequent versions that have been re-coded by the original author and others, but additional components and functionality have been added. The version that is used in this study is based upon modifications added during the application of the model for Phase I of the SA FRIEND programme (Hughes, 1997). This version has now been incorporated, together with a reservoir water balance model, into the SPATSIM (SPatial and Time Series Information Modelling – see Section 4.2) package developed at the Institute for Water Research (IWR).

The model structure is outlined in Figure 4.1, while Table 4.1 provides a list of the parameters of both the rainfall-runoff model and the reservoir water balance model and brief explanations of their purpose. Additional compulsory data requirements for the rainfall-runoff model include catchment area, a time series of catchment average rainfall, seasonal distributions of evaporation (fractions), irrigation water demand (mm), other water demands (fractions) and monthly parameter distribution factors. Two values for parameters PI1, PI2 and ZMIN are provided as part of the input parameter data set, one for January and one for July. The monthly parameter distribution factors are then used to generate the values for the other months of the year. Optional data requirements include optimisation ranges for some parameters (ZMIN, ZMAX, ST, POW and FT), and time series of catchment average

potential evaporation, upstream inflow, transfer inflow and downstream compensation flow requirements.

The compulsory requirements for the reservoir water balance model are monthly distributions of normal drafts (fraction of annual abstraction requirement, ABS in Table 4.1), monthly distributions of drafts (fractions) for up to five reserve supply levels (defined by parameters RES1 to RES5), monthly distributions of normal compensation flow requirements (fractions of annual requirement – COMP in Table 4.1) and distributions of compensation flow (fractions) for the five reserve supply levels.

The SPATSIM version represents a semi-distributed implementation of the model, whereby all identified sub-catchments are modelled with independent compulsory parameter sets and input time series. However, not all sub-catchments need have optional input requirements specified and if they are missing, they are assumed to be not present or not relevant to that specific area. This applies to the rainfall-runoff component of the model as well as to the reservoir component.

Reference can be made to the original report (Pitman, 1973) for a full description of the model algorithms. The details provided below are a summary of the main functions of the model, as utilised in this study and how changes in model parameters affect the simulation results.

4.1.1 Rainfall distribution function

The model operates over four iterations and the distribution of the total monthly rainfall is controlled by an S-curve function that depends on total rainfall and the RDF parameter. Lower values of RDF result in a more even distribution of rainfall, the effect being more pronounced for higher total rainfalls. In the original Pitman model this parameter was fixed at a value of 1.28.

4.1.2 Interception function

This function is based on the interception parameter PI, which can vary seasonally and have values for two different vegetation types (typically, but not necessarily, natural vegetation

and plantation forest). The parameter AFOR specifies the proportion of the catchment under vegetation type 2. The depth of rainfall intercepted in any month is based on an empirical relationship between the relevant PI parameter and rainfall depth. Interception storage contributes to satisfying the evaporation demand at the potential rate.

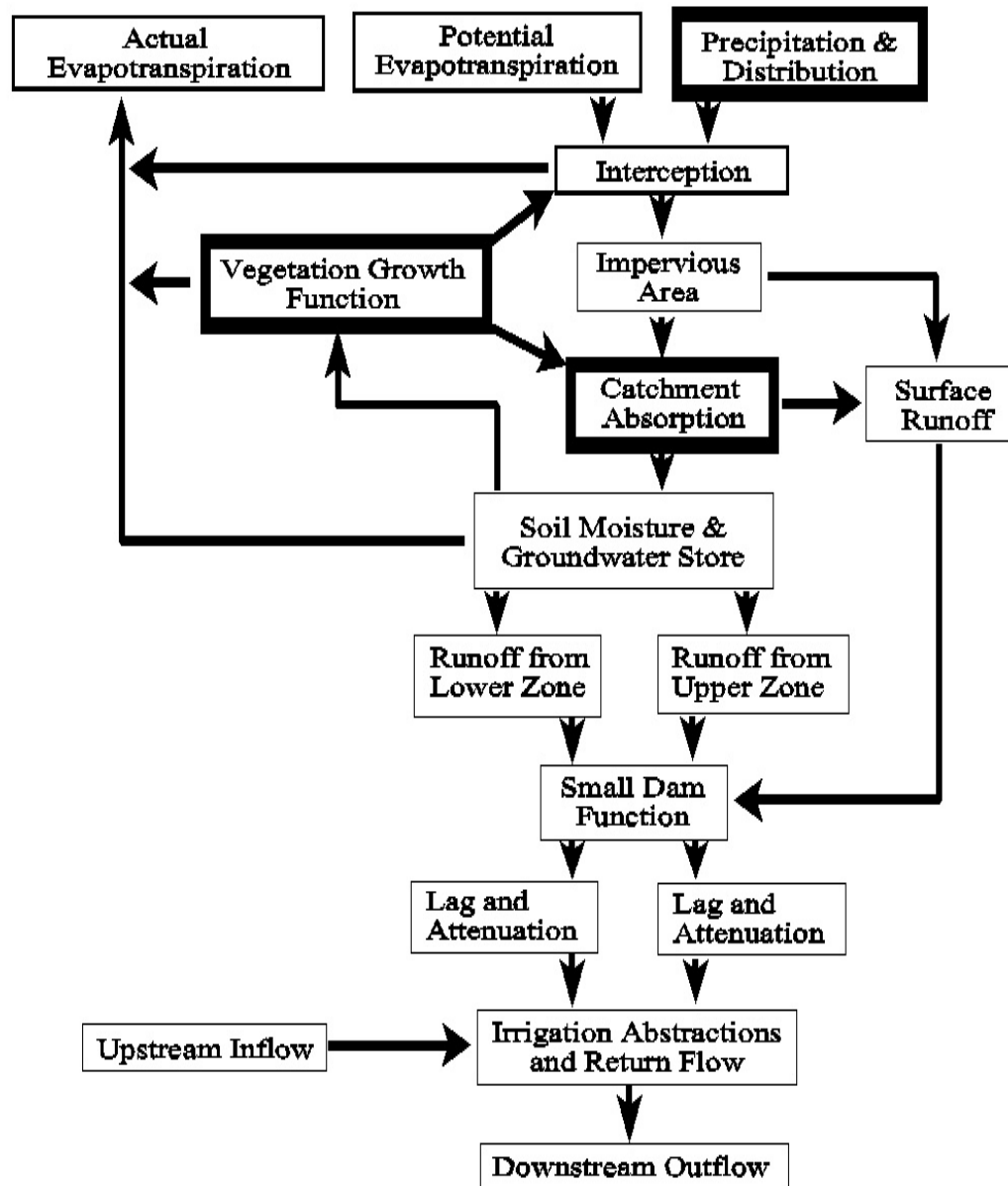


Figure 4.1 Flow diagram representation of the Pitman model (the bold type highlights functions which were modified during the first Phase of the SA FRIEND project).

Table 4.1 Pitman and Reservoir model parameters (additions to the original version are highlighted in bold type).

Parameter	Units	Pitman model description
RDF		Rainfall distribution factor. Controls the distribution of total monthly rainfall over four model iterations.
AI	Fract.	Impervious fraction of sub-catchment.
PI1 and PI2	mm	Interception storage for two vegetation types.
AFOR	%	% area of sub-catchment under vegetation type 2.
FF		Ratio of potential evaporation rate for veg2 relative to Veg1.
PEVAP	mm	Annual catchment evaporation
ZMIN	mm mnth ⁻¹	Minimum catchment absorption rate.
ZAVE	mm mnth ⁻¹	Mean catchment absorption rate.
ZMAX	mm mnth ⁻¹	Maximum catchment absorption rate.
ST	mm	Maximum moisture storage capacity.
SL	mm	Minimum moisture storage below which no runoff occurs.
POW		Power of the moisture storage-runoff equation.
FT	mm mnth ⁻¹	Runoff from moisture storage at full capacity (ST).
GW	mm mnth ⁻¹	Maximum ground water runoff.
R		Evaporation-moisture storage relationship parameter.
TL, GL	months	Lag of runoff (surface and ground water, respectively).
AIRR	km ²	Irrigation area.
IWR	Fract.	Irrigation water return flow fraction.
EFFECT	Fract.	Effective rainfall fraction.
RUSE	MI y ⁻¹	Non-irrigation demand from the river.
MDAM	MI	Small dam storage capacity.
DAREA	%	% sub-catchment above dams.
A, B		Parameters in non-linear dam area-volume relationship
IRRIG	km ²	Irrigation area from small dams
		Reservoir model description
CAP	Mm ³	Reservoir capacity.
DEAD	%	Dead storage.
INIT	%	Initial storage.
A, B		Parameters in non-linear dam area-volume relationship.
RES1 to 5	%	Reserve supply levels (% of full capacity).
ABS	Mm ³	Annual abstraction volume.
COMP	Mm ³	Annual compensation flow volume.
AR and BR		Parameters of the compensation flow-storage relationship.

4.1.3 Surface runoff function

In the original model surface runoff calculations 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. In the revised version of the model, ZMIN is allowed to vary seasonally and a third parameter (ZAVE) has been introduced to allow the triangle to become asymmetric.

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

4.1.4 Soil moisture storage and runoff function

The proportion of rainfall that is not intercepted or contributing to surface runoff increments the moisture store and if the maximum value (ST) is exceeded, the balance becomes part of the runoff from the upper zone (Figure 4.1). It should be noted that the ST parameter is referred to in the original model as soil moisture storage, while in fact this really represents all sub-surface storages in the catchment (i.e. including ground water). Runoff from the moisture storage is controlled through a non-linear relationship between runoff and storage through the parameter POW. At full storage, the runoff rate is $FT \text{ mm month}^{-1}$, of which $GW \text{ mm month}^{-1}$ is considered to be ground water runoff (or runoff from the lower zone) and is lagged separately (see Figure 4.1). At or below the parameter SL, no runoff occurs from the moisture store.

4.1.5 Evaporation from the moisture store

This function is controlled by the parameter R ($0 < R < 1$), as well as the current months potential evaporation value relative to the month with the highest potential evaporation. 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. A low R therefore implies deeper rooting of vegetation. To allow for two different rates of evaporative loss for the different vegetation types, parameter FF is used and simply scales the potential evaporation rate for the area of the catchment covered by the second vegetation type.

4.1.6 Runoff delays and lags

The 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 (Nash, 1959) 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.

4.1.7 Functions to represent artificial modifications to the hydrology

The first of these is the small farm dam routine, which allows runoff generated in part of the catchment (DAREA) to be intercepted by the available storage in any number of dams grouped together and represented by the storage given by the parameter MDAM. Evaporation losses from the dam surface are accounted for through a non-linear area-volume relationship (parameters A and B) and abstractions from the dam using the IRRIG parameter and the monthly irrigation requirements. These dams only influence runoff generated from within the specific sub-catchment of the distribution system and cannot be filled from water generated in upstream catchments.

The second artificial influence is through direct pumping of irrigation water from the main channel. This function operates on water available at the sub-catchment outlet (i.e. including upstream runoff) and is controlled by the monthly distribution of gross irrigation demand, the area of irrigation parameter (AIRR) and the effective rainfall fraction (used to reduce gross demand to net demand after rainfall). A proportion of the irrigation abstraction can be returned to the river as return flow (IWR).

The final artificial modification is through the annual value representing non-irrigation demand (RUSE) and the monthly distribution values. This water is also taken from the main channel at the sub-catchment outlet.

4.1.8 Main reservoir water balance model

This was originally a separate model that could be run with the output from the rainfall-runoff model being used to generate the reservoir inflows. In the SPATSIM version it has been incorporated into the rainfall-runoff model and is used if a set of reservoir model parameters is supplied. It is different from the small farm dam routines, previously referred to, in that the inflows include all water from the current sub-catchment, as well as from

upstream sub-catchments. In other respects, the water balance calculations are similar to those used for the small farm dam routine.

The main water balance calculations are based on the full supply capacity (CAP), dead storage (DEAD), initial storage (INIT) and area-volume relationship parameters (A and B). Abstractions are specified using an annual total volume and monthly distributions, while these can be changed for up to five reserve supply levels (to allow for different operating rules and supply curtailment levels). Compensation flows can be specified, both as an annual value (with associated monthly distributions at the five reserve levels), as well as a time series of required downstream flows (generated outside the model). If the latter is supplied, the parameters AR and BR can be used to modify the supplied requirements depending upon the storage level in any month.

4.1.9 Calibration procedures

Manual calibration

Pitman (1973) provides some very general guidelines for calibrating the model under different climate types. These guidelines provide an indication of which aspect of the simulation results will be dominantly affected by changes to different parameter values. The main parameters that should be involved in any manual calibration are ZMIN, ZAVE, ZMAX, ST, POW, FT, GW and R. The majority of the other parameters should be determined *a priori*, or remain fixed during the calibration process. The ZMIN, ZAVE and ZMAX parameters are frequently not used (i.e. set to very high values beyond the range of likely monthly rainfalls) in catchments with good vegetation cover, temperate to humid climates and naturally perennial flow systems. 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. However, it should be noted that extreme maximum monthly runoff values are not always accurate because of gauging problems at high flows. 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, ZAVE and ZMAX parameters rather than POW, FT, GW and R, while ST can be just as important.

For any programme of calibration it is important to establish a set of principles that are applied across all catchments. 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. This can usually be achieved if a few basic rules are adhered to.

- Ensure that all artificial influences are catered for (using the relevant parameters for these components, or input time series of transfer inflows), before beginning to calibrate the main hydrological parameters of the model. The alternative is to naturalise the data first (remove all artificial influences)
- Establish an understanding of the physical meaning of the parameters (e.g. thinner soils and less permeable aquifers should mean lower ST values) and interpret the known physical differences between catchments on the basis of this understanding.
- Analyse the daily distributions of typical monthly rainfall inputs to quantify the most appropriate value for parameter RDF.
- Identify the two main vegetation type groups within the catchments and evaluate suitable values for the PI parameters, AFOR and FF.
- Be aware that using a fixed monthly distribution of potential evaporation will not be as suitable as using a time series (although it is recognised that a time series may not

always be available and that even if one is, it may not be adequately representative of mean catchment evaporation rates). This means that temporal variations in seasonal potential evaporation rates will not be represented, which will inevitably impact on the success of the simulations.

- Be able to recognise the limitations of the available rainfall and flow data and try and avoid calibrating erroneous rainfall-runoff signals. This is never an easy rule to follow, as information on the limitations of the data is not always available or clear.

Automatic calibration

The SPATSIM version of the model incorporates an automatic calibration facility that allows ZMIN, ZMAX, ST, FT and POW to be automatically calibrated (using a link to a program provided by Ndiritu and Daniell, 1999). The user is then required to supply inner and outer ranges for all of these parameters, which are used to control the automatic calibration process. The objective function used is a combination of the coefficient of efficiency based on both normal flow volumes and flow volumes transformed by natural logarithms. The overall objective function for any single sub-catchment is the mean of the two values and if more than one sub-catchment in the distribution system has observed data, the final objective function value represents the mean for all of them.

Given the points noted in the previous section on manual calibration, it is clear that some form of manual calibration is required before any automatic calibration process can be started. The alternative is that the automatic calibration process could end up trying to modify some of the main hydrological parameters to compensate for deficiencies in the way in which other parameters have been quantified. The other problem with automatic calibration procedures are that they assume ‘perfect’ input data and it is difficult to achieve useful results if there are serious errors or inconsistencies in the input data (or in the observed flows that are used for comparison and objective function calculations).

If the accuracy of some individual monthly flows are in doubt (for example, during flood periods when the gauge is known to be unable to measure high flows) it is frequently better to set these months to missing data values so that they are excluded from the objective function calculations.

4.1.10 Recent modifications to the Pitman model

Recent applications of the Pitman model by the Institute for Water Research highlighted the need for a more explicit approach to simulating the ground water recharge and discharge processes within a catchment. Part of the reason for this is associated with the use of Pitman simulated data within environmental flow requirement studies within South Africa and the need for a better understanding of the proportion of total streamflow that is derived from ground water and therefore has the potential to be impacted by ground water resource abstractions. Hughes (2004) discusses the initial modifications that were made to include more explicit ground water functions within the original model. The principles that were followed in the modification were based on adding model algorithms that are consistent with the level of complexity of the original model, rather than attempting to add the type of simulation routines typically found in ground water models (such as finite element or finite difference schemes). The ground water storage component of a catchment is therefore simulated using very simplistic geometry, where recharge inputs and discharge outputs are used to determine the ground water drainage gradient within a series of slope elements, the number of which depend on the effective drainage density of the catchment. The other main parameters that have been added include those that determine the amount of recharge for a given surface storage condition (ST from the original model), storativity and transmissivity that are used with the drainage density and drainage gradient to determine discharge to streamflow. Further details of the initial version of the revised model can be found in Hughes (2004), while an example application can be found in Hughes, et al. (2005).

A further version of the model has now been developed (Hughes, pers. comm.) that allows for evaporative losses within channel riparian zones, down-catchment drainage, transmission losses (from the river to the ground water), as well as abstractions from ground water. The model is now able to simulate situations where the ground water surface fluctuates between being above and below the channel and therefore between losing water to, and gaining water from, the river system.

Neither version of the model was sufficiently finalised for use during the main model calibration component of the Kafue basin study and therefore the results are still based on the original model referred to in the previous sub-sections of Section 4.1. However, some limited

tests of the revised model were undertaken using some of the headwater sub-catchments of the Kafue basin and are reported in the discussion section.

4.2 SPATSIM – SPATIAL AND TIME SERIES INFORMATION MODELLING SOFTWARE

SPATSIM is a software package designed as a database, data analysis and modelling system, specifically for hydrological and water resource applications (Hughes, 2002; Hughes and Forsyth, 2002). It has been developed at the Institute for Water Research, largely with financial support from the Water Research Commission of South Africa. It has been developed using the Delphi programming language with links to Paradox database tables and uses ESRI Map Objects to provide the spatial data display and analysis facilities.

A large part of the background information on SPATSIM contained within this section has been extracted from the 'Help' facilities and paraphrased by the author. Specific examples of various SPATSIM utilities and applications have been included based on the work undertaken for the Kafue Basin project by the author.

Figure 4.2 provides an example of a screen image of the main SPATSIM window, while Figure 4.3 illustrates the basic principles of the data access design of SPATSIM. Spatial data are accessed through shape files, while other information associated with specific spatial elements are accessed through linked database tables. The links are made through four data dictionaries, which allow efficient access to any of the non-spatial attribute data, through the spatial elements (points, polygons or lines) of a displayed map. A wide range of different attribute types are allowed for in SPATSIM, ranging from single numbers and short text, through tables of values (1 or 2 dimensional matrices), to graphics, memos and time series data. The latter three are stored as single fields in the attribute database tables using Binary Large Object (BLOB) field types. This makes it straightforward to design generic database table structures that can be used to store virtually any type of information relevant to hydrological or water resource type studies.

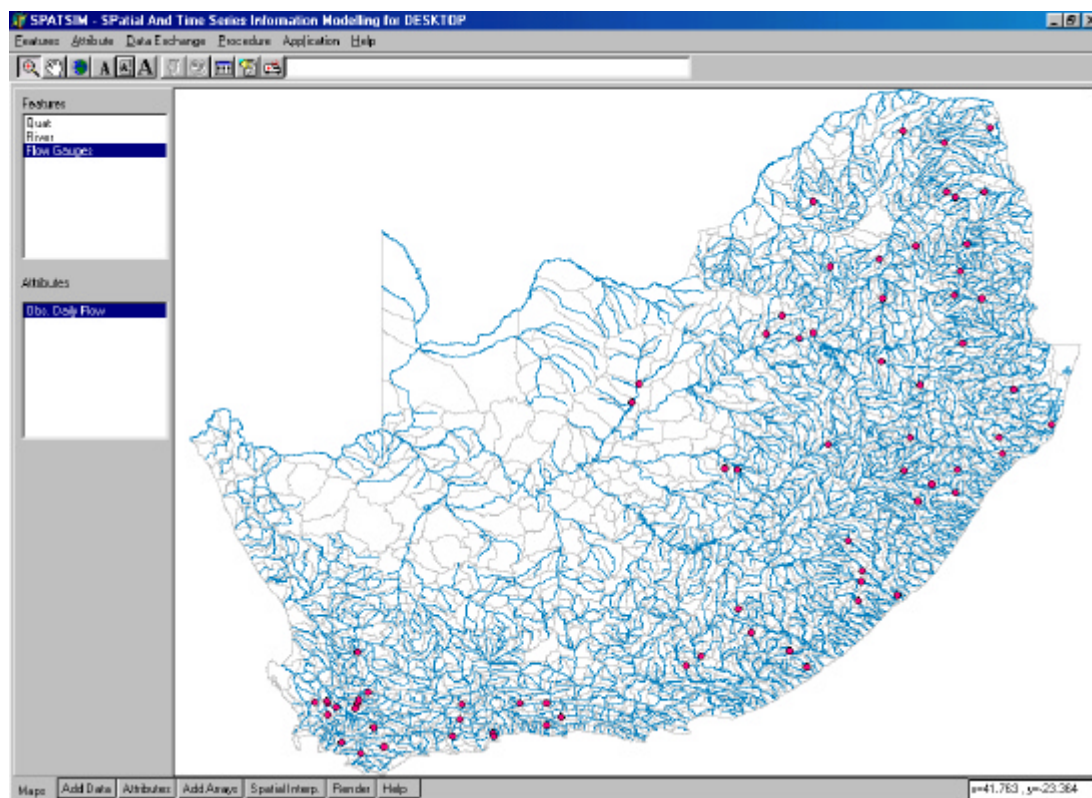


Figure 4.2 Main window of SPATSIM

4.2.1 Structure of the SPATSIM package

The software is designed to make use of a spatial interface to drive access to other data and to have a series of additional utilities that either use those data, or generate and store additional data. Some of the utilities are part of the main program, while others are external programs that can be called from the main program. Example utilities include data importing routines, database management routines, model parameter estimation and editing routines, time series simulation models and graphical display programs. The software has been designed to be flexible, such that the number of possible add-on utilities is limitless and their implementation quick and efficient. This approach facilitates the development of new utilities by a range of contributors, rather than just the IWR.

The design of the data access process forms the core of SPATSIM and is illustrated in figure 4.3 Spatial data (referred to as FEATURES) are accessed through shape files, while other data (referred to as ATTRIBUTES) associated with the spatial data are accessed through database tables (using Paradox tables by default). The links between the two data sources are

controlled by a set of four data dictionary tables. Each application of SPATSIM is based upon a database alias name that contains a unique set of the four data dictionaries, as well as all the associated attribute tables.



Figure 4.3 Basic data access structure in SPATSIM.

The facilities that are included with SPATSIM to enable data to be stored, displayed and processed can be divided into internal facilities that are not specific to any application and external processes that include a wide range of hydrological, water resource and eco-hydrological models. Help facilities are available within the program using html files with a number of hyperlink cross-references. The same help can be accessed through the IWR website (<http://www.ru.ac.za/institutes/iwr> and look for the hydrological models and software link) and both provide a detailed explanation of each aspect of the software and its application.

For the purpose of this study, it is relevant to provide a brief summary of the range of facilities that are available and to provide a little more detail about those facilities that have been designed specifically to facilitate the setting up and running of rainfall-runoff models, as applied to the Kafue basin.

4.2.2 Internal SPATSIM facilities

The internal SPATSIM utilities are mainly designed to allow data of various types to be imported and exported, associated with spatial data, viewed and edited. There are standard facilities for adding or deleting features (spatial data coverages) and data attributes, importing data from a range of different file types, exchanging data with other SPATSIM users and viewing or editing data. In addition to these, a few data processing facilities have been added

as they represent commonly used hydrological analyses, regardless of the model or application. Examples are the generation of frequency of occurrence tables from time series data and the generation of spatially averaged (over defined polygons) data from point data using an inverse distance weighting procedure. There are also procedures available for intersecting a coverage of soil or vegetation type (for example) with a sub-basin coverage to generate spatially weighted values of a variable for the sub-basin coverage.

In situations where SPATSIM does not provide the required data processing facilities, it is frequently a simple matter to export the required data to a text file, import that into a spreadsheet program, process the data in the spreadsheet and import the processed data back into SPATSIM.

Spatial interface facility

The SPATSIM design makes use of a spatial interface to drive access to other data and has a series of additional utilities that either use those data, or generate and store additional data. The spatial interface facility makes use of MAP OBJECTS within a DELPHI program, using coverages (as Shape Files), which are digitised externally. Each of the coverages is identified as a *feature* which has *attributes* associated with it. While it is possible to have some attributes defined as part of the shape files, the SPATSIM attributes are stored separately within the SPATSIM database. The shape files are used to define the *features* and their spatial characteristics only. The main reason for adopting such an approach is that shape file tables are not readily capable of storing (as attributes) some types of data.

Map manipulation facilities

These include the ability to add and remove features, modify features (i.e. add or remove points, etc.), annotate and render features, as well as creating new features from merged or intersected data. Rendering refers to the use of a single integer or real attribute to generate a classification of the polygons in a Feature and colour them according to the classified values. It is also possible to use one element of an array attribute to provide the value for classification. This facility is very useful in showing the geographic distribution of a particular attribute (a model parameter, for example). Figures 4.4, 4.5, and 4.6 provide screen images of the procedure followed in rendering

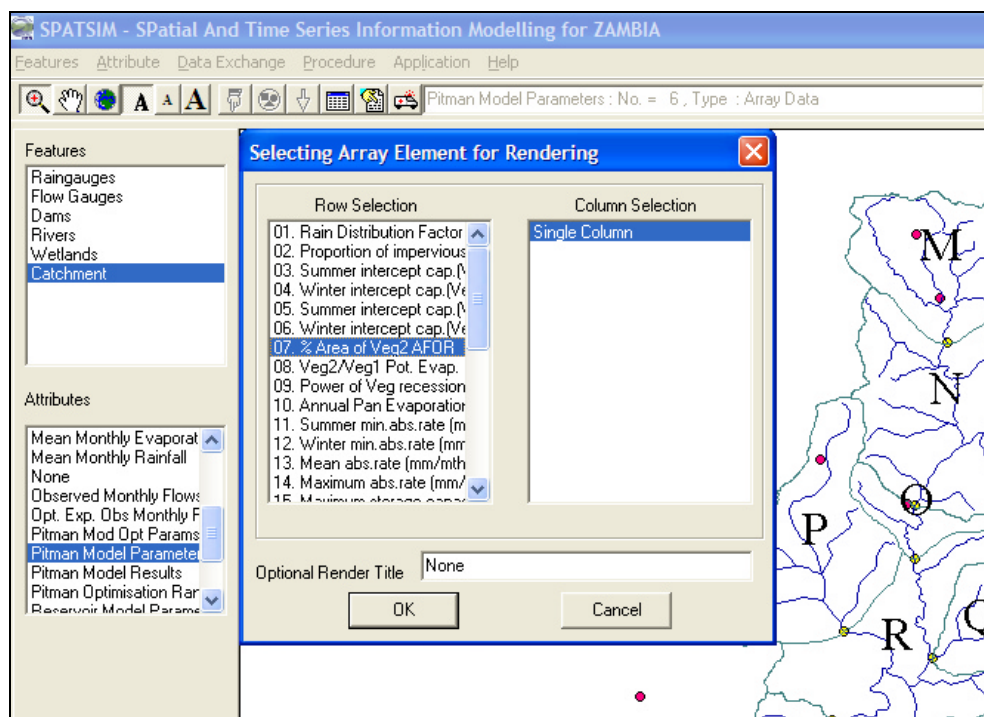


Figure 4.4 Selection of an attribute to render from an array attribute.

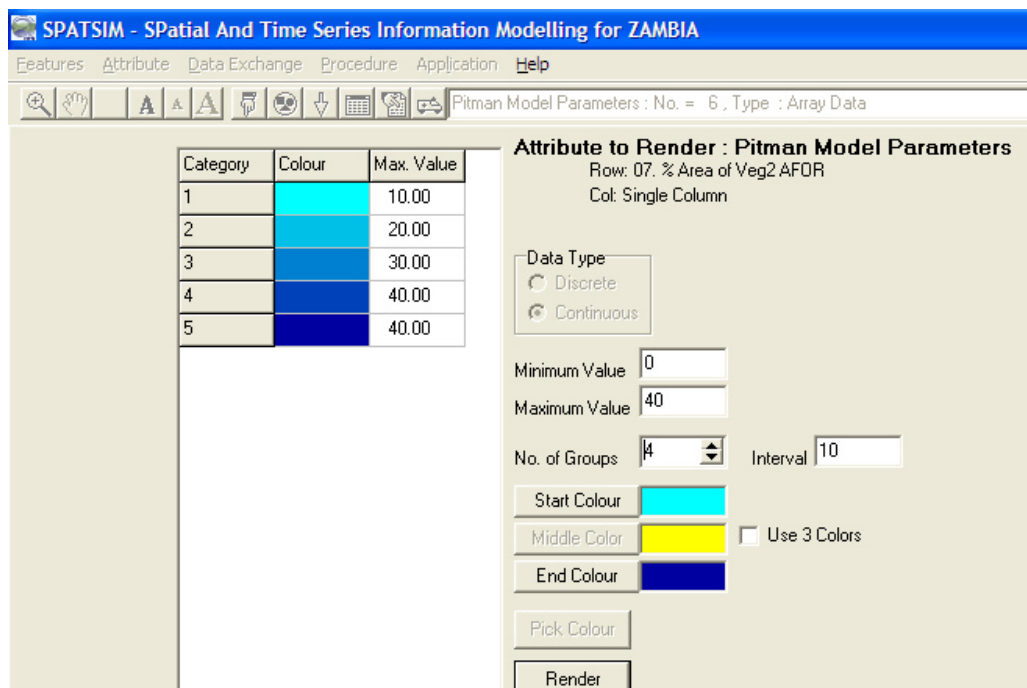


Figure 4.5 Specifying the scale and colour for the render.

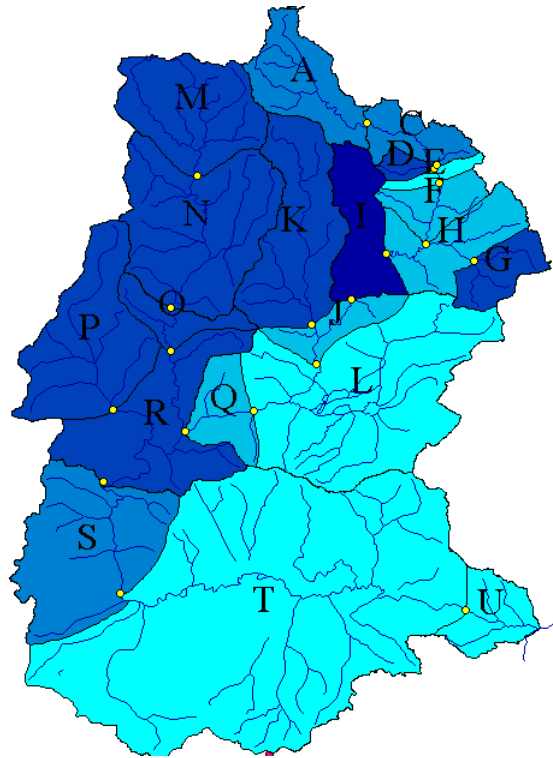


Figure 4.6 Rendered map - showing the spatial distribution of parameter AFOR.

Attribute manipulation facilities

These include the ability to create new attributes, load data from a variety of different raw data sources, edit some of the attribute data and display attribute data in different ways. It is possible to load time series attributes from other database tables, as well as arrays from simple text files. Also available is a generalised time series data loading facility that allows access to a number of different raw data formats.

The importing of time series is a very important facility, in that input data required is normally stored in different databases and different formats. A good database design should therefore be flexible enough to be able to import many different types of data. There are many different types and raw formats for time series data and a special facility exists for importing these type of data. The assumption is that the data for a single spatial element are contained within a single data file and that some form of identification (either the filename or text within the file) can be used to associate with the description field of the shape file spatial components. The SPATSIM procedure for importing time series data is illustrated in Figures 4.7 and 4.8.

Data Input - V1.74 8 June 2004

Select a Data type first

Select Input File Type

- ☐ DWAF Flow
- ☐ DWAF Monthly
- ☐ DWAF Breakpoint
- ☐ WeatherBureau/CCWR Daily Rain
- ☒ Spreadsheet
- ☐ Continuous Text
- ☐ CLICOM
- ☐ IWR Binary
- ☐ Breakpoint Text
- ☐ Water Quality Data

Now select options for this data type Example

Spreadsheet

- ☒ Continuous
- ☐ Blocked

Time Period

- ☐ Daily
- ☒ Monthly

Start Month: 10

Input Conversion

☐ Convert m³/s to Mm³

Header Lines: 3

Station Name Width: 0

Header Lines: 0

Rows: 5

Columns: 6

Date of change to MM units: 01/01/1800

Spreadsheet Continuous Monthly
optional header line
another optional header line:
1984 12 13 15 12 15 16 12
1985 1 23 12 14 18 13 12
1986 1 2 3 4 5 6 7 8 9 10
1990 12 11 10 9 8 7 6 5 4
1991 1 23 12 14 18 13 12

Data : 4669 Monthly Flows
Fixed Interval, Data only : 1 Months :
Start month is October (10)

1973	50.900	75.200	251.800	9
1974	91.100	64.800	573.200	2
1975	125.900	85.500	254.400	1
1976	265.200	210.000	310.700	
1977	150.000	103.700	551.800	
1978	466.000	593.600	1012.400	

Finally, accept it

Accept

Figure 4.7 Import time series data facility – step to specify data format type.

Generic Time Series Import

Select Data Import Files

rfFileForm

File Select Type

- ☒ Select Multiple Files
- ☐ Select All files in a Folder

Select StationName Source

- ☒ From Filename
- ☐ From File Contents

Select Files

Generic T/S Attributes
(Applies to all imported data)

GeogID: Station Name (from file)

DataID: Generic Name

Data Obj.: 0

Time Units: 4

Time Interval: 1

Time Int. Type: 0

Var. Type: 3

Var. Unit: 4

MD Code: -9.9

Done

Figure 4.8 Import Time Series data facility - step for specifying data variable type and selecting data import files.

Spatial interpolation facility

Interpolation of point data to areal averages is a facility which is frequently required in hydrological and water resource modelling. (e.g. converting point rainfall data to catchment rainfall data). A procedure has been developed that allows point data to be interpolated to areal data using an inverse distance weighting method and an additional weighting using gridded mean monthly data. The main application is for the determination of weighted catchment average rainfall from coverages of point rainfall. Figures 4.9 and 4.10 give an illustration of the steps taken in interpolating point rainfall data to areal rainfall averages for sub-catchments M, N and O. The starting point is to define the maximum search radius (Figure 4.9) for a group of selected sub-catchments and then to define the attributes that will be used to access the point rainfall data and any gridded weights, as well as the attribute that will be used to store the areal interpolated results.

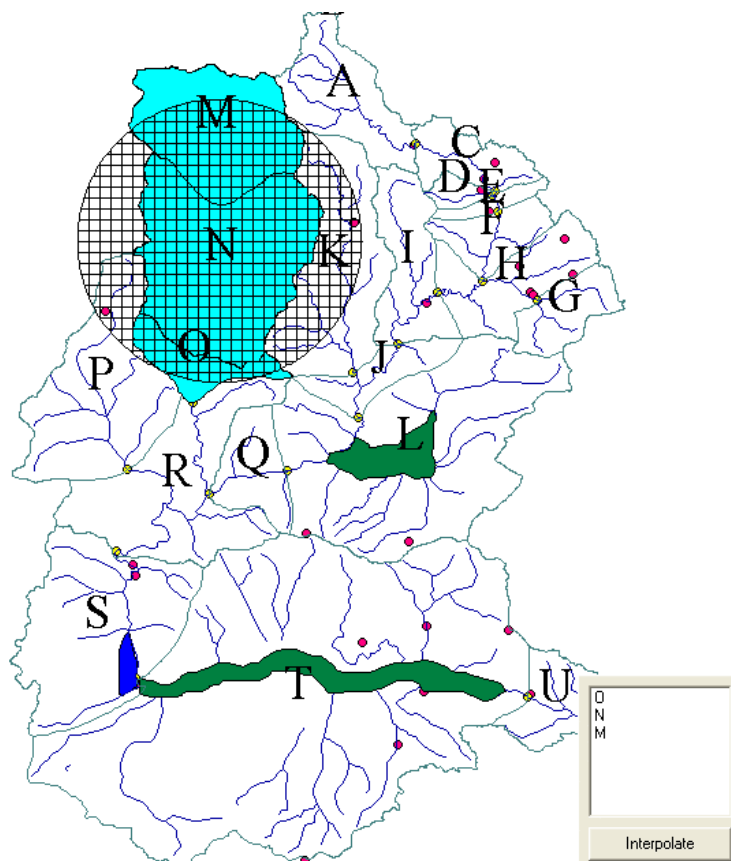


Figure 4.9 Selection of sub-catchments and search radius for interpolation.

SPATSIM - Spatial And Time Series Information Modelling for ZAMBIA

Features Attribute Data Exchange Procedure Application Help

Downstream Area : No. = 5 , Type : Text (max. 80 chars)

Details of Spatial Interpolation from point sources to area destination

Interpolation Period From 01/01/1960 To 31/12/2000 Time Step ☐ Daily ☒ Monthly

	Attribute Code	Map No.	Feature Code	None
Destination Data	0	0	0	None
Source Data	0	0	0	None
Weighting Data Source 1	0	0	0	None
Weighting Data Source 2	0	0	0	None
Weighting Data Source 3	0	0	0	None
Weighting Data Source 4	0	0	0	None

Search Radius 0.877 Max. Search Items 5

Progress for each areal unit 0% Total Progress (all areal units) 0%

Interpolate Finished

Features: Raingauges, Flow Gauges, Dams, Rivers, Wetlands, Catchment

Attributes:

Figure 4.10 Specification of the interpolation period, time step, search radius, maximum search items and data attributes to be used for interpolation.

4.2.3 External SPATSIM utilities

The external utilities are models or data processing tools that have been developed as separate programs to SPATSIM, but are linked in various ways with the internal database tables. The following is the range of external model and data analysis tools that are currently available in SPATSIM.

- TSOFT, a generic time series data display and analysis program.
- General Hydrology Data Analysis Models
 - Baseflow Separation Calibration Model
 - Patching Model (Flow Data)
 - Patching Model (Using Rain Data)
 - Tributary Inflow Analysis Model
 - Residual flow diagrams generation model
- Catchment Rainfall-Runoff Models
 - Pitman Monthly Model

- Pitman Monthly Model with Groundwater Routines
 - VTI Model Requirements
- Flood Models
 - Design Flood Model
- Water Resource Systems Models
 - Rapid Simulation Model
- Ecological Reserve Models
 - Reserve Method DSS
 - Present Day Hydrological Class Model
 - Desktop Reserve Model
 - Desktop Parameter Calibration Model
 - Daily IFR Design Model
 - Stress/Flow & Risk Indicator Model
 - Flood Stress/Event Model
 - Hydraulic Model
 - Reserve Licensing Model linked to the Desktop Model
 - Water Quality Data Analysis Model

TSOFT – A generic time series data display and analysis program

TSOFT is a generic time series data display and analysis program (Hughes *et al.*, 2000), which has been established as a flexible tool for analysis of various types of time series data. With respect to rainfall-runoff model applications, it is useful for visually comparing observed and simulated time series, seasonal distributions and flow duration curves, as well as performing some limited statistical analyses of the relationships between two time series using the scatterplot option. For the purpose of this study a few demonstrations and illustrations can be used to illustrate how TSOFT has been used in the Kafue basin modelling study.

The model calibration process is made easier by having a facility that is linked to the model output data to allow comparison of the simulated flows with the observed flows. Once a model run has been completed, a TSOF profile is created containing the observed flows and the simulated flows for selected sub-catchments. The profile is then opened in TSOF as can be seen in Figure 4.11 Once the profile is opened, any of the included time series data can be added to one of two graphs, allowing the user to perform either visual analysis or some basic statistical analysis using objective functions to measure the degree of success of the model run. All data resulting from each calibration run for the Kafue basin project were subjected to the basic analysis tools provided by TSOF. Figure 4.12 shows the screen image of TSOF graph display and X-Y scatterplot and statistical analysis display. In addition, TSOF is able to plot monthly distributions, duration curves and is also able to perform baseflow analysis of either daily or monthly flow data (Figure 4.13).

The graphical and statistical analyses that TSOF provides, were also used in data preparation and checking of input data quality both for rainfall and observed streamflow data. The basic test to check on the quality of data was to perform a comparison of data from the nearest station to check for consistency. Figure 4.14 shows a scatterplot for one the comparisons between rainfall stations Ndola and Roan, while Figure 4.15 shows a scatterplot for streamflow stations Kafironda and Raglan Farm

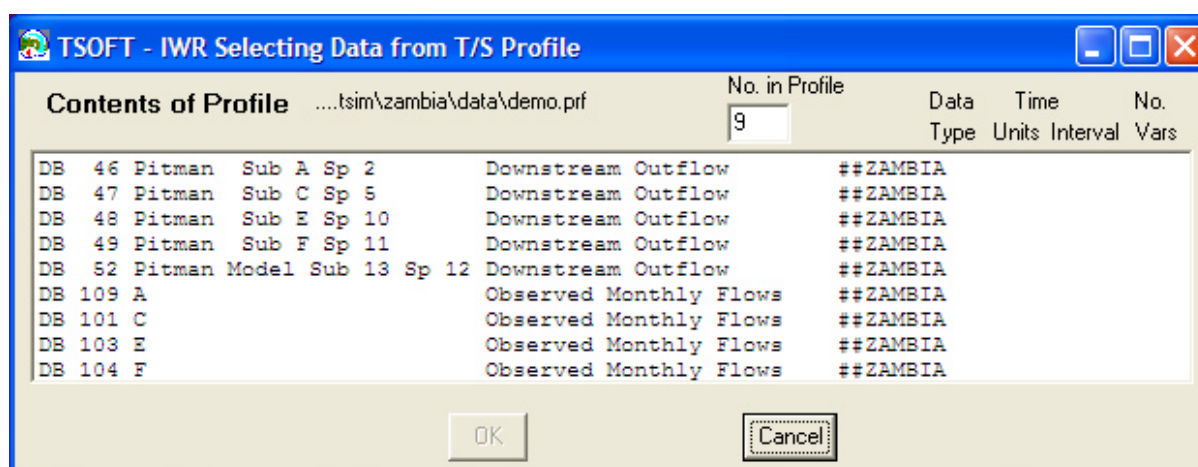


Figure 4.11 TSOF profile containing observed and simulated flows for sub-catchments A, C, E and F.

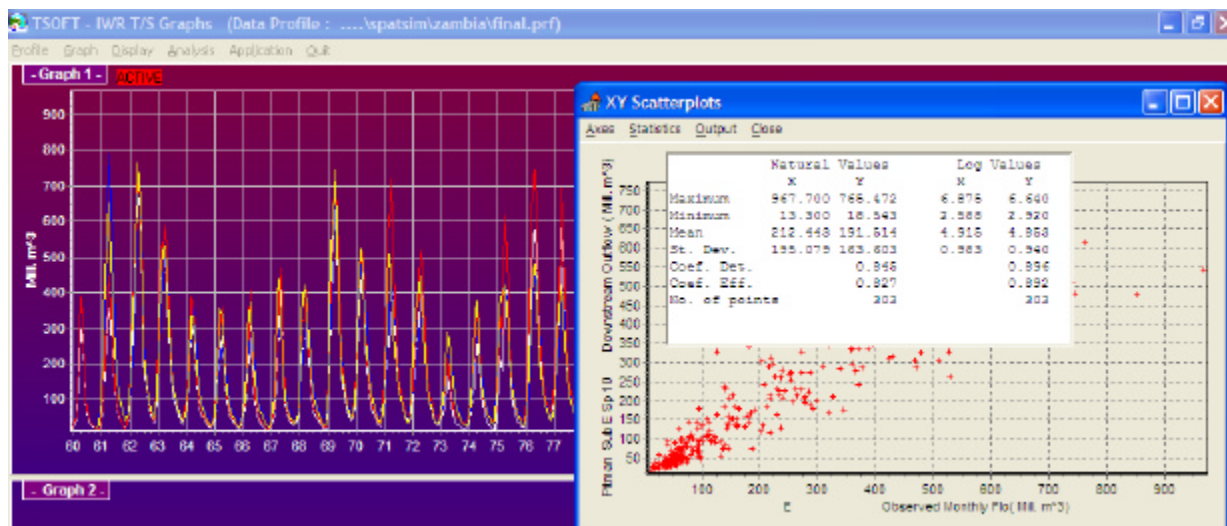


Figure 4.12 TSOFT graphical and statistical analysis facility

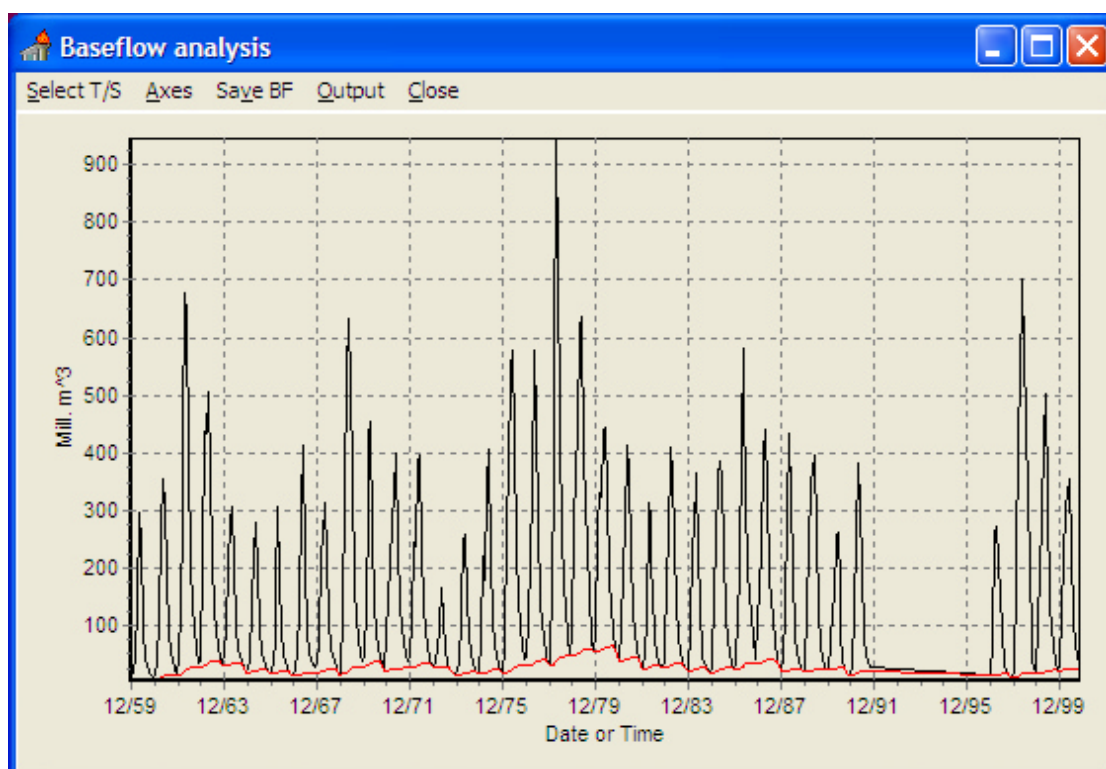


Figure 4.13 Baseflow analysis for observed streamflows for sub-catchment C (note the period of missing data from 1991 to about 1995).

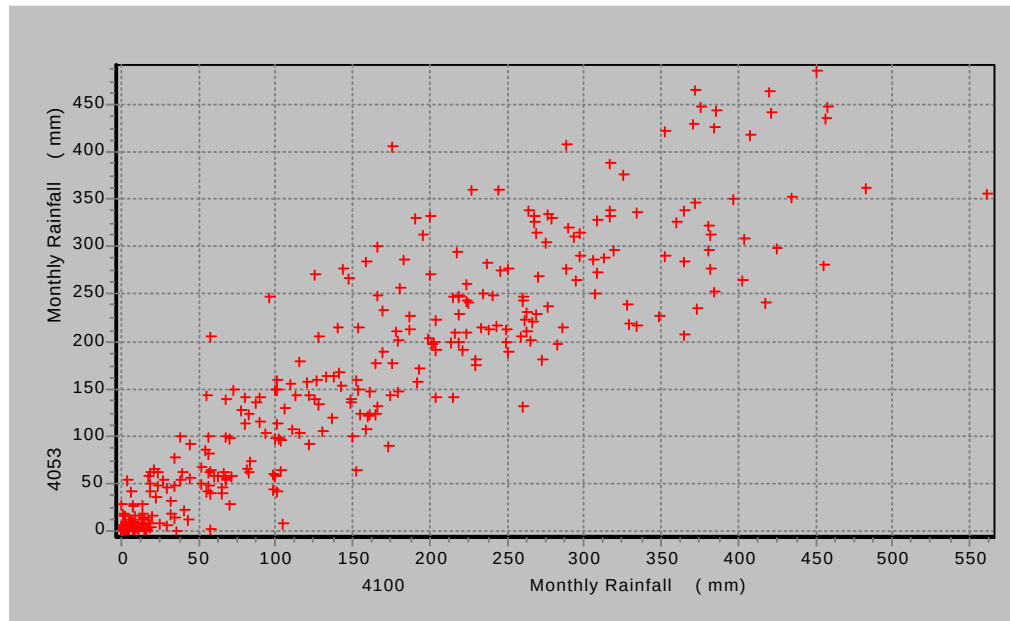


Figure 4.14 TSOFT X-Y scatterplot for rainfall stations, Ndola (4100) and Roan (4053) (R^2 of 0.878).

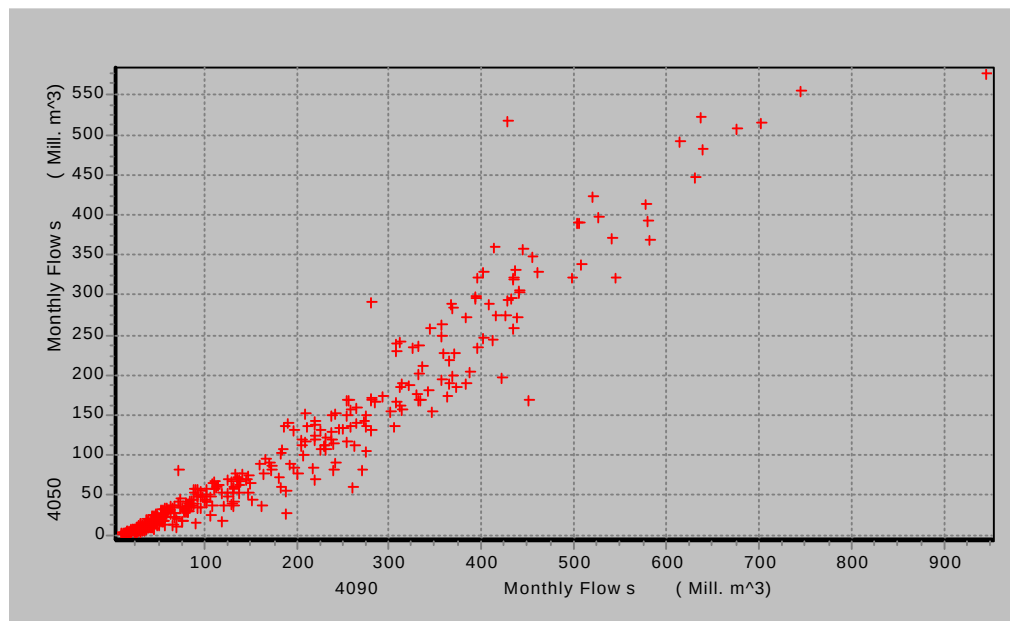


Figure 4.15 TSOFT X-Y scatterplot for streamflows stations, Kafue river at Kafironda (4090) and Kafue river at Raglan Farm (4050): (R^2 of 0.936).

External model utilities

The most important group of external utilities from the point of view of rainfall-runoff modelling applications are the external models, of which one is the Pitman monthly model.

All of these are set up in a similar way, by selecting the spatial elements of a feature that will be modelled and then linking the attribute data stored in the SPATSIM database tables with the data requirements of the model. These requirements are defined using simple text files, which are accessed by SPATSIM and used to generate a record in an external application data table. An example, using the Pitman monthly and combined reservoir water balance model is provided in Table 4.2. The first three lines of the file are mainly for information purposes, while the next three pairs of lines define the program to be run (an exe file), a further text file that defines the content of temporary binary files in which model state variables are stored during the model run and a user specified filename for the previously referred to output file. The remaining pairs of lines specify the data requirements of the model, whether they are required or optional and the type of attribute required (e.g. 2 = single real number, 3 = time series data, 5 = matrix or array type data).

When an external application is initially established, the user selects the spatial components (sub-catchments in the case of a rainfall-runoff model) and then chooses which external application to apply. The requirements (from Table 4.2, for example) are displayed and the user selects SPATSIM attributes, from those available, that will satisfy the model requirements (see Figure 4.16 as an example). All of this information is then checked and saved, after which the application can be run. The first part of any external application then reads the saved application information and accesses the relevant SPATSIM database tables. At the end of the application, if any of the requirements relate to data generated during the model run (Downstream Outflow, for example in Table 4.2), these are saved back to SPATSIM for later analysis. Once an application is established, it can be run directly without even running SPATSIM first.

The procedures adopted for linking models and other data analysis procedures to SPATSIM have been designed so that new applications can be added to SPATSIM (or existing ones modified) without having to modify the code of the core program. It is simply necessary to establish the text definition files and code the data input and output routines of the model in the correct way. It is therefore possible for users, other than the main developers at the IWR, to develop their own external applications by following a few relatively straightforward guidelines.

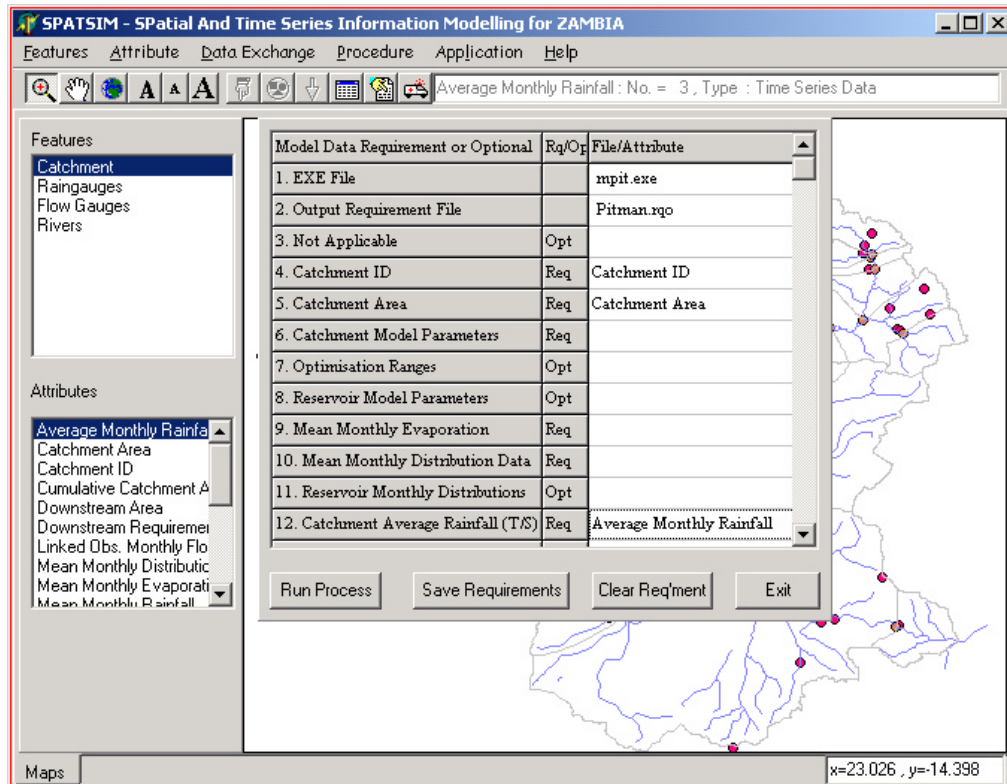


Figure 4.16 Matching model requirements with available data from a SPATSIM database (a suitable 'Attribute' is highlighted and then the relevant model requirement is double-clicked to select that attribute information for use with the model)

Calibrating the Pitman model using SPATSIM should be relatively efficient and should follow the steps outlined below:

- A. Prepare all the input data in a format suitable for importing into SPATSIM.
- B. Obtain or generate (through ARCINFO or similar GIS) spatial coverages for sub-catchments, hydrometeorological measuring network, catchment characteristics, etc.
- C. Process gauged or catchment characteristic data to create sub-catchment time series and parameter value data.
- D. Establish a model application and carry out an initial run to ensure that all the required data are present and do not contain fatal errors.
- E. Correct any mistakes, quantify the non-calibrated parameter values for all sub-catchments.
- F. Establish a TSOFT application that allows (at least) the observed and simulated data to be graphically viewed.

Table 4.2 Example of a text file defining the data requirements of the Pitman model.

```
Pitman Monthly Model
1st parameter 0:Required, 1:Optional
2nd parameter=Table Type (-9:Multiple Var. File, 99: Other File)
1. EXE File
0 99 mpit.exe
2. Output Requirement File
0 99 Pitman.rqo
3. Model Results Data (T/S)
0 -9
4. Catchment Area
0 2
5. Catchment Model Parameters
0 5
6. Optimisation Ranges
1 5
7. Reservoir Model Parameters
1 5
8. Mean Monthly Evaporation
0 5
9. Mean Monthly Distribution Data
0 5
10. Reservoir Monthly Distributions
1 5
11. Catchment Average Rainfall (T/S)
0 3
12. Catchment Average PE (T/S)
1 3
13. Upstream Inflow (T/S)
1 3
14. Transfer Inflow (T/S)
1 3
15. Downstream Reserve Requirements (T/S)
1 3
16. Downstream Outflow (T/S)
1 3
17. Reservoir Storage (T/S)
1 3
18. Observed Monthly Flows (T/S)
1 3
```

- G. Run the model.
- H. View the results (TSOFT) and assess the simulations (if the TSOFT program is left open between model runs it is possible to view the results from a number of previous runs to check that the calibration is progressing satisfactorily)
- I. Edit the parameter values (using the matrix attribute editing facility of SPATSIM), or correct any mistakes in the non-calibration data.
- J. Repeat steps G to I until the calibration process is complete.
- K. Assess the result using a different time series to validate the calibration

If automatic optimisation is required at any stage, an attribute containing data for the ‘optimisation ranges’ requirement of the model should be established and the optimisation option selected at run time. The progress of optimisation can be viewed graphically and text files are created that summarise the process.

Help facility for external utilities

There are also other external applications that have been established for support or application assistance purposes (see the Help options), which effectively lead users through various analysis processes, indicating which of the SPATSIM utilities can be used at which stage. One example of this is the ‘Road Map’ that explains some aspects of the use of the Pitman model within the SPATSIM environment (Figure 4.17). The help facility has a link to the IWR website where more information is provided.

4.3 GENERAL

This section has focused on the model and software package that was made available to the study to facilitate the use of the model. While these have not formed part of the development work of the study, it has been necessary for the author to become familiar with their application and to evaluate them in the context of the study. As SPATSIM has been designed for widespread use within the SADC region, this evaluation formed a substantial component of the study.

This section has not dealt with the other major component of the study and that is the collection, collation and preparation of the data required to establish a hydrological model. It

was considered better to present the data and the methods that were used to analyse and prepare the data for use in a single section (see Section 5 following).

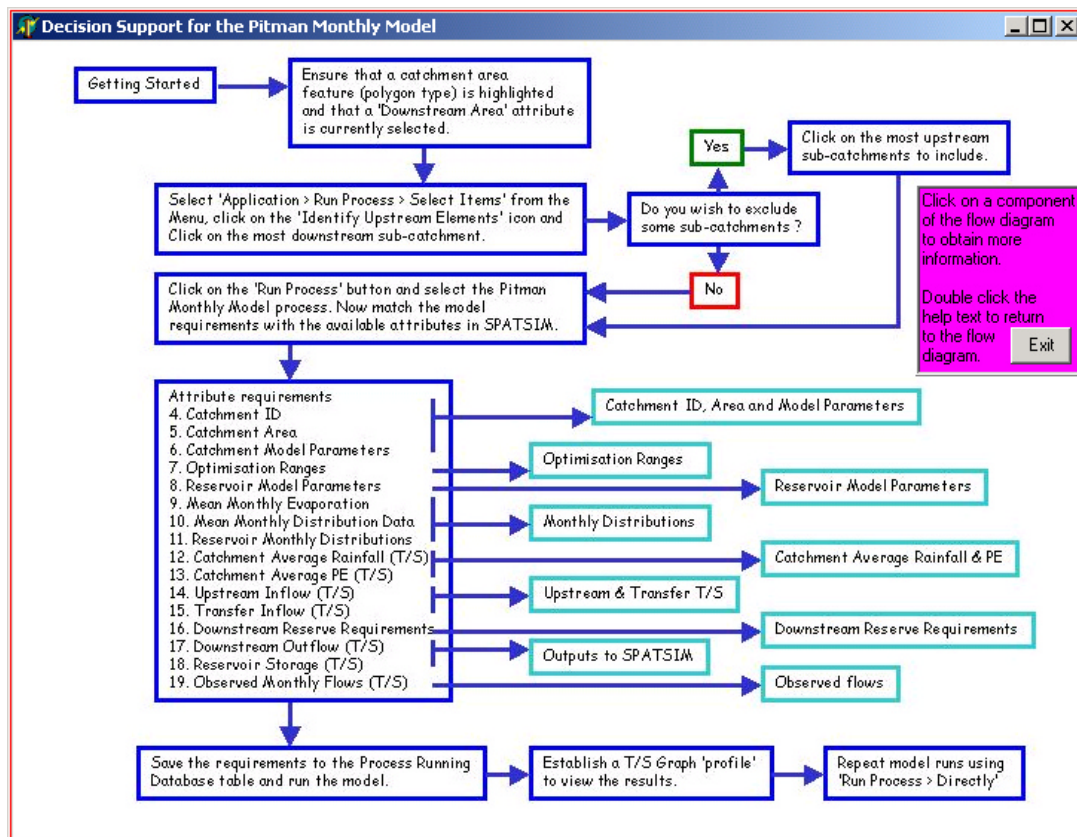


Figure 4.17 The Pitman model 'Road Map' supplied as part of the Help facilities of SPATSIM.

5 STUDY AREA AND AVAILABLE DATA

This section provides the geographical context of the study area and a description of the Kafue River basin in terms of climate, topography, drainage, geology, soils, vegetation, landuse and water resource development levels for specific sub-catchments. The available data are also discussed and analysed for their suitability in terms of the application of the model.

5.1 THE KAFUE BASIN

The Kafue River is one of the major tributaries of the Zambezi River. The whole Kafue basin lies within Zambia and has an area of 156 995 km² at the river's confluence with the Zambezi. The basin area is 20% of Zambia's total land area. The Kafue River has a length of 1 300 km and originates at the eastern end of the Zambezi - Congo divide in the Northwestern Province, and flows in a south-easterly direction to a point near Kitwe. It then turns southwards or south-westwards close to the Lukanga Swamps and flows into the Itezhi-tezhi dam reservoir. Thereafter it turns eastwards and flows for 353 km across the Kafue Flats (wetland area under the RAMSAR Convention) and into the Kafue Gorge Dam reservoir. From the Kafue Gorge Hydropower Station, it flows through the steep sided Kafue Gorge before joining the Zambezi River near Chirundu. The density of tributaries is high in the northern parts of the basin, and becomes lower in the southern part of the basin. The mean flow from the Kafue basin is estimated to be 316 m³ s⁻¹, and 101 m³ s⁻¹ in the most severe drought year (30 year record period of 1963 – 1992). See Figure 5.1 for the geographical location of the Kafue basin.

The Kafue basin plays a central role in Zambia's economy with most of the nations mining, industrial and agricultural activities and approximately 50% of the Zambia's total population concentrated within the basin area. The basin is the most urbanised in Zambia (Hywel, 1971).

5.1.1 Climate

The Kafue basin has a tropical climate with two distinct seasons, a wet season between November and March and a dry season between April and October. Thus, almost all of the

mean annual rainfall at any location in the basin falls within five months. Mean daily temperatures vary from 13⁰ to 20⁰C in July and between 21⁰ and 30⁰C in November. Humidity decreases from 75% at the end of the wet season down to 45% at the end of the dry season. Sunshine hours during the dry season (13 hours per day) are almost double those of the wet season.

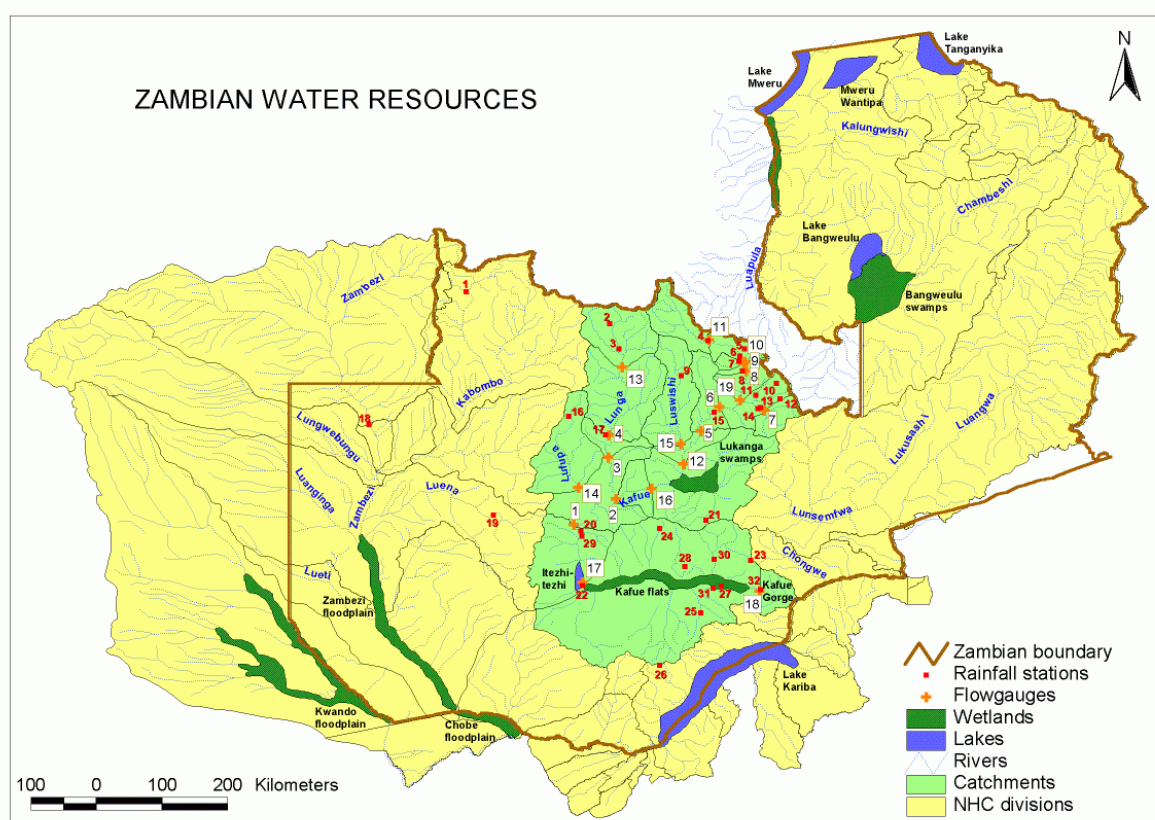


Figure 5.1 Location of the Kafue basin in the Zambezi River Basin.

Rainfall over the Kafue basin is derived from a low-pressure system caused by the convergence of the Trade Winds known as the Inter Tropical Convergence Zone (ITC). Annual rainfall varies from 1300 mm in the north to 800 mm in the south. Variations in rainfall are more significant in the southern areas where the frequency and duration of dry spells is greater (Hywel, 1971). This is caused by the inter-annual changes in the southern extent of the ITCZ. Table 5.1 gives the mean monthly distribution of rainfall within the basin.

Table 5.1 Mean monthly rainfall in Kafue basin (refer to Figure 5.2 for the location of the sub-catchments and 5.8 for the mean annual rainfall distribution)

Province	Sub-catchments	Average Monthly Rainfall Total											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Copperbelt	A,C,D,E,F, G,H,I,J,K	34	139	289	299	230	177	55	5	0	0	0	3
Northwestn	M,N,O,P,R	57	158	237	245	201	199	61	6	1	0	1	8
Central	L,Q,T	24	89	235	245	199	115	32	4	3	0	0	1
Southern	S,T,U	24	76	186	188	151	83	21	5	0	0	0	1

Source: Yachiyo, 1995 (Records 1963-92)

The average annual pan evaporation in Zambia ranges from 1 666 mm to 2 814 mm and the Zambian average is 2 061 mm. Annual pan-evaporation is low (1 700 – 2 000 mm) in the north, and is very high in the east (2 200 – 2 600 mm) and is moderate in the centre, the west and the south of Zambia. The Copperbelt Province, which forms much of the upper Kafue basin has the lowest annual pan-evaporation, of 1 865mm on average and the Eastern province has the highest of 2 211 mm on average. Monthly pan-evaporation is high from August to November at 200 – 300 mm per month, and is low from December to July at 100 – 200 mm per month. Therefore evaporation is high in areas and in months with little rainfall and is low in areas and in months with higher rainfall (Hywel, 1971,Yachiyo, 1995).

Potential evapotranspiration rates are relatively constant at about 6mm per day during the wet season decreasing to 4mm per day in the colder dry season (see Table 5.2). This small variation is due to the moderating effect of increased cloud cover and atmospheric vapour pressure during the rainy season compared with the lower temperatures, clearer skies and drier atmospheric conditions of the cooler dry season.

5.1.2 Topography, soils and drainage

Most of the land surface of tropical Africa has been exposed as continental land above sea level for over 200 million years. In the Kafue basin, the resulting modern landforms are extensive old surfaces interrupted by isolated highlands, scarps and broad linear valleys of tectonic origin. This landscape is the result of two main erosion surfaces; the middle and lower basin lies mainly on the Post-African erosion surface; the Kafue flats occupy one of the linear tectonic valleys, which was possibly initiated in the late Cretaceous and has been subsequently re-activated. The African surface in the Kafue basin is characterised by an

Table 5.2 Calendar month average daily potential evapotranspiration in the Kafue basin
(refer to Figure 5.2 for sub-catchment locations)

Province	Sub-catchments	Monthly Average Daily Evapotranspiration (mm d ⁻¹)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Copperbelt	A,C,D,E,F, G,H,I,J,K	5.6	4.7	3.9	2.9	3.7	3.8	4.0	3.8	3.5	4.1	4.7	5.8
Northwestn	M,N,O,P,R	5.1	4.3	3.8	3.0	3.8	3.9	4.0	3.8	3.5	3.8	4.5	5.2
Central	L,Q,T	6.6	5.4	4.1	3.1	3.9	4.1	4.2	4.0	3.7	3.8	4.7	5.9
Southern	S,T,U	6.4	5.8	4.8	3.7	4.3	4.4	4.3	3.8	3.5	3.6	4.6	5.9

Source: Yachiyo, 1995

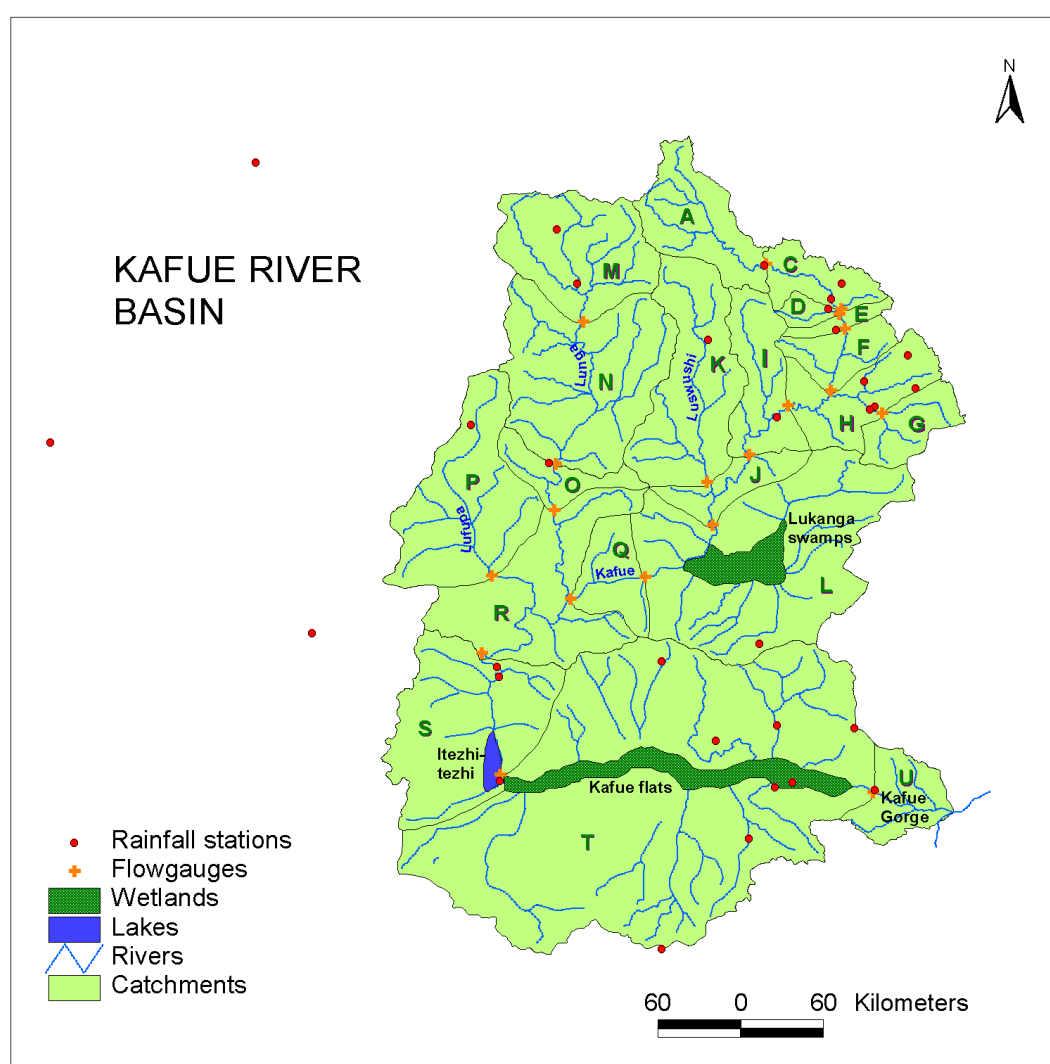


Figure 5.2 Kafue basin physical features and sub-catchment divisions.

extremely smooth plateau surface with subdued slopes, shallow and wide drainage patterns and scattered inselbergs. The Post-African surface is poly-cyclic and more hilly and incised than the African surface. Approximately 65% of the basin area is underlain by fissured crystalline and metasedimentary Basement Complex. Dambo drainage systems are common over the Basement Complex outcrops.

In situ chemical weathering of the rocks underlying the African and Post-African surfaces has produced a continuous cover of thick saprolite soils. These weathering horizons range from 25 to over 60m in thickness and play an important role in the hydrological cycle of the basin. The upper soil horizons are very permeable and have high infiltration capacities. These soil characteristics coupled with the gently rolling topography has led to low surface runoff from all but the most intense rain events. The high recharge to the top of the weathered aquifer is, however, rapidly released to streamflow, as sub-surface flow and baseflow after the soil moisture requirements are satisfied. Deeper recharge to the lower saprolite zone appears to be released more slowly and becomes the dominant component of the baseflow towards the end of the dry season. Both shallow and deep recharge are subject to heavy evapotranspiration losses where the water table is close to the surface.

The small areas of limestone and dolomite outcrop associated with complex folding on the eastern margin of the basin form distinct elevated limestone pavements. The Kalahari Beds and associated alluvium in the west of the basin form low undulating relief on the highly permeable soils with shallow water tables and locally impeded drainage mainly dambos, where silts have accumulated. The broad alluvial plains associated with the major areas of impeded drainage such as the Lukanga swamp and the Kafue Flats are of neo-tectonic origin. The combination of low relief and a thick and stable residue soil cover has helped minimise erosion rates, even over lands that have been cleared through deforestation especially in the northern and eastern parts of the basin which are around the urban centres (Hywel, 1971; Scott Wilson, 2003a).

5.1.3 Geology and geomorphology

The Upper Kafue basin, made up of sub-catchments A, C, D, E, F, G, H, I K and J (see Figure 5.2), has geological formations that include Kundelungu limestone, basement complex

culminations, muva-conglomerate and small areas of Alluvium and Kalahari sands (Figure 5.3).

The Middle Kafue basin, made up of sub-catchments L, Q, M, N, O, P, R and S, lies on Kundelungu limestone, Alluvium, Hook granites, Karoo deposits and Kalahari sands. The hydrology here is strongly influenced by the Mpongwe block storage and losses. This gives way to Kundelungu shales and alluvium associated with the Lukanga swamps depression. Just upstream of the Lunga confluence, the Basement Complex culminates in the Hook granites. Also present are Karoo and Kalahari deposits. The middle basin terminates at the start of the Kafue flats with upstream lateral inflow from granite sub-catchments.

The lower Kafue basin, made up of sub-catchments T and U, begins with the Kafue flats and is underlain by Karoo deposits, Kalahari sands and Alluvium surrounded by dolomite to the north and folded Basement Complex to the south. Most of the Kafue flats is carpeted by a layer of recent alluvium dating back to the Tertiary. In the Kafue Gorge, the river cuts through rocks of the Basement Complex (at least six main types of rocks are found including gneiss, granite and schist), which are more than 800 million years old. The dam, tunnel and power installations of the Kafue Gorge power station are located in these rocks. The river then falls onto the Karoo deposits associated with the Zambezi rift valley. It is believed that during the Pleistocene, much of the Kafue Flats was probably under water forming a great lake whose headwaters were only in recent millenia captured by the headwaters of a stream flowing in the Kafue Gorge near the Kafue Bridge to form the current feature (Handlos, 1984; Coats et.al., 2001; Sikatali, 1994; Burke, 1994). Refer to Figure 5.3 and Table 5.3 for more detailed information about the spatial distribution of the geology of the Kafue basin.

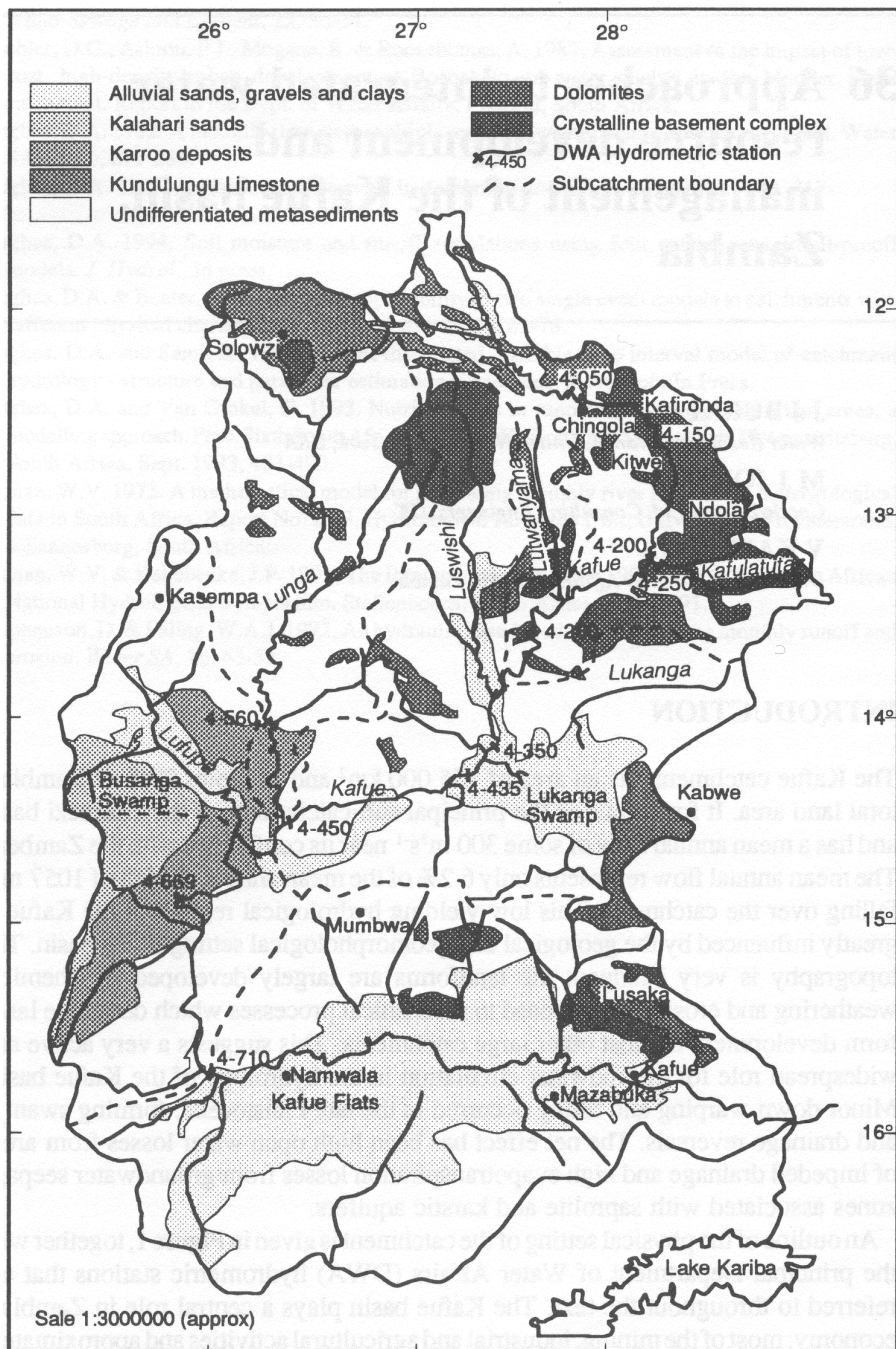


Figure 5.3 Geology of the Kafue basin (After Burke,1994).

Table 5.3 Description of the geology of Kafue sub-catchments.

Map Label	Station Number	Area Km ²	Sub-catch. Name	Description of geology
A	4050	4 999	Kafue at Raglan Farm	- Folded Kundelungu limestone, shales, banded iron formations.
C	4090	2 149	Kafue at Kafironda	- Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite
D	4120	869	Mwambashi at Mwambashi	60% Folded Kundelungu limestone, shales, banded iron formations 40% basement complex culminations of granitic, gneiss, migmatite and granite
E	4150	1178	Kafue at Wusakile	80% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 20% Folded Kundelungu limestone, shales, banded iron formations
F	4200	2 460	Kafue at Mpatamato	50% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 30% Folded Kundelungu limestone, shales, banded iron formations 20% Muva-conglomerate with mudstone and slate
G	4205	2 499	Kafulafuta at Ibenga	30% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 60% Muva-conglomerate with mudstone and slate 10% Folded Kundelungu limestone, shales, banded iron formations
H	4260	4 572	Kafue at Ndubeni	60% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 20% Muva-conglomerate with mudstone and slate 10% Folded Kundelungu limestone, shales, banded iron formations
I	4280	4 194	Kafue at Machiya	90% Folded Kundelungu limestone, shales, banded iron formations 10% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite
K	4340	8 708	Luswishi at Kangondi	60% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 10% Folded Kundelungu limestone, shales, banded iron formations 30% Alluvium, colluvium and laterite (wetlands formations) 5% Kalahari sands
J	4350	2 534	Kafue at Chilenga	95% Folded Kundelungu limestone, shales, banded iron formations 5% Alluvium, colluvium and laterite (wetlands formations)
L	4307	16 317	Kafue at Mswebi	55% Folded Kundelungu limestone, shales, banded iron formations 40% Alluvium, colluvium and laterite (wetlands formations) 5% Kalahari sands

Map Label	Station Number	Area Km ²	Sub-catch. Name	Description of geology
Q	4450	3 963	Kafue at Lubungu	50% Folded Kundelungu limestone, shales, banded iron formations 45% Alluvium, colluvium and laterite (wetlands formations) 5% Hook Granite and metamorphic equivalents
M	1	8 100	Lunga at Chipembele	90% Folded Kundelungu limestone, shales, banded iron formations 10% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite
N	4550	11 455	Lunga at Kelongwa	Folded Kundelungu limestone, shales, banded iron formations
O	4560	1 890	Lunga at Chifumpa	95% Folded Kundelungu limestone, shales, banded iron formations 5% Kalahari sands
P	2	9 450	Lufupa at Ntemwa Camp	50% Folded Kundelungu limestone, shales, banded iron formations 25% Karoo deposits of sandstone, mudstone and basalt 10% Alluvium, colluvium and laterite (wetlands formations) 15% Kalahari sands
R	4669	9 716	Kafue at Hook Bridge	50% Karoo deposits of sandstone, mudstone and basalt 20% Kalahari sands 20% Hook granites and metamorphic equivalents 5% Alluvium, colluvium and laterite (wetlands formations) 5% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite
S	460995	10 619	Itezhi-tezhi	50% Karoo deposits of sandstone, mudstone and basalt 50% Hook granites and metamorphic equivalents
T	470800	47 138	Kafue Gorge	40% Alluvium, colluvium and laterite (wetlands formations) 20% Kalahari sands 15% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite 10% Folded Kundelungu limestone, shales, banded iron formations 5% Volcanic and metaquartzite rocks 5% Hook granites and metamorphic equivalents
U	-----	4 185	Zambezi-Kafue confluence	40% Karoo deposits of sandstone, mudstone and basalt 30% Folded Kundelungu limestone, shales, banded iron formations 30% Kundelungu schist, gneiss and granulite and lower basement complex culminations of granitic, gneiss, migmatite and granite

Source: Coats et.al., 2001; Sikatali, 1994; Burke, 1994.

5.1.4 Land cover and Land use of the Kafue basin

The major vegetation of Zambia can be divided into four types. The characteristics of each type can be summarised as follows:

- The dense miombo woodland of the plateau, divided by grass and swamps along dambos, covering the North, Copperbelt, Luapula and North-western Provinces.
- Kalahari Chipya alternating with grass in the South and West
- The Mopane woodlands of the lower Luangwa and Zambezi valleys
- The dry evergreen woodlands and their Chipya derivatives in the northwest on the Kalahari sands and northeast on lake basin soils in Luwigu and Kasama.

Miombo woodland accounts for 80% of the forested area, the dominant species being *Brachystegia*, *Isoberlinia* and *Julberna*. The distribution of these forests is influenced by the climate, which is subtropical, moderated by altitude (Hywel, 1971).

Land use and land cover in the upper Kafue basin are dominated by the impacts of the mining industry, its related industrial and urban activities and pressure on the woodland areas for timber, charcoal, fuelwood and cultivation. The satellite image dated August 2002 (Figure 5.4) shows a sharp contrast with the largely undisturbed vegetation in the Congo – top right of the image. The impacts of this land use and reduced land cover on the upper basin are greater wet season runoff and higher sediment loads.

The middle basin has a low population density and no large towns and industries, and therefore has better land cover. The sub-catchment has several protected areas of National parks, game management areas and Forest reserves. It also has numerous dambos and wetlands and water bodies, such as the Lukanga and Busanga swamps and the Itezhi-tezhi reservoir. This sub-catchment contains the Mpongwe agricultural area (Figure 5.5, showing centre pivot fields), which uses mainly ground water for irrigation (see Figure 5.5 and the upper part of Figure 5.6)

The Kafue Flats area is mainly covered with wetland vegetation, which is predominantly grassland, mainly used for cattle and wildlife grazing. Irrigated land is an important land use in this sub-catchment with more than 12 000 hectares under irrigation (Scott Wilson, 2003a, b)

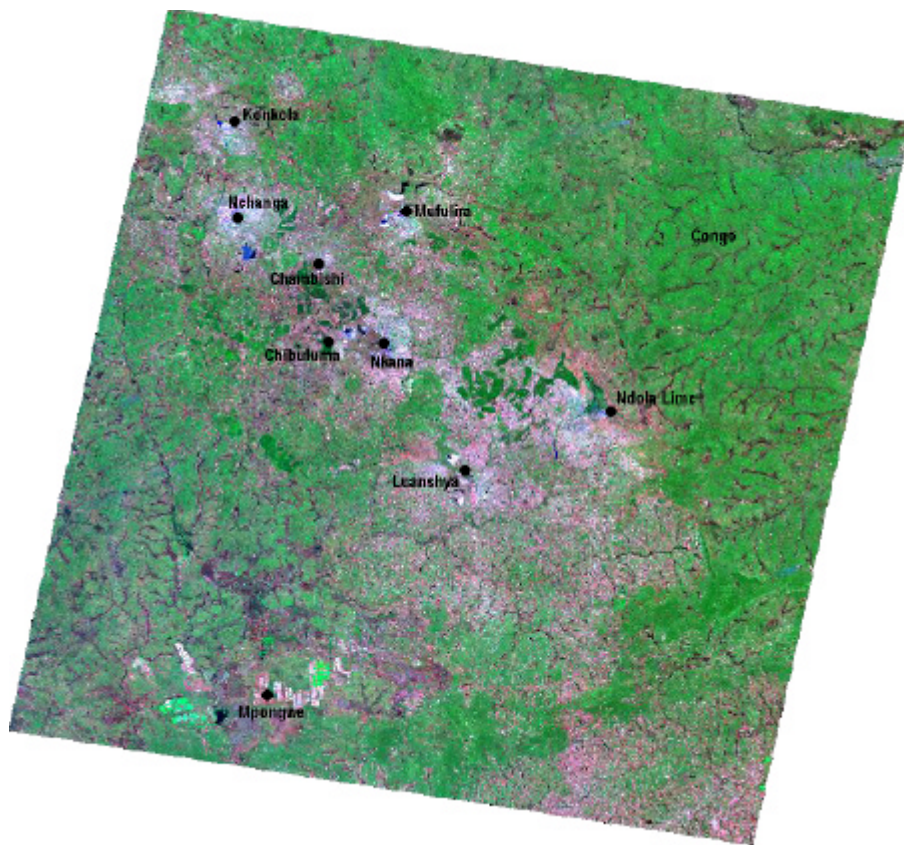


Figure 5.4 Upper Kafue basin showing landuse and landcover.

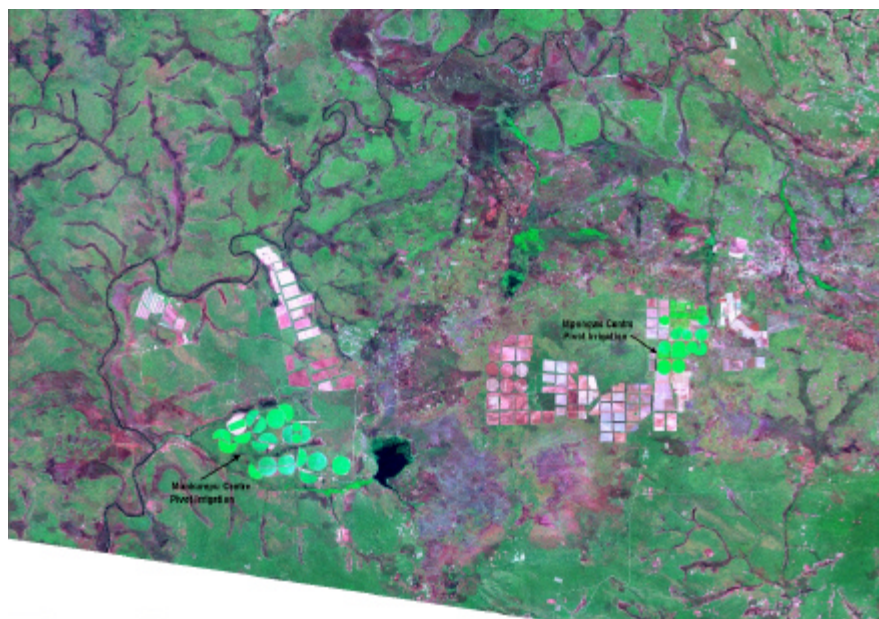


Figure 5.5 Mpongwe block with agricultural activities (irrigated and rainfed).

Meteorology's inability to mount regular inspections of rainfall stations owing to insufficient funds (Yachiyo, 1995). Therefore only 46% of the total registered stations are currently operating.

The 36 main meteorological stations (Figure 5.7) spread through out the country, have both continuous recording raingauges and collector raingauges, while the voluntary stations, are mostly equipped with collector type of raingauges which are measured on a daily basis, the meteorological day being the period from 09.00 hours to 09.00 hours. Data collection at the moment is mainly by radio-telephone, telephone and by post. The major problem in communication is that the radios are unreliable and reception often quite poor; in addition, the local postal service no longer accepts mail that does not bear postage stamps. This means that many voluntary observers are not able to send meteorological returns on time.

Table 5.4 Summary of Kafue sub-catchment characteristics.

Sub-catchments	Climate	Geology	Soils	Drainage	Land cover	Main features
A,C,D,E,F,G,H,I,J,K,M,N,O	High rainfall (>1200mm/year) Low pan evaporation (<1900mm/year)	Mainly hard rock basement complex of granites gneiss with some areas of more permeable limestone	Soils are sandy to medium texture, strongly leached and often contain lateritic deposits	Moderately steep gradients, narrow channel. Frequent dambos	Mixed Miombo woodlands deforested in some areas replaced by exotic species of pine and Eucalyptus	Mining, forestry, industry and towns. Mine Groundwater discharge
L,Q,P,R,S	Moderate rainfall (about 1000mm/year) Pan evaporation (2000mm/year)	Granite outcrop eastwards from Kafue Hook to Mumbwa and southwards to Itezhi-tezhi, also shales, siltstones and sandstones and Karoo deposits	Marshy and swampy area soils are subject to seasonal flooding and tend to be heavy with high clay content	Shallow gradients, wide channels some marshy areas and Lukanga swamp	Open bush with extensive areas of dry season burning, grassland dominating	Kafue National Park, areas of marsh and swamp along Lufupa and Luswishi rivers also Lukanga swamps (2,600km ²), Itezhi-tezhi.
T	Variable with low rainfall (800mm/year) High pan evaporation (2000mm/year)	Alluvial Karoo deposits	Soils are subject to seasonal flooding and tend to be heavy with high clay content	Shallow gradient, multiple channels, areas of open water Kafue Flats	Grassland dominated open bush	Cattle farming, irrigated sugar estates, fisheries, Lochinvar and Blue Lagoon National Parks, Kafue Flats (6,500km ²) wetland
U	Variable with low rainfall (800mm/year) and high pan evaporation (2000/year)	Hard rock basement complex forming a steeply incised gorge opening out into an alluvial plan of Karoo deposits	Sandy to medium textured	Very steep gradients, incised channel. Natural drop in river of about 610 meters over a distance of 24km	Open bush	Kafue Gorge hydropower, Lusaka water supply intake, irrigation, tourism

Considerable progress has been achieved through the installation of the Climate Computing (CLICOM) system which was acquired through the assistance of the World Meteorological Organisation (WMO). Data lengths for all the main meteorological stations shown in Figure 5.7, are available on computer and can easily be retrieved. Efforts are being made to enter data from the voluntary stations, however, most of the data currently is still on hard copies (monthly returns), filed in box files.

For the purpose of simulating the streamflows of the Kafue basin, 28 rainfall stations which are reasonably evenly distributed over the entire basin were selected (Table 5.5 and Figure 5.8). Three of these rainfall stations are outside the Kafue basin, but within the Zambezi basin. The rainfall record lengths range from 14 years for Ibenga Mission (4131) and Shibuyungi (2433) to 62 years for Roan (4053) and Kasempa (3180) stations. However, most stations with longer records also have larger number of missing data gaps, i.e. Kasempa (3180), which has a 62 year record, has 88 months of missing data and Kelongwa (3360), with 38 years of record, has 65 months of missing data. The good record rainfall stations include Choma (5350) with 51 years of record and only 5 months of missing data, Ndola (4100), with 51 years record, has 12 months of missing data and Magoye (2525), with 22 years record, has only 3 months of missing data (Table 5.5).

In general terms, raingauges located in the mining towns, agricultural centres and main provincial towns have better records compared to the rural and remote stations, mainly because some stations are manned by full time employees, while others are manned by volunteers.

[illegible]

Figure 5.7 Data availability for all meteorological stations in Zambia.

Table 5.5 General information on available monthly rainfall data.

	Station No.	Station Name	Length of Record (years)	Missing data months
1	2193	Lusaka City Airport	1966-2000 (34)	26
2	2264	Namalundu Gorge	1973-1988 (15)	46
3	2400	Kafue Polder Agromet	1956-2000 (41)	15
4	2402	Nakambala Sugar Estate	1965-2000 (35)	8
5	2433	Shibuyunji Agric	1976-1990 (14)	3
6	2505	Blue Lagoon	1952-1984 (32)	19
7	2525	Magoye Agromet	1977-1999 (22)	3
8	2755	Mumbwa Met	1979-2000 (21)	7
9	2800	Namwala	1958-1989 (31)	56
10	2998	Chunga Camp	1961-1979 (18)	30
11	3180	Kasempa	1937-1999 (62)	88
12	3360	Kelongwa	1951-1989 (38)	65
13	3555	St. Francis Mission	1953-1989 (36)	17
14	3570	Solwezi Met	1960-2000 (40)	13
15	3890	St. Marys' Mission	1951-1986 (35)	9
16	3955	Kafue Ndubeni	1969-1990 (21)	38
17	4053	Roan Antelope	1927-1989 (62)	16
18	4100	Ndola Met	1949-2000 (51)	12
19	4131	Ibenga Mission	1970-1984 (14)	5
20	4235	St. Josephs Mission	1968-1983 (15)	21
21	4277	Kitwe Sewage	1959-1984 (25)	12
22	4320	Mwambashi	1962-1984 (22)	21
23	4375	Kafironda	1966-2000 (34)	9
24	460010	Itezhi-tezhi ZESCO	1979-2000 (21)	6
25	5350	Choma	1949-2000 (51)	5
26	6210	Kaoma	1960-2000 (40)	12
27	6525	Mwinilunga	1949-1996 (47)	15
28	6840	Zambezi	1953-2000 (47)	20

5.2.1 Suitability of available rainfall data for streamflow simulation

To investigate patterns of spatial variability and to assess the representativeness of the rainfall data from the 28 stations, X-Y scatter plots were generated using data from all possible station pairs. Table 5.6 presents the distances (km) between the station pairs (top right of the matrix) as well as the coefficient of determination (R^2) representing the relationships between monthly rainfalls recorded at station pairs (bottom left of the matrix). Mean annual rainfall decreases from north to south in the Kafue basin, and rainfall stations in the northern part of the basin are well correlated with each other, even with separation distances of over 200 km. Mwambashi (4320) is 270 km to the north east of Kasempa (3180) and they have similar

patterns of rainfall (coefficient of determination of 0.821), while Mumbwa (2755) and Kelongwa (3360) which are 160 km apart in a north–south direction have a poor relationship with a coefficient of determination of 0.518. Namalundu Gorge (2264) and Mwinilunga (6525) are 630 km apart in a north–south direction and have a weak relationship with an R^2 of 0.487.

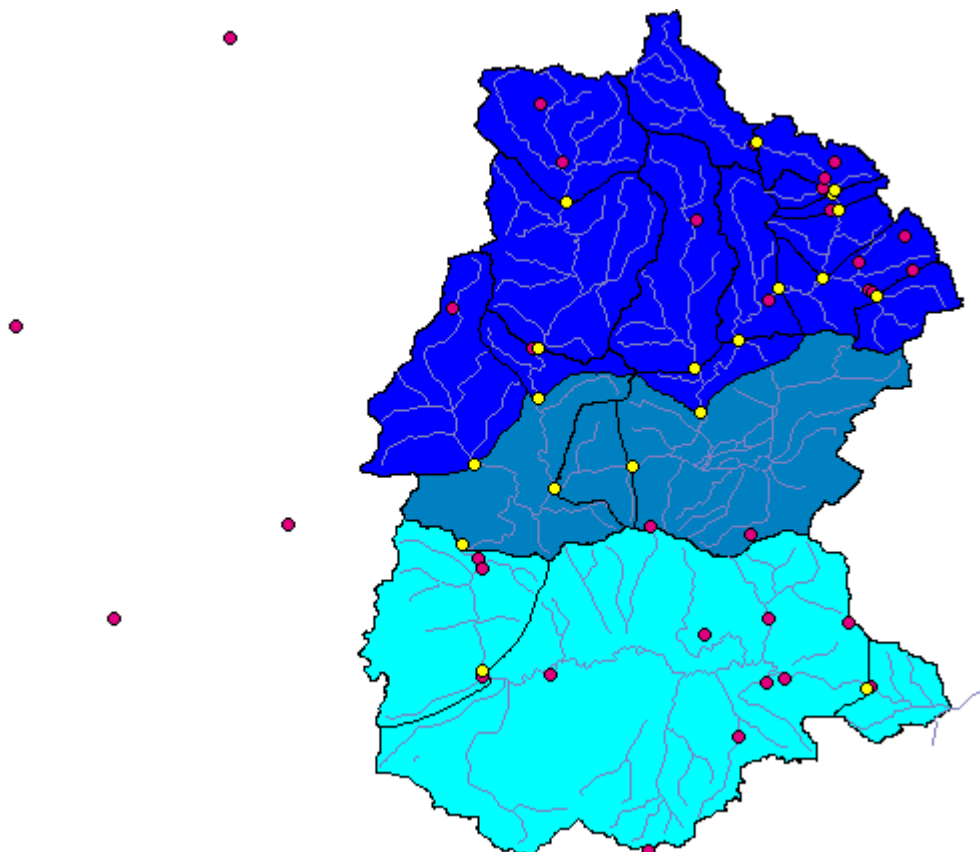


Figure 5.8 Kafue basin raingauges and mean annual rainfall distribution (the lighter colour $\leq 800\text{mm}$ darker colour $800 - 1000$ darkest colour $1000 - 1300\text{mm}$).

For all the rainfall stations in the western part of the upper Kafue basin, which is a high rainfall region ($1200 - 1300\text{ mm}$), the general trend for the X – Y scatter plots for all possible station pairs, is that better relationships occur for months with rainfall below 300mm , while monthly rainfall of more than 300mm show poor relationships, as can be seen from Figure 5.9. A few outliers occur at lower rainfall ranges, which could be attributed to the quality of data records, but could also be due to the convectional type of rainfall whose storms tend to be localised in some cases. There is less scatter for lower monthly rainfall than there is for

higher monthly rainfall. The relationship between Kasempa (3180) and St. Francis (3555) data which are 130 km apart with R^2 of 0.798, conforms to this pattern (Figure 5.9).

The rainfall stations in the eastern part of the upper Kafue basin, which is also a high rainfall area (1200 – 1300 mm) show very good rainfall distribution relationships both at lower rainfall ranges and higher rainfall ranges. With data stations of long records of more than 50 years, for Ndola and Roan, which are 30 km apart and have an R^2 of 0.878 (Figure 5.10), the rainfall distribution shows a regular pattern both at lower and higher rainfall ranges. In general terms, the data quality in the stations on the copperbelt area is reasonably good and therefore can be relied on for flow simulation purposes

The rainfall stations in the lower Kafue basin which is a lower rainfall area (900 – 800 mm), show even and regular distributions of monthly rainfall, with good relationship at both lower and higher rainfall ranges. A few outliers at the lower ranges, may be attributed to the localised nature of convectional storms that are common in this region. This good distribution can be seen in the relationship between Magoye and Nakambala which are 22 km apart and have an R^2 of 0.866 (Figure 5.11).

Reference has already been made to the number of missing months in the gauged rainfall records. In order to generate continuous time series (without missing data gaps) of average rainfall (see section 4.2.1 on methodology) over the sub-catchments of the Kafue, it would be necessary to use station data, which are not necessarily the closest to the sub-catchments. From the analysis of the spatial variations in monthly rainfall patterns, it is apparent that it would be better to use stations, which are at similar latitudes to fill missing data gaps. Stations to the north or south may be closer but will clearly be not as good for filling gaps. A facility within SPATSIM was used for interpolation of point data to generate areal averages to convert point rainfall data to catchment average rainfall data. This procedure allows point data to be interpolated to areal data using an inverse distance weighting method.

Table 5.6 Monthly rainfall analysis – Coefficient of determination / Distances between stations.

2193		62	92	80	47	87	100	140	198	245	336	280	373	407	295	235	250	270	225	220	285	293	305	240	210	375	580	595
2264	0.672		102	92	90	120	100	185	225	275	392	335	435	475	355	295	305	320	280	275	335	352	350	265	195	415	630	625
2400	0.807	0.768		15	60	46	15	120	122	190	325	276	400	435	332	185	317	345	196	195	345	350	355	165	120	315	565	535
2402	0.763	0.764	0.868		50	47	22	120	135	205	335	280	395	435	330	375	315	335	290	285	345	355	360	180	132	331	575	550
2433	0.817	0.617	0.764	0.772		35	70	95	150	195	305	250	352	390	285	230	260	285	240	235	282	294	302	195	180	330	510	510
2505	0.742	0.716	0.816	0.804	0.775		60	75	115	165	290	235	345	385	290	240	270	302	260	255	317	315	322	160	157	290	525	511
2525	0.802	0.697	0.837	0.866	0.768	0.792		129	127	200	340	290	405	440	347	295	330	355	310	305	360	373	380	170	112	325	582	547
2755	0.738	0.574	0.713	0.679	0.69	0.552	0.747		106	115	215	160	284	320	235	200	250	284	230	225	273	284	286	137	202	241	457	450
2800	0.547	0.538	0.601	0.495	0.448	0.67	0.476	0.548		90	265	225	360	395	330	310	360	385	340	340	377	385	391	40	130	205	495	430
2998	0.711	0.682	0.766	0.771	0.704	0.751	0.933	0.753	0.644		180	155	290	325	280	277	335	365	320	320	345	375	380	80	220	133	405	375
3180	0.633	0.576	0.629	0.621	0.622	0.66	0.69	0.626	0.637	0.722		60	130	155	175	220	28	305	277	282	270	270	270	255	390	175	245	290
3360	0.645	0.572	0.556	0.522	0.534	0.609	0.533	0.518	0.577	0.681	0.69		137	170	145	170	235	265	228	232	230	230	230	230	355	205	300	345
3555	0.615	0.556	0.517	0.545	0.588	0.6	0.605	0.51	0.562	0.706	0.798	0.636		36	105	170	220	239	230	235	190	180	175	365	485	310	239	380
3570	0.565	0.586	0.52	0.528	0.553	0.58	0.565	0.481	0.492	0.66	0.768	0.696	0.797		130	200	240	255	250	257	210	200	197	398	520	335	218	380
3890	0.63	0.547	0.626	0.599	0.69	0.601	0.74	0.619	0.556	0.736	0.784	0.63	0.753	0.734		75	115	140	125	130	95	95	95	345	440	345	345	465
3955	0.704	0.634	0.662	0.653	0.699	0.663	0.739	0.597	0.538	0.747	0.702	0.725	0.73	0.697	0.651		64	92	60	64	70	80	88	330	395	360	410	505
4053	0.674	0.595	0.633	0.625	0.716	0.683	0.709	0.665	0.623	0.761	0.786	0.672	0.798	0.735	0.816	0.763		30	25	30	40	52	60	385	435	428	455	565
4100	0.673	0.588	0.604	0.599	0.653	0.669	0.662	0.593	0.619	0.747	0.766	0.663	0.761	0.698	0.748	0.778	0.878		50	52	45	55	65	415	455	460	472	595
4131	0.675	0.524	0.629	0.615	0.667	0.612	0.707	0.645	0.454	0.694	0.663	0.674	0.666	0.692	0.673	0.705	0.79	0.757		8	62	75	82	365	410	415	465	562
4235	0.626	0.633	0.65	0.593	0.598	0.686	0.616	0.4	0.583	0.692	0.796	0.743	0.779	0.781	0.762	0.758	0.836	0.8	0.766		69	80	90	365	410	415	470	567
4277	0.663	0.524	0.67	0.634	0.612	0.696	0.677	0.6	0.547	0.747	0.784	0.634	0.76	0.724	0.769	0.689	0.833	0.804	0.673	0.805		15	20	399	464	425	425	548
4320	0.654	0.619	0.684	0.653	0.695	0.651	0.701	0.466	0.545	0.724	0.821	0.671	0.784	0.763	0.783	0.723	0.835	0.829	0.754	0.876	0.86		7	410	474	430	420	550
4375	0.638	0.599	0.592	0.571	0.622	0.641	0.648	0.578	0.528	0.669	0.811	0.673	0.775	0.757	0.761	0.718	0.836	0.777	0.73	0.819	0.829	0.857		412	480	430	415	548
460010	0.699	0.713	0.667	0.716	0.747	0.813	0.769	0.631	0.301	0.872	0.71	0.516	0.611	0.562	0.598	0.662	0.695	0.558	0.627	0.476	0.61	0.517	0.599		155	170	475	396
5350	0.761	0.707	0.779	0.761	0.75	0.772	0.797	0.738	0.641	0.745	0.654	0.595	0.566	0.521	0.608	0.708	0.655	0.636	0.595	0.631	0.653	0.657	0.61	0.729		325	627	550
6210	0.712	0.613	0.664	0.68	0.73	0.748	0.746	0.65	0.652	0.794	0.743	0.602	0.689	0.628	0.688	0.709	0.756	0.715	0.723	0.737	0.725	0.726	0.673	0.694	0.724		340	230
6525	0.443	0.487	0.457	0.442	0.481	0.47	0.488	0.443	0.438	0.597	0.657	0.531	0.679	0.678	0.643	0.633	0.661	0.57	0.649	0.715	0.661	0.673	0.638	0.395	0.463	0.557		245
6840	0.604	0.452	0.58	0.549	0.608	0.624	0.608	0.553	0.545	0.699	0.725	0.618	0.718	0.684	0.692	0.651	0.723	0.665	0.642	0.731	0.689	0.669	0.7	0.611	0.625	0.686	0.638	
	2193	2264	2400	2402	2433	2505	2525	2755	2800	2998	3180	3360	3555	3570	3890	3955	4053	4100	4131	4235	4277	4320	4375	460010	5350	6210	6525	6840

Top right of the table – straight line map distances

Bottom left of the table – coefficient of determination

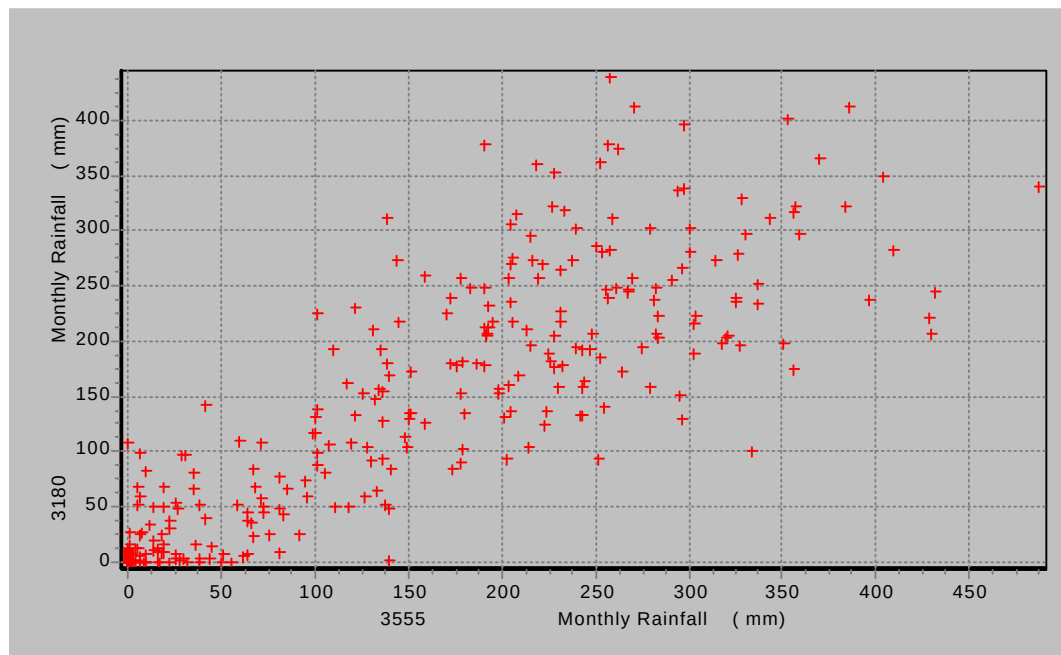


Figure 5.9 X-Y scatterplot for Kasempa (3180) and St. Francis (3555) which are 130 km apart with an R^2 of 0.798.

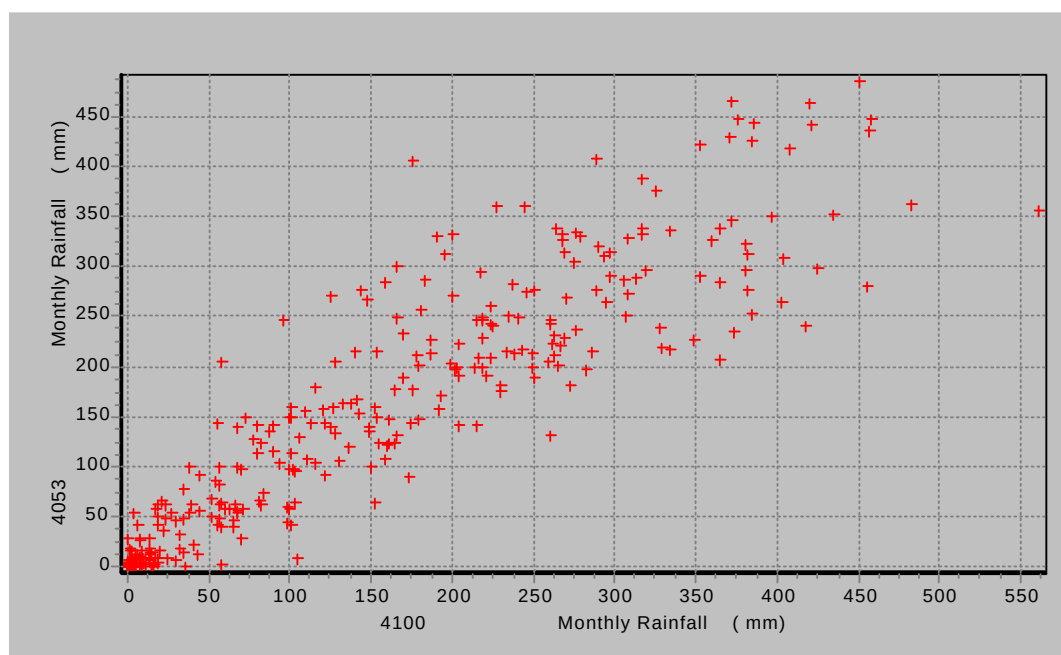


Figure 5.10 X-Y scatterplot for Ndola (4100) and Roan (4053) which are 39 km apart with an R^2 of 0.878.

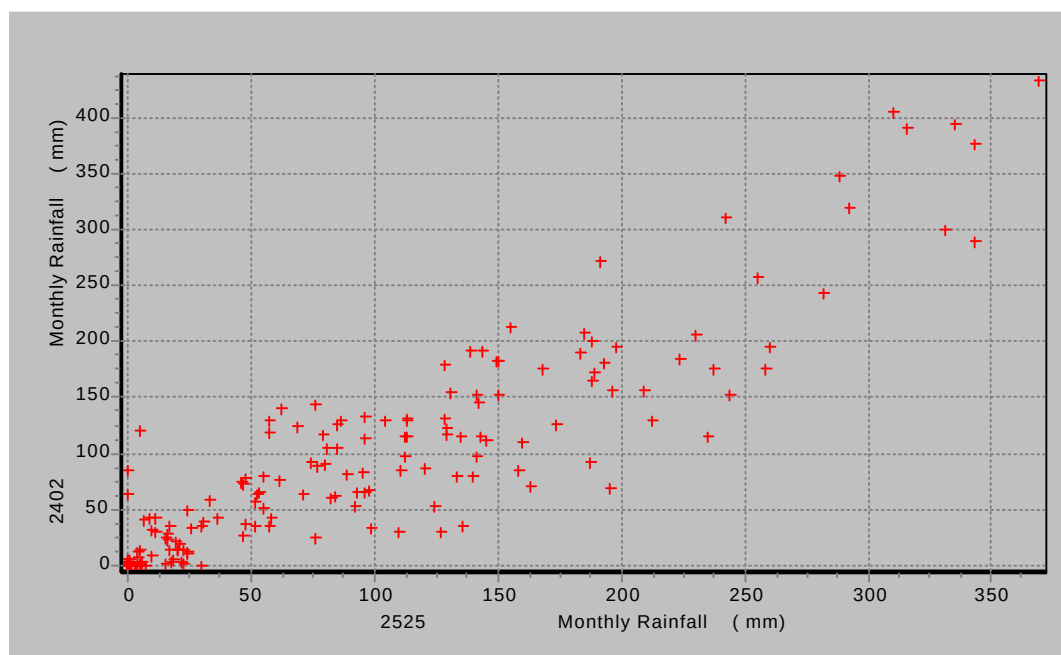


Figure 5.11 X-Y Scatterplot for Magoye (2525) and Nakambala (2402) which are 22 km apart with an R^2 of 0.866.

5.2.2 Distribution of rainfall within months of different rainfall amounts

Distribution of daily rainfall was analysed using data from four rainfall stations, which were chosen from the upper, middle and lower catchment areas. The daily rainfall distributions were analysed in comparison with the Pitman model assumption of rainfall distribution with the rain distribution factor (RDF) parameters of 0.6, 0.8 and 1.28 (Hughes, 1997). Daily rainfall distributions were plotted in ranges of monthly rainfall totals of 70 – 100 mm, 150 – 180 mm, 220 – 280 mm and 300 – 490 mm (refer to Figures 5.12 to 5.23). The rainfall distribution graphs, plotted as percentage of total monthly rainfall *versus* days of the months (see the lines labelled using month/year in the key), were compared with distribution graphs using the model RDF parameters (see the lines labelled M1.28, M0.8, M0.6 in the key) in order to determine the most appropriate RDF value to use. In examining these diagrams, it is important to remember that the model operates over four iterations. The most appropriate RDF value would be the one that generates similar 7 – 8 day rainfall totals, as appears in the observed daily rainfall sequences.

From the analysis, it was found that, for the Kafue basin, daily rainfall distribution for monthly rainfall of 70 – 100 mm tended to relate closely to an RDF value of 1.28 (see

Figures 5.12, 5.18 and 5.21). An RDF parameter of 1.28 would therefore be appropriate when the model is simulating runoff from lower monthly rainfall ranges. For monthly rainfall of 150 – 180 mm the daily rainfall distribution tended to relate more closely to lower RDF values of 0.6 and 0.8. For monthly rainfall 220 – 280 mm and 300 – 490 mm, the daily rainfall was found to be much more evenly distributed throughout the months, suggesting RDF values closer to 0.6. The shape of daily rainfall distributions for higher monthly rainfall therefore tended to relate closely to the lower RDF values of 0.6 to 0.8. This indicates that the lower the monthly rainfall, the higher would be the RDF parameter and the higher the monthly rainfall, the lower would be the RDF parameter. Unfortunately, the RDF parameter value is fixed for all months within the model.

Since monthly rainfall amounts are highly variable in each year depending on whether a particular year's rainfall is below, above normal or normal rainfall, it would be better to adopt a parameter that would work reasonably well for both high and low monthly rainfall. An RDF of 0.6 would tend to work well in runoff simulation for higher monthly rainfall but would be less appropriate for runoff simulations for lower monthly rainfall, while the rainfall distribution factor of 1.28 would tend to work reasonably well for the lower monthly rainfall but would tend to perform poorly for higher monthly rainfall. Therefore a model rainfall distribution factor parameter of 0.8 would seem to be a reasonable compromise for the Kafue basin.

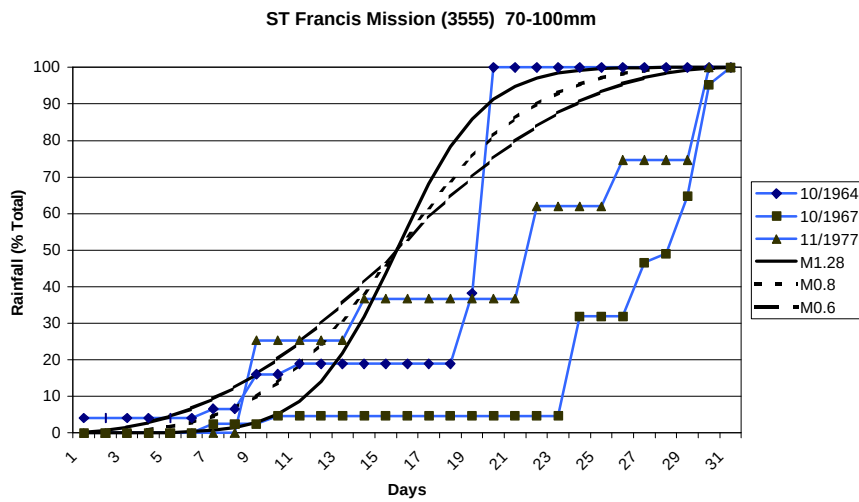


Figure 5.12 Daily rainfall distributions tending to be closely related to an RDF of 1.28.

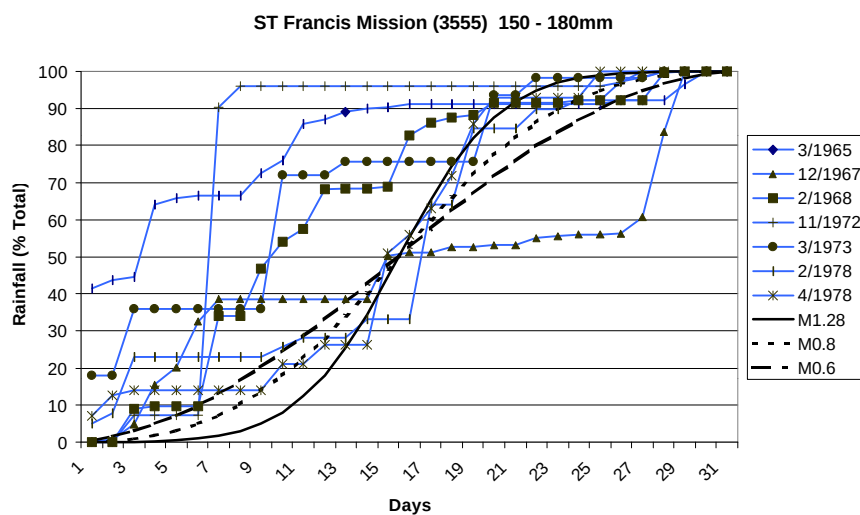


Figure 5.13 Daily rainfall distributions tending to be closely related to RDF values of 0.6 and 0.8.

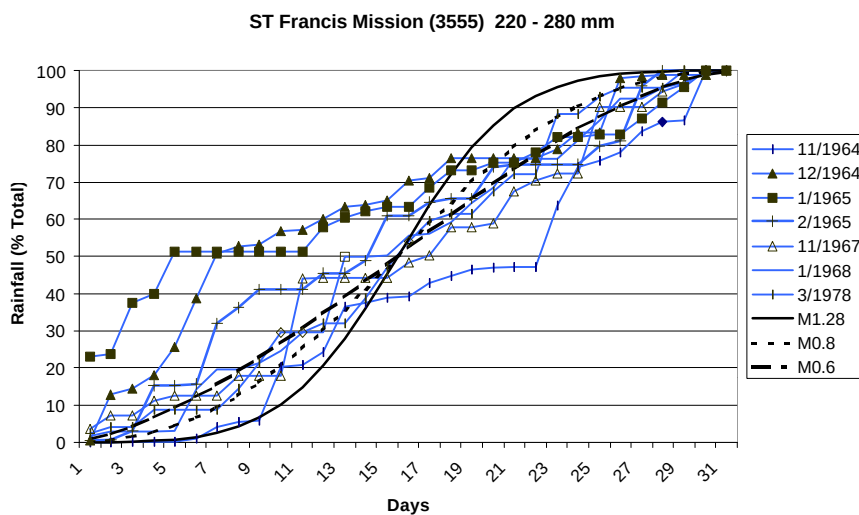


Figure 5.14 Daily rainfall is evenly distributed and closely related to an RDF of 0.6.

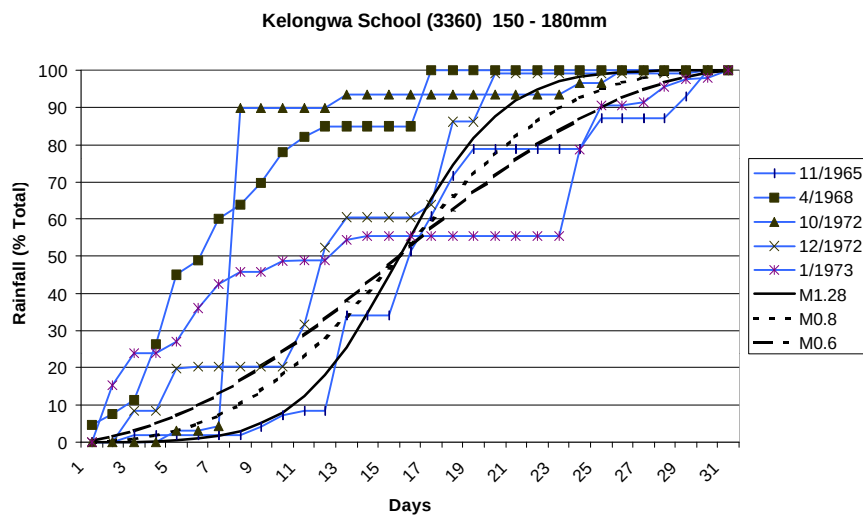


Figure 5.15 Daily rainfall distributions tending to be closely related to RDF values of 0.6 and 0.8.

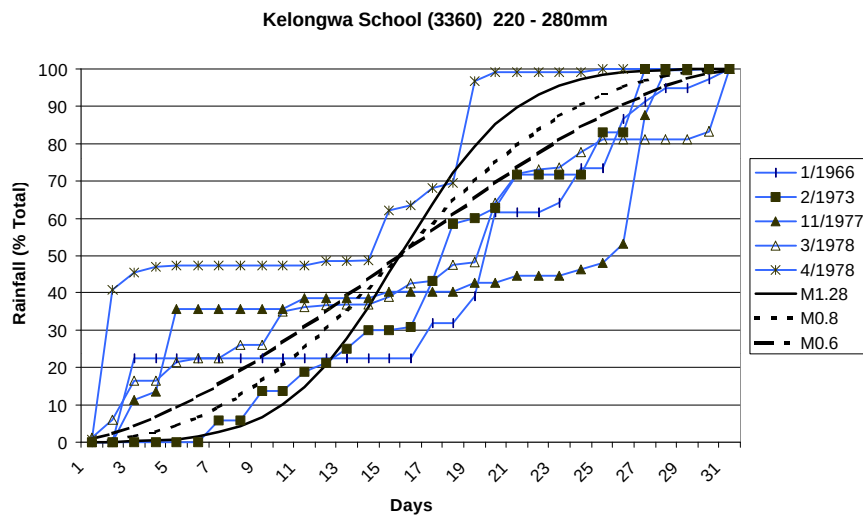


Figure 5.16 Daily rainfall evenly distributed tending to be closely related to an RDF of 0.6.

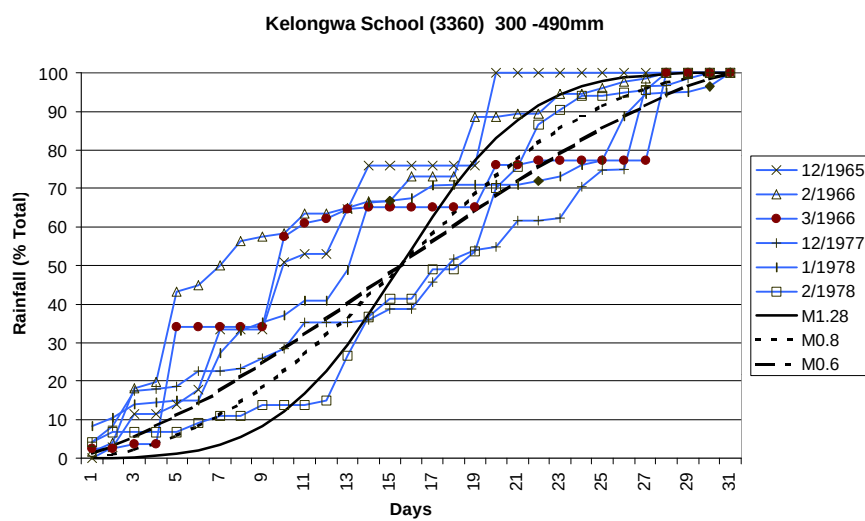


Figure 5.17 Evenly distributed daily rainfall tending to be closely related to an RDF of 0.6.

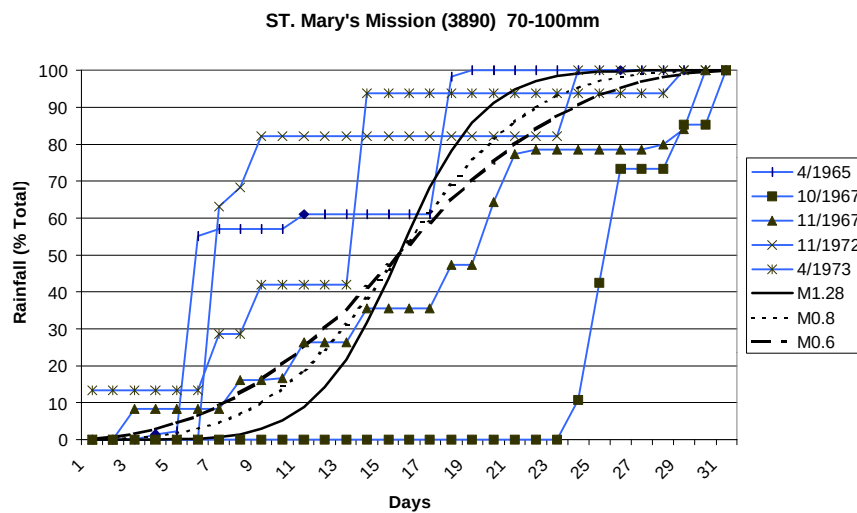


Figure 5.18 Daily rainfall distributions tending to closely relate to an RDF of 1.28.

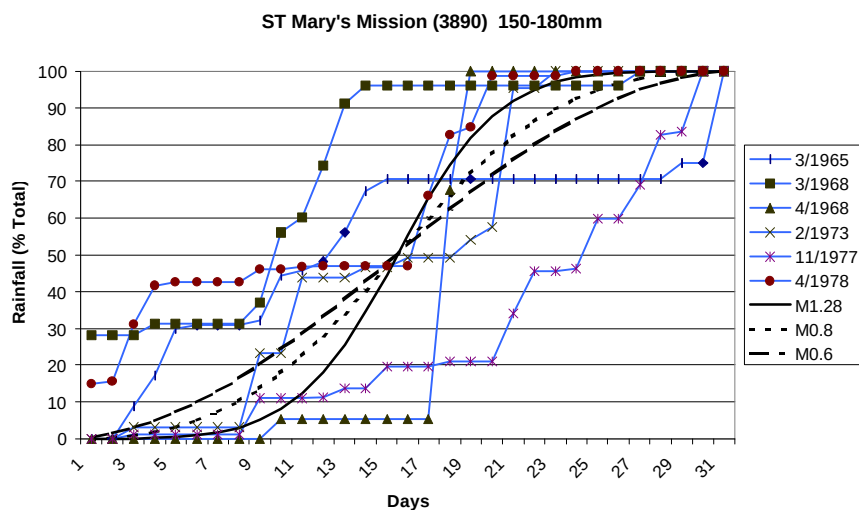


Figure 5.19 Daily rainfall distributions tending to be closely related to RDF values of 0.6 and 0.8.

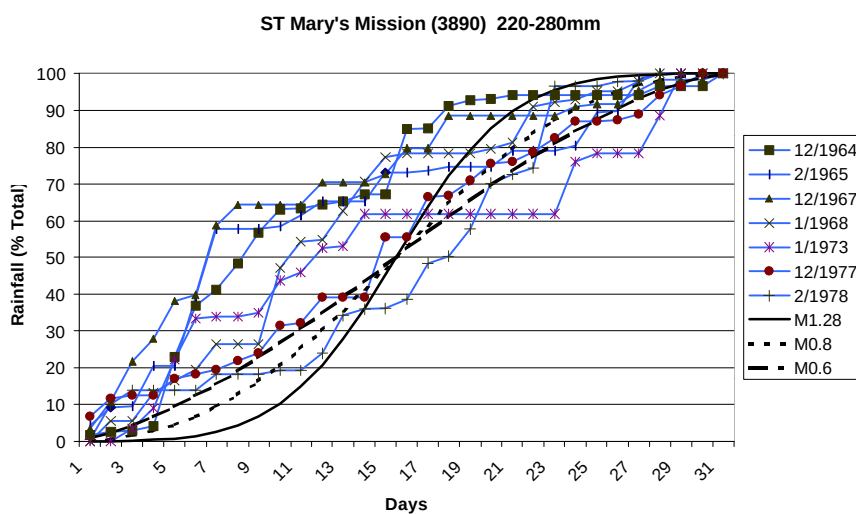


Figure 5.20 Daily rainfall distributions tending to be closely related to an RDF of 0.6.

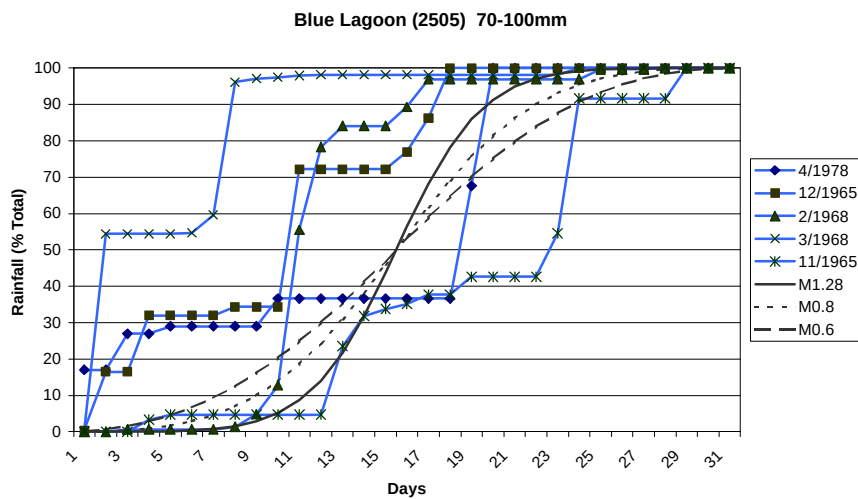


Figure 5.21 Daily rainfall distributions tending to be closely related to an RDF of 1.28.

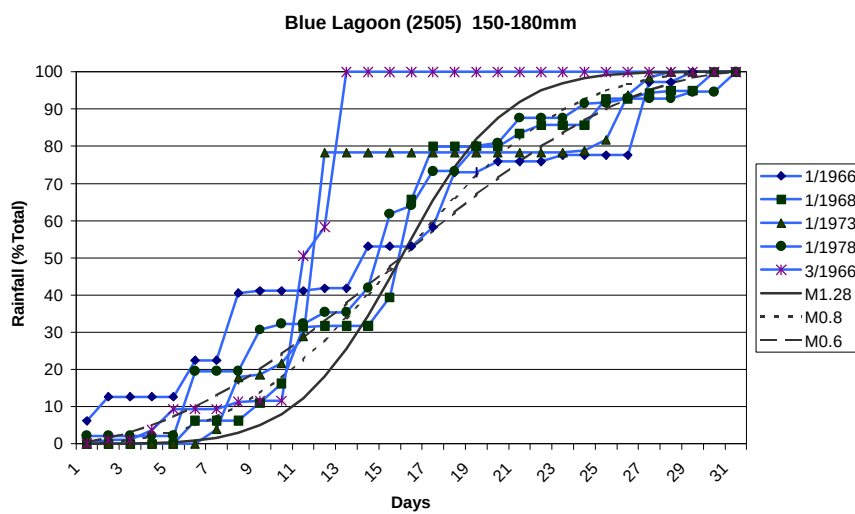


Figure 5.22 Daily rainfall distributions tending to be closely related to RDF values of 0.6 and 0.8.

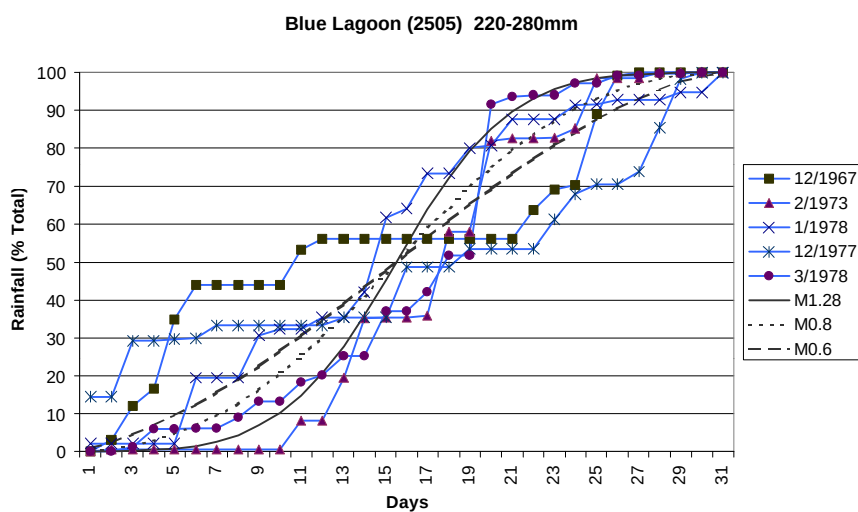


Figure 5.23 Daily rainfall distribution tending to be closely related to RDF values of 0.6 and 0.8.

5.3 AVAILABILITY OF OBSERVED STREAMFLOWS

The Department of Water Affairs under the Ministry of Energy and Water Development has the mandate to maintain the Zambian hydrometric network. There are some telemetry stations of interest to the hydroelectric power generation industry in the Kafue and Zambezi basins, which are manned by the Zambezi River Authority (ZRA) and ZESCO Ltd. The earliest station was opened in 1905 on the Kafue river at Rail Bridge. In the 1950s most of the important stations were opened on the Kafue River. However the situation at the moment is quite critical and very little continual monitoring and station maintenance is being undertaken because of a lack of resources. Since many more resources and effort are required to run and maintain a good quality hydrometric station, the state of the hydrometric network in Zambia is in a much worse situation than the meteorological network. The total number of registered stations is 284 and only 127 (45%) stations are still operational, with some vital basins like Kafue having only 33% of the stations still operational. Table 5.7 lists the current status of the Zambian hydrometric network as at June 2001.

Table 5.7 Status of the hydrometric network in Zambia.

Catchment	No. of stations	No. open stations
Luangwa	22	16
Tanganyika	12	11
Zambezi	81	40
Chambeshi	30	12
Luapula	39	15
Kafue	100	33
Total	284	127

Source: DWA, June 2001

The hydrometric network comprises water level stations and discharge measuring stations. Of the 284 hydrometric stations, 174 stations are discharge measuring stations and therefore have established discharge rating curves. The discharge measuring stations use rated channel sections and there are no gauging structures, such as weirs or flumes. The water level information is collected by gauge readers employed by the Department of Water Affairs and is returned on a monthly basis to the regional offices. The data are then checked and forwarded to the Hydrological Branch at the head office in Lusaka where it is entered into the Hydrological Data database (HYDATA, a program developed by the Centre for Ecology and Hydrology, United Kingdom), while hard copies, which are monthly water level returns, are

filed. Occasional discharge measurements are carried out for the purpose of checking the rating curves. Therefore data are stored both as daily water levels and as daily flows and these data are readily available at the Hydrological Branch in electronic format upon request.

Since 1992, collection of water level data has decreased because of the retrenchment of gauge readers at a large number of stations. Discharge measurement data collection and station maintenance have also become irregular due to insufficient funds. However, most stations have very good rating curves, which were established in the period before the 1990s when data collection was better. Since most river channels in Zambia are quite stable, the old rating curves have proved to be sufficiently useful and reliable for conversion of water levels to flows. The only problem which results from a lack of regular maintenance of the water level gauge plates is that once the gauge plates (staff gauges) are out of range through people or animals knocking them down or disturbances to staff gauges caused by river debris during flood peaks, wrong water level readings are given which will in turn give incorrectly converted flows. Table 5.8 lists the rating curve equations for some of the stations in Kafue basin.

Table 5.8 Rating curves for some Streamflow Gauging Stations in Kafue basin.

Number	Station Name	Discharge rating curve	Water level range
4050	Raglan Farm	$Q = 7.586(H-1.007)^2$ $Q = 3.587(H+1.144)^2$	$H \leq 2.5 \text{ m}$ $H > 2.5 \text{ m}$
4120	Mwambashi	$Q = 2.112(H-0.069)^2$ $Q = 6.168(H-1.223)^2$	$H \leq 2.8 \text{ m}$ $H > 2.8 \text{ m}$
4200	Mpatamato	$Q = 7.507(H+0.619)^2$	All of H
4280	Machiya	$Q = 11.409(H-1.075)^2$	All of H
4350	Chilenga	$Q = 9.716(H+0.291)^2$ $Q = 51.843(H-2.976)^2$	$H \leq 5.5 \text{ m}$ $H > 5.5 \text{ m}$
4450	Lubungu	$Q = 32.665(H-0.509)^2$	All of H
4560	Chifumpa	$Q = 26.533(H+0.484)^2$	All of H
4669	Hook Bridge	$Q = 61.063(H-0.767)^{2.8}$ $Q = 304.938(H-1.531)^{1.395}$	$H \leq 2.2 \text{ m}$ $2.2 < H \leq 6.5 \text{ m}$

Source: Yachiyo, 1995 and Institute of Hydrology, 1994

For the purpose of the Pitman model calibrations in the Kafue basin, observed monthly streamflow volume data were needed. The availability of observed streamflow data therefore strongly influenced the sub-catchment delineation process and 17 gauging stations were available (Table 5.9 and Figure 5.2). The available streamflow record lengths range from 24 years for Itezhi-tezhi (460995) to 43 years for Mswebi (4307). Because of various problems

faced by the Department of Water Affairs in running and maintaining the hydrometric network, most of the stations were closed temporarily and re-opened whenever resources were available. This has compromised the quality of available data because of the many missing data gaps. The only exception for the Kafue basin is the group of stations of vital importance to the hydroelectric power industry, which have better records since they are manned and maintained by the power company ZESCO Ltd. The missing data gaps range from 6 missing months at Kafue Hook Bridge (4669) to 200 missing months at Kangondi (4340). Notwithstanding the missing data gaps, most of the stations have good rating curves and good quality data up to the late 1980s. Therefore for the purpose of model calibration, the periods with the least missing data are used.

5.3.1 Suitability of observed streamflow data for Pitman model calibration

To assess the spatial variability of the observed streamflow data and to investigate the consistency of patterns of streamflow in connected sub-catchments, the data from the 17 stations were subjected to pairwise correlation analysis. Table 5.10 presents distances between the stations (top right part of the matrix) together with the coefficients of determination (R^2 – bottom left part of the matrix). It is assumed that one of the measures of data quality would be the degree of correlation between nearby stations, though in this case the straight map distances are not necessarily a good measure for comparison. This analysis shows that data from most station pairs are well correlated with coefficient of determinations of between 0.7 and 0.9 (Table 5.10). A few outliers exist and these can be mainly attributed to gauge plate errors before correction and maintenance.

Table 5.9 General information on available monthly streamflow data (refer to Figure 5.2 for sub-catchment divisions).

Map Label	Station Number	Sub-catch Area Km ²	Cum. Catch Area Km ²	Sub-catchment Name	Record length	Missing data Months
A	4050	4 999	4 999	Kafue at Raglan Farm	(1960-2001) 41	48
C	4090	2 149	7 148	Kafue at Kafironda	(1959-2000) 41	200
D	4120	869	869	Mwambashi at Mwambashi	(1959-2000) 41	66
E	4150	1178	9,195	Kafue at Wusakile	(1959-2000) 41	122
F	4200	2 460	11 655	Kafue at Mpatamato	(1952-1886) 34	7
G	4205	2 499	2 499	Kafulafuta at Ibenga	(1970-2000) 30	144
H	4260	4 572	18 726	Kafue at Ndubeni	(1962-1997) 35	97
I	4280	4 194	22 920	Kafue at Machiya	(1962-1998) 36	18
K	4340	8 708	8 708	Luswishi at Kangondi	(1970-1999) 29	157
J	4350	2 534	34 162	Kafue at Chilenga	(1969-2000) 32	126
L	4307	16 317	50 479	Kafue at Mswebi	(1950-1993) 43	63
Q	4450	3 963	54 442	Kafue at Lubungu	(1959-1991) 32	86
M	1	8 100	8 100	Lunga at Chipembele	-	-
N	4550	11 455	19 555	Lunga at Kelongwa	(1963-2001) 38	171
O	4560	1 890	21 445	Lunga at Chifumpa	(1959-2001) 42	74
P	2	9 450	9 450	Lufupa at Ntemwa Camp	-	-
R	4669	9 716	95 053	Kafue at Hook Bridge	(1973-2001) 28	6
S	460995	10 619	105 672	Itezhi-tezhi	(1977-2001) 24	11
T	470800	47 138	152 810	Kafue Gorge	(1971-2001) 30	13
U	-----			Zambezi-Kafue confluence	-	-

Table 5.10 Monthly Streamflow data analysis – coefficient of determination and straight map distances.

4050		60	65	80	97	125	107	137	234	160	185	205	225	270	335	410	398
4090	0.936		10	30	60	85	92	130	234	160	180	230	246	285	352	415	365
4120	0.771	0.869		22	52	72	82	120	225	155	175	225	241	275	346	410	358
4150	0.931	0.978	0.922		35	51	70	110	211	142	160	225	239	265	335	395	335
4200	0.887	0.936	0.928	0.968		30	40	80	180	110	128	205	215	235	308	362	305
4205	0.419	0.546	0.540	0.533	0.671		60	92	187	122	140	225	232	245	317	367	285
4260	0.882	0.916	0.861	0.942	0.965	0.590		40	145	70	90	166	173	195	265	325	293
4280	0.894	0.911	0.859	0.941	0.964	0.615	0.983		108	35	52	137	140	160	235	290	275
4307	0.839	0.873	0.735	0.837	0.845	0.529	0.859	0.893		77	58	110	90	60	133	181	233
4340	0.786	0.855	0.684	0.846	0.857	0.532	0.859	0.889	0.908		25	115	116	126	200	258	263
4350	0.869	0.868	0.759	0.899	0.879	0.531	0.928	0.958	0.927	0.922		122	116	115	285	237	240
4550	0.767	0.769	0.703	0.771	0.781	0.509	0.739	0.804	0.663	0.775	0.717		30	98	150	235	345
4560	0.696	0.697	0.633	0.679	0.730	0.536	0.719	0.758	0.624	0.628	0.687	0.918		68	120	203	322
4450	0.857	0.840	0.716	0.811	0.824	0.387	0.864	0.888	0.896	0.797	0.902	0.727	0.712		75	143	268
4669	0.774	0.785	0.715	0.847	0.819	0.513	0.866	0.899	0.864	0.885	0.923	0.815	0.803	0.841		92	301
460995	0.420	0.389	0.275	0.477	0.486	0.205	0.484	0.498	0.495	0.501	0.648	0.521	0.482	0.605	0.695		268
470800	0.147	0.137	0.115	0.169	0.130	0.114	0.146	0.196	0.197	0.179	0.211	0.16	0.179	0.11	0.296	0.282	
	4050	4090	4120	4150	4200	4205	4260	4280	4307	4340	4350	4550	4560	4450	4669	460995	470800

Top right of the table – straight line map distances

Bottom left of the table – coefficient of determination

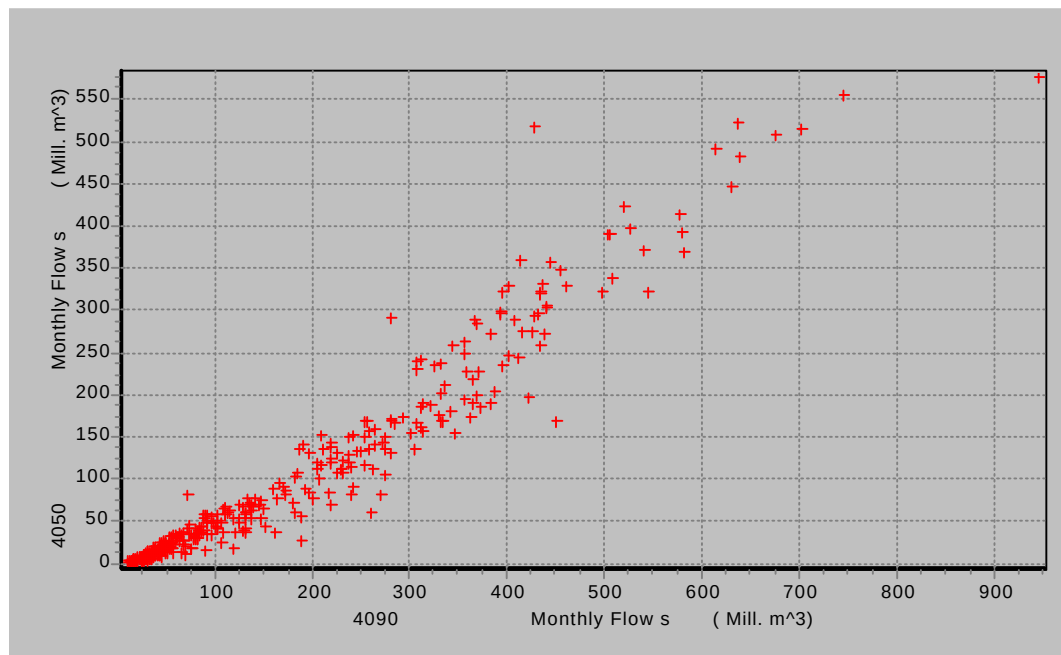


Figure 5.24 Kafue river at Kafironda (4090) against Kafue river at Raglan Farm (4050), R^2 of 0.936.

The tributary flows are less well correlated with the main river system flows because of differences in the hydrological response to rainfall events over the catchment; however, there is a very good correlation between the stations on the same tributary streams (Figure 5.24, for example). For the Lunga sub-catchment (stations Chipembele (1), Kelongwa (4550) and Chifumpa (4560)), the correlation between the upper and lower basin station data is high with an R^2 value of 0.9. This initial result indicates that the data are consistent and suggests good quality (Figure 5.25). However, there is an anomaly between the upper basin flows and the lower basin flows, in that the Upper basin 4550 (19 555 km²) gives higher flows than the lower basin 4560 (21 445 km²) for all flows equal or lower than 1 100 MCM while the lower basin shows higher extreme flows (greater than 1100 MCM). Moreover, the base flows for the lower basin are lower than the baseflows for the upper basin. This indicates some problems in the data quality of the two stations, as there are no wetlands or water abstractions in between these stations to account for the observed losses. Kelongwa data may be suspect, as it has 171 missing data months for the record length of 38 years, indicating poor station maintenance and irregular discharge measurements. As the relationship between the two data sets is quite good, the problem is expected to be related to the established rating curve for Kelongwa, which may be giving higher flow values than really occur. In the case of these two

stations, the flow simulation results may be able to help with determining the station which has flows closer to the natural flows.

The two outliers above the general distribution trend in Figure 5.25 are Chifumpa (4560) data plotted against the missing data (-9.9) for Kelongwa (4550) for February 1982 and for May 1985 (a problem with the TSOFIT computer program); however, the outlier below the general distribution trend has an anomalous figure for Kelongwa for the month of March 1994 of 1 168 MCM against 492 MCM for Chifumpa. The Kelongwa figure appears in a row of missing monthly data, which may be an indication of poor data entry and therefore should be disregarded.

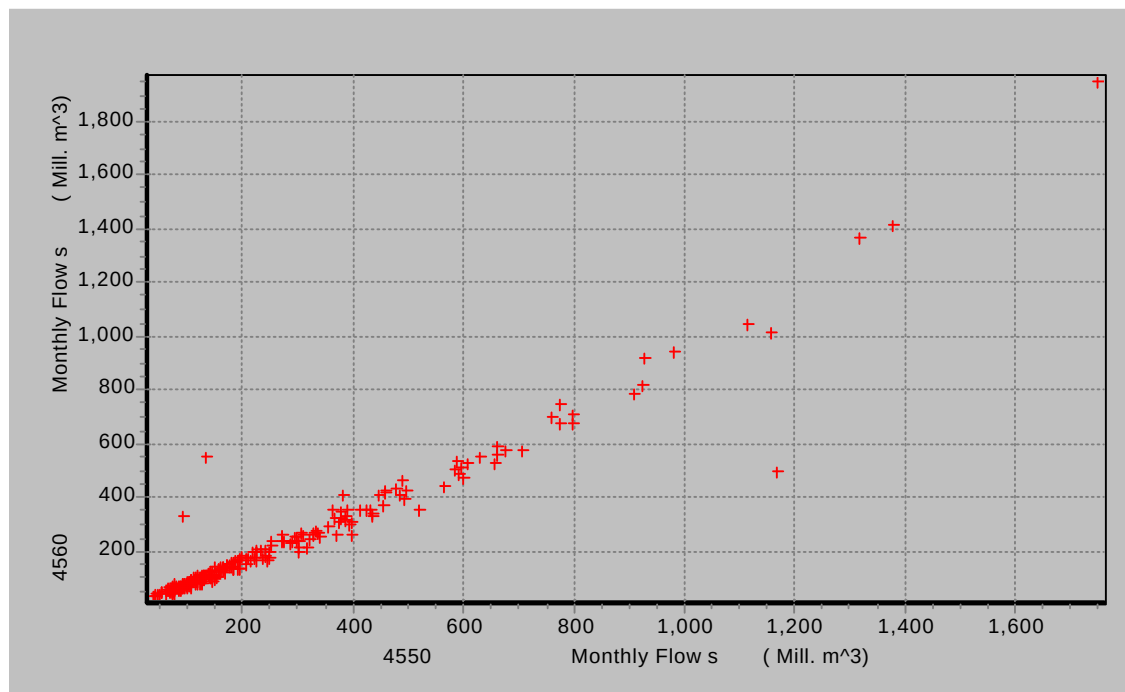


Figure 5.25 Tributary flows for Lunga at Chifumpa (4560) against Lunga at Kelongwa (4550) with R^2 of 0.918

The regulated flow stations (reservoir outflows) generally have poor relationships with other stations, having R^2 values of 0.1 to 0.6. The Itzhi-tezhi (ITT) reservoir (460995) outflows, especially for peak flows of 1 000 MCM and above, tend to show a good correlation with the peak flows of the upstream station of Hook Bridge (4669) (Figure 5.26). However outliers observed below the general trend, can be accounted for by high flows at Hook Bridge and very low outflows from the ITT reservoir for years preceding very dry years in order to allow

for filling of the reservoir. Outstanding are the flows of February 1984 (Hook Bridge was 2 204 MCM – ITT was 592 MCM) and March 1992 (Hook Bridge was 2 893 MCM – ITT was 734 MCM). A few outliers are observed above the general trend showing reservoir outflows which are higher than the inflows from Hook Bridge, these represent deliberate drawing down of the reservoir in anticipation of flood flows in very good rain years.

The Kafue Gorge reservoir outflows show a very poor correlation with all the stations including the upstream ITT reservoir outflows. This may be partly explained by the losses that occur over the extensive wetland, the Kafue Flats. The Kafue Flats are very flat and peak flood travel time is estimated at 2 months over a distance of 353 km. It is also related to the fact that releases are made from Kafue Gorge reservoir for hydro-power generation.

The impact of wetland losses is also observed in the differences in peak flows at the stations before and after the Lukanga swamps. Considerable losses are observed to occur from the Kafue river flood flows into the Lukanga swamps. For a wet year of 1979/80, Chilenga (4350) gauging station, which is a station just before the Lukanga swamps and has a catchment area of 34 162 km², experienced a peak flow of 1 533 MCM, while Mswebi which is just after the Lukanga swamps and has a catchment area of 50 479 Km² had a peak of 1 096 MCM (Figure 5.27). The effect of this wetland should be taken into account when it comes to model calibration, especially for the sub-catchment upstream of Mswebi (4307) gauging station.

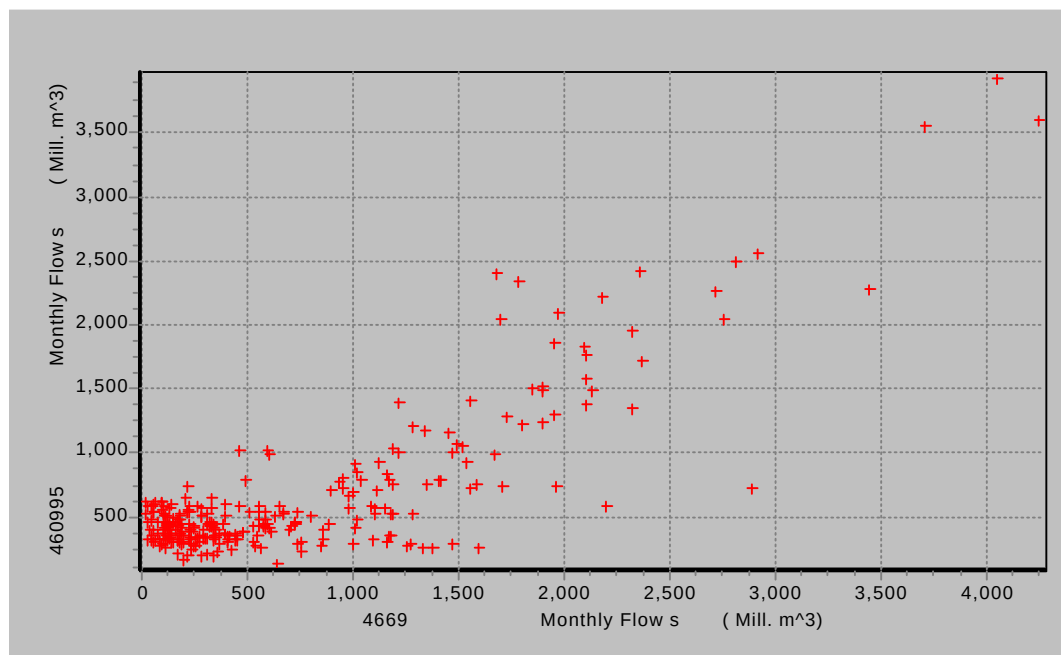


Figure 5.26 Kafue river at Hook Bridge (4669) against Itezhi-tezhi (460995) reservoir outflows with an R^2 of 0.695.

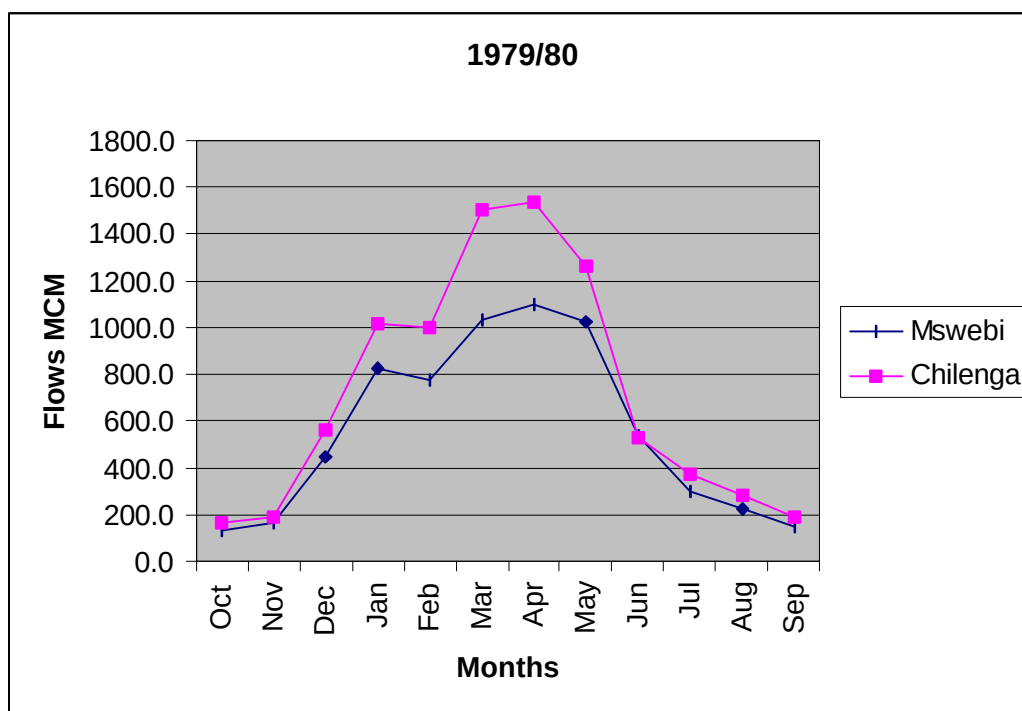


Figure 5.27 Flow losses to Lukanga Swamps between Chilenga (4350) and Mswebi (4307).

The quality of data for the non-regulated flows appears to be reasonable and can be considered largely suitable for calibrating the Pitman model for the Kafue basin to simulate historical flows. However, special consideration should be made when calibrating the model for the sub-catchments with wetlands and reservoirs, taking into account the evaporation losses, reservoir water regulation rule curves and water abstraction for domestic and agricultural purposes.

5.4 EVAPORATION DATA FOR THE KAFUE BASIN

Catchment monthly evaporation data, required for running of the Pitman model, is derived from Class A-pan evaporation, which is measured in the 36 main meteorological stations country wide. The main meteorological stations are manned by full time workers and therefore data from these stations are of sufficiently good quality. The data which were used in this study are derived from the collection done during the compilation of the Water Resources Master Plan (Yachiyo, 1995).

Table 5.11 provides the evaporation data details for the Kafue basin. The monthly distributions of evaporation were converted to percentages of the annual totals and entered into the database as a requirement for the Pitman model. The mean annual evaporation values for each sub-catchment were converted to S-pan values and entered in the Pitman model parameter tables. The Pitman model uses S-pan evaporation values and therefore the evaporation data were converted from A-pan values to S-pan values using the following conversion factor.

Conversion of mean annual evaporation (MAE) as derived from Class A-pan data to equivalent Symons pan MAE:

$$(S\text{-pan}) = 130 + 0.726 \times \text{MAE (A-pan)}$$

Conversion of monthly pan readings (after Bosman, 1990)

$$(S\text{-pan}) = -16.2354 + 0.8793 \times (\text{A-pan})$$

or

$$(\text{A-pan}) = 26.3622 + 1.0786 \times (\text{S-pan})$$

Various figures have been estimated for the mean annual evaporation for the Kafue basin, Table 5.12 presents these together with the methods of estimation used by a number of researchers.

Table 5.11 General information on available A-pan evaporation data.

Map Label	Sub-catchment Name	Nearest Meteorological station data used	Period of data	A-pan MAE	S-pan MAE
A	Kafue at Raglan Farm	Solwezi	1977 - 1990	2 080	1 640
C	Kafue at Kafironda	Kafironda	1973 - 1993	1 892	1 504
D	Mwambashi at Mwambashi	Kafironda	1973 - 1993	1 892	1 504
E	Kafue at Wusakile	Kafironda	1973 - 1993	1 892	1 504
F	Kafue at Mpatamato	Ndola	1963 - 1992	1 838	1 464
G	Kafulafuta at Ibenga	Ndola	1963 - 1992	1 838	1 464
H	Kafue at Ndubeni	Ndola	1963 - 1992	1 838	1 464
I	Kafue at Machiya	Ndola	1963 - 1992	1 838	1 464
K	Luswishi at Kangondi	Ndola	1963 - 1992	1 838	1 464
J	Kafue at Chilenga	Kabwe	1977 - 1993	2 105	1 658
L	Kafue at Mswebi	Kabwe	1977 - 1993	2 105	1 658
Q	Kafue at Lubungu	Kabwe	1977 - 1993	2 105	1 658
M	Lunga at Chipembele	Kasempa	1959 -1967	1 847	1 471
N	Lunga at Kelongwa	Kasempa	1959 -1967	1 847	1 471
O	Lunga at Chifumpa	Kasempa	1959 -1967	1 847	1 471
P	Lufupa at Ntemwa	Kaoma	1967 - 1993	1 845	1 470
R	Kafue at Hook Bridge	Kaoma	1967 - 1993	1 845	1 470
S	Itezhi-tezhi	Magoye	1967 - 1993	1 991	1 576
T	Kafue Gorge	Kafue Polder	1961 - 1990	2 122	1 671
U	Zambezi-Kafue Conf.	Kafue Polder	1961 - 1990	2 122	1 671

Table 5.12 Summary of annual open water evaporation estimates (mm) for the Kafue basin.

Method of Estimation						
A-Pan	Water Balance		Morton	Penman		
(All reliable data)	Sharma	SLHP	Sharma	Sharma	DHV	SLHP
2 030	1 800	1 620	1 500	1 790	2 050	1 770 or 1 620

5.5 EVAPORATION DATA FOR THE KAFUE FLATS

Despite the changes caused to the natural flow pattern of the river by hydropower development, there is one feature which has not changed and that is the high evaporation on the plains. Several estimations of evaporation loss for the Kafue flats exist using various methods. Ellenbroek measured evapotranspiration in Lochinvar National Park on the plains from 1978 to 1981. It was found that the monthly average of daily evapotranspiration ranged between 4.1 to 7.4 mm d⁻¹. Sharma made the same computation with data compiled from various places in the Zambian headwaters. He found an average daily evapotranspiration of 3.8 mm d⁻¹ from December through March. The corresponding mean value on the Kafue Flats was 5.1 mm d⁻¹ (Institute of Hydrology, 1994).

The capacity of the main channel of the Kafue River in the middle of the Flats around Lochinvar is said to be 170 m³s⁻¹. This capacity is now exceeded by about 13 m³s⁻¹ most times of the year and therefore has resulted in the formation of permanent lagoons where temporary aquatic habitats existed before. The increase in permanently flooded areas is reflected in higher evaporation. FAO (1968) estimated the evaporation in the flats to be 1 850 MCM in a water balance for the dry year 1963/64 - before the regulation, while a total evaporation of 2 352 MCM was estimated in the Flats for the dry year 1972/73 as obtained by DHV Consulting Engineers (1980). Therefore regulation of flows in the Kafue Flats has increased evaporation losses by 23.5% more than that which occurred before regulation, because of the increase in areas of permanent inundation. It is these increased areas of inundation which led to the proposal for the construction of canals and levees to try and increase the capacity of the main river channel (DHV, 1980).

The effect of weed proliferation has been discussed in detail by DHV (1980) and the Institute of Hydrology (1994). As a consequence of the past analysis, Shawinigan (1990a) in their simulation of the Itezhi-tezhi and Kafue Gorge system, adjusted estimates of open water evaporation upwards for the Kafue Gorge reservoir because of the weed coverage in the water body. A factor of 1.3 was recommended for application to the open water evaporation. Table 5.13 provides estimates of evaporation in Kafue flats.

Table 5.13 Mean monthly A-pan evaporation estimate for the Kafue flats.

	DHV (1980)										SHP (1990a)		IH (1994) Study		
	Kasaka			Namwala Pontoon			Kafue Polder		MT. Makula		Kasaka	Namwala Pontoon	Itezhi-tezhi	Kafue Polder	Nakam bala
	1959-1968	1963-1968	1971-1977	1959-1968	1963-1968	1971-1977	1963-1970	1968-1977	1963-1970	1968-1977			1978-1994	1968-1994	1965-1994
Jan	143	136	130	158	164	164	149	149	124	124	137	155	177	130	136
Feb	102	122	102	138	147	141	130	130	113	116	117	130	143	121	121
Mar	152	161	127	174	183	171	164	164	146	133	150	169	165	143	143
Apr	144	150	138	165	174	156	180	162	150	144	150	165	200	150	155
May	143	143	136	155	164	155	162	150	138	141	142	148	198	146	154
Jun	126	126	126	132	138	135	138	138	123	129	127	128	175	132	140
Jul	143	140	136	146	152	152	164	155	143	158	140	144	193	146	160
Aug	186	186	177	186	195	189	186	189	198	192	185	186	246	183	205
Sep	234	231	225	237	240	249	225	219	255	258	238	234	304	222	248
Oct	291	279	267	288	288	295	270	233	288	279	290	279	310	245	267
Nov	198	207	216	225	213	249	189	201	201	204	202	187	246	201	204
Dec	155	161	149	174	189	202	146	158	152	143	150	162	200	146	156
TOTAL	2016	2041	1930	2178	2248	2257	2103	2048	2031	2021	2028	2087	2556	1965	2089
	Mean 1959-1977 = 1973			Mean 1959-1977 = 2218			Mean 1963-1977 = 2076		Mean 1963-1977 = 2026						

Source: Institute of Hydrology, 1995

5.6 WATER USE INFORMATION

5.6.1 Natural flood control features

The Kafue basin has two major natural flood control features, which contribute to the low yield of catchment outflows compared to the catchment average rainfall. The Kafue has a mean annual flow of $350 \text{ m}^3\text{s}^{-1}$ near the confluence with the Zambezi River. The mean annual flow represents only 6.2% of the mean annual rainfall of 1057 mm falling over the basin. This low-yielding hydrological regime is greatly influenced by the geological and geomorphological setting of the basin, the main features of which the Lukanga Swamps and the extensive Kafue Flats, have been known to contribute extensively to water losses through evaporation.

Lukanga swamps

The Lukanga Swamps are extensive, covering an area of $2\,600 \text{ km}^2$ at peak water level and have a shallow average depth of 6.1m. The capacity of the swamp depression between its average low water level and maximum water level is said to be about $7\,398 * 10^6 \text{ m}^3$. The Lukanga Swamps constitute one of the major wetlands of the Kafue River System. It is said that the Lukanga falls into the category of a sidestream reservoir for the flood flows of the Kafue River (Balek, 1971). They are located between latitudes 13.5° to 14.50° south and longitudes 27.15° to 28.10° east, in the central part of the Kafue basin.

Considerable losses are observed to occur from the Kafue river flood flows into the Lukanga Swamps. For the wet year of 1978/79, Chilenga gauging station, which is a station just before the Lukanga swamps and has a catchment area of $34\,162 \text{ km}^2$ had a peak flow of $2\,165 * 10^6 \text{ m}^3$, while Mswebi which is just after the Lukanga swamps with a catchment area of $50\,479 \text{ km}^2$ had a peak flow of $1\,517 * 10^6 \text{ m}^3$ (Figure 5.28). The effect of this wetland should be taken into account when it comes to model calibration especially for the sub-catchment upstream of Mswebi gauging station.

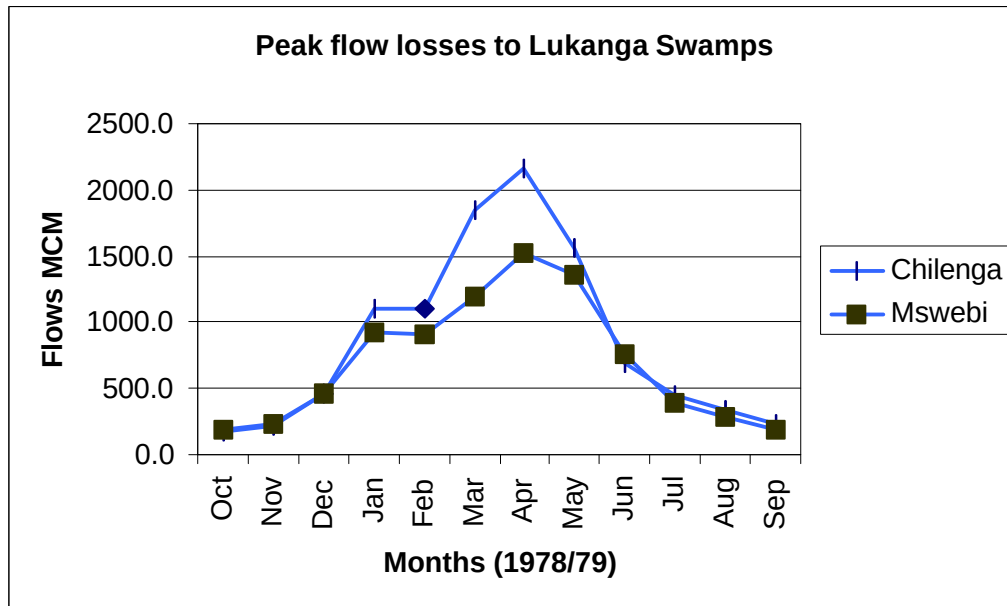


Figure 5.28 Peak flow losses to Lukanga swamps.

Kafue Flats

The Kafue flats is the second biggest flood plain in Zambia, extending for about 353 km long and covers an area of 6 500 km², comprising the Kafue main river channel, lagoons and swampy areas. For most of this river reach, the Kafue meanders through a large flat grassland flood plain, with a minimum elevation of 1 065 mamsl and the height difference between Itezhi-tezhi dam and Kafue Gorge being only 15 m over a distance of 353 km. The main lagoons are, Chansi, Chunuka, Luwato, Namatanga, Namwala and Lukwato. The evaporation losses over this area are considerable with annual pan-evaporation being estimated as 2203 mm (Institute of Hydrology, 1994). The Kafue flats area is said to act as a natural reservoir with a natural outlet at Nyimba, which is about midway from Itezhi-tezhi to Kafue Gorge

5.6.2 Reservoirs

The Lower Kafue basin system is considered to have three reservoirs; Itezhi-tezhi, which is the main reservoir; Kafue flats, a natural reservoir with a natural outlet at Nyimba and the Kafue Gorge reservoir downstream. The two reservoirs in the lower Kafue basin were constructed mainly for water storage to meet the needs of a hydroelectric power generation scheme.

Kafue Gorge Reservoir

The Kafue Hydroelectric Scheme involved two phases of construction. In the first phase, a dam and a 900 MW power plant were constructed at Kafue Gorge. The dam at Kafue Gorge was completed and commissioned in 1971. The maximum storage of $900 \times 10^6 \text{ m}^3$, results in the upstream inundation of a reservoir area of $1\,180 \text{ km}^2$, while the minimum storage of $218 \times 10^6 \text{ m}^3$ results in a reservoir surface area of 460 km^2 . However, because of the low topography, the reservoir is very shallow and therefore evaporation losses have been estimated to show an increase of 60 percent over that of free water surface evaporation (Shawinigan, 1993). Therefore, the principle of operation is to keep the Kafue Gorge reservoir elevation at the lowest level possible to reduce evaporation losses. The reservoir at this minimum level has enough storage to meet the required variation in power generation from day to day, week to week and month to month. The travelling time, estimated at two months, which the water from Itezhi-tezhi will take to reach Kafue Gorge reservoir is the main function for determining the Kafue Gorge reservoir storage.

The normal operation rule curve of the Kafue Gorge Reservoir is that the reservoir will be at the minimum elevation of 975.40 m (storage of $218 \times 10^6 \text{ m}^3$) in the period August to November; the level will rise from December onwards to the full retention level of 976.6 m (storage of $900 \times 10^6 \text{ m}^3$) which will be maintained until the following March – April to August from the inflow of tributaries between Itezhi-Tezhi and Kafue Gorge and the spilling from Itezhi-tezhi reservoir. This operation is subject to minor modifications according to the hydrological condition in the year. Such modifications, however, do not affect the absolute upper and lower limits of storage but only affect the period of the year when these levels are maintained.

Since the power plant requires a minimum flow of $120 \text{ m}^3 \text{ s}^{-1}$ to maintain its firm energy target of 450 MW, it became necessary to construct an upstream storage reservoir at Itezhi-tezhi.

Itezhi-tezhi Reservoir

In order to guarantee the flow of $120 \text{ m}^3 \text{ s}^{-1}$ flow throughout the year, to meet the needs of the Kafue Gorge power station, in the second phase of the hydroelectric project, another dam was

built at Itezhi-tezhi, 450 km upstream of Kafue Gorge. This dam was completed and commissioned in 1977. The resulting reservoir has an area of about 300 km² and a live storage capacity of $4\,925 \times 10^6 \text{ m}^3$, equivalent to 56% of the long-term mean annual flow into the reservoir. The power company, ZESCO Ltd. operates both the Kafue Gorge and Itezhi-tezhi dams (Shawinigan, 1993).

Regulation of the river to maximise the power generation potential at Kafue Gorge Power Station, was found to be necessary but could not be effected entirely at the Kafue gorge reservoir, which would entail flooding the Kafue Flats, and so regulation is consequently effected upstream of the Kafue Flats at Itezhi-tezhi Dam. Regulated flows are routed through the flats area from Itezhi-Tezhi reservoir to the Kafue Gorge reservoir. The travel time of the water from Itezhi-tezhi to Kafue Gorge is estimated at two months because of the routing through the Kafue flats natural reservoir. The outflows from Itezhi-tezhi that are required to satisfy power generation at Kafue Gorge have been calculated for a dry year (1972/73) and are given in Table 5.14. Under the operation rule, a storage of $3\,400 \times 10^6 \text{ m}^3$ is required in the Itezhi-tezhi reservoir to meet the following year's requirement, if the previous year is dry. It also stipulates that once the reservoir refills, it would be kept at the full retention level of 1 030 m as long as possible.

Table 5.14 Itezhi-tezhi reservoir outflow requirement.

Months	ITT reservoir outflow required (m³/s)
January	180
February	210
March	300
April	200
May	230
June	240
July	240
August	240
September	240
October	220
November	220
December	180

5.6.3 Water abstraction in the Kafue basin

The data regarding water abstraction has been taken from the register of water rights maintained by the Water Development Board. The data provide an indication of the water allocation within the basin and may not represent the actual abstractions. However, for the purposes of modelling, the data are considered to be sufficient to show indications of the amount of water abstracted from each sub-catchment.

Most demand and water rights are concentrated in the upper and lower reaches of the basin with an intervening middle basin with low demand and few water rights. Domestic, industrial and agricultural sectors dominate the upper basin while agriculture and hydropower demand dominate the lower basin.

The Kafue River is subjected to the heaviest water demand in Zambia from the point of view of water rights and water abstraction. About 283 water rights totaling $1\,078 \times 10^6 \text{ m}^3$ per year represent direct water abstractions for both domestic/industrial and agricultural abstractions. ZESCO Ltd holds the biggest water right of $15\,137 \times 10^6 \text{ m}^3$ per year in the lower Kafue basin, but this is a non-consumptive water right, as it does not take the water out of the system. Water is stored in reservoirs and used to drive the turbines for electric power generation. Table 5.15 gives an outline of the water abstraction for sub-catchments, while Figures 5.29 and 5.30 provide a graphical presentation of water abstractions by sectors for sub-catchments and illustrates the extent to which these have changed over time on the basis of known water abstraction rights, rather than actual abstraction amounts).

Table 5.15 Summary of water abstraction data for Kafue basin.

Sub-catchment	No. of water users	Purpose	Quantity MCM/YEAR
C	7	Domestic / industrial supply	58.81
C	26	Agricultural use	13.71
D	2	Domestic / industrial supply	0.63
D	13	Agricultural use	3.52
E	5	Domestic / industrial supply	78.20
E	24	Agricultural use	14.11
F	3	Domestic / industrial supply	13.18
F	35	Agricultural use	9.93
G	1	Domestic supply	0.02
G	5	Agricultural use	2.75
H	7	Domestic / industrial supply	21.09
H	103	Agricultural use	172.85
I	3	Agricultural use	1.02
M	1	Domestic supply	2.63
M	1	Agricultural use	0.33
P	1	Domestic supply	0.32
S	1	Domestic supply	0.73
T	6	Domestic / industrial supply	117.81
T	39	Agricultural use	566.77
Total Consumptive abstraction			1 078.41
T & S	1	Electric power generation (non-consumptive)	15 137.28

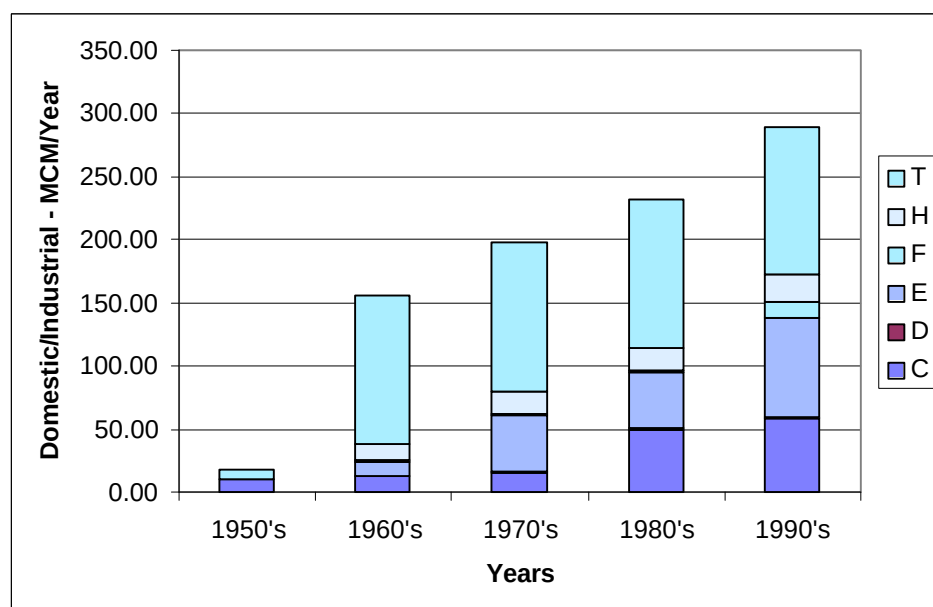


Figure 5.29 Domestic / Industrial water abstraction in the Kafue basin.

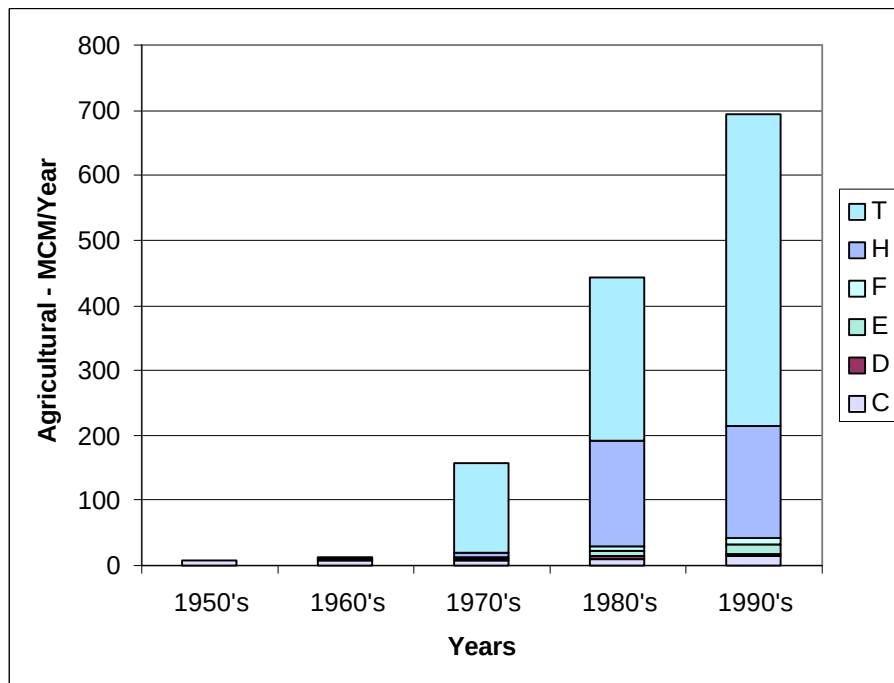


Figure 5.30 Agricultural water abstractions in the Kafue basin.

6 INITIAL CONFIGURATION OF THE MODEL

This section attempts to describe the initial configuration of the Pitman model with consideration given to the various physical characteristics of the basin in order to enhance the model calibration for the Kafue River basin.

6.1 INITIAL CONFIGURATION OF THE PITMAN MODEL FOR THE KAFUE BASIN

For the most of the Kafue basin (see Figure 6.1), there are no special model configuration requirements. One minor exception to this is the need for a time series of transfer inflows to represent the mine waste pumping within sub-catchment C. Two major exceptions are the configurations required for the Lukanga swamps (from the outlet of J down to Q) and the sub-catchments and reservoirs from sub-catchment S downstream (which includes the Kafue flats).

6.1.1 Lukanga Swamps

The physical setting of the Lukanga swamps is described in section 5.6.1 and can be seen in Figure 5.6, while flow anomalies can be seen from Figure 5.28. Comparison of the observed monthly flows for the outlets of sub-catchments J and L suggests that flow to the swamps occurs in months with flow volumes greater than 800 Mm³. There appears to be very little flow out of the swamps back into the Kafue channel and this only occurs during wet years.

There are no model components that have been designed to cater for this type of process, although channel losses have been frequently simulated using ‘dummy’ reservoirs to represent either evaporative or channel bed seepage losses. The same approach has been used here to represent the storage and losses from the incremental catchment L. A reservoir has been established in the model for catchment L (Figure 6.2, Dam B, maximum volume = 7400 Mm³) with a large surface area to represent the swamp, through which all the runoff from catchment L is routed. However, the original spatial configuration of the model had flows from J being routed through L to Q. Establishing a reservoir at the outlet of catchment L would suggest that all the upstream flow of the Kafue would have to pass through the reservoir representing the swamps. To prevent this and to represent reality more accurately,

outflows from J have been re-routed into Q (bypassing L). In addition, the area of Q has been increased and L decreased, so that the part of L that does not contribute to the swamps bypasses the ‘dummy’ reservoir (Dam B).

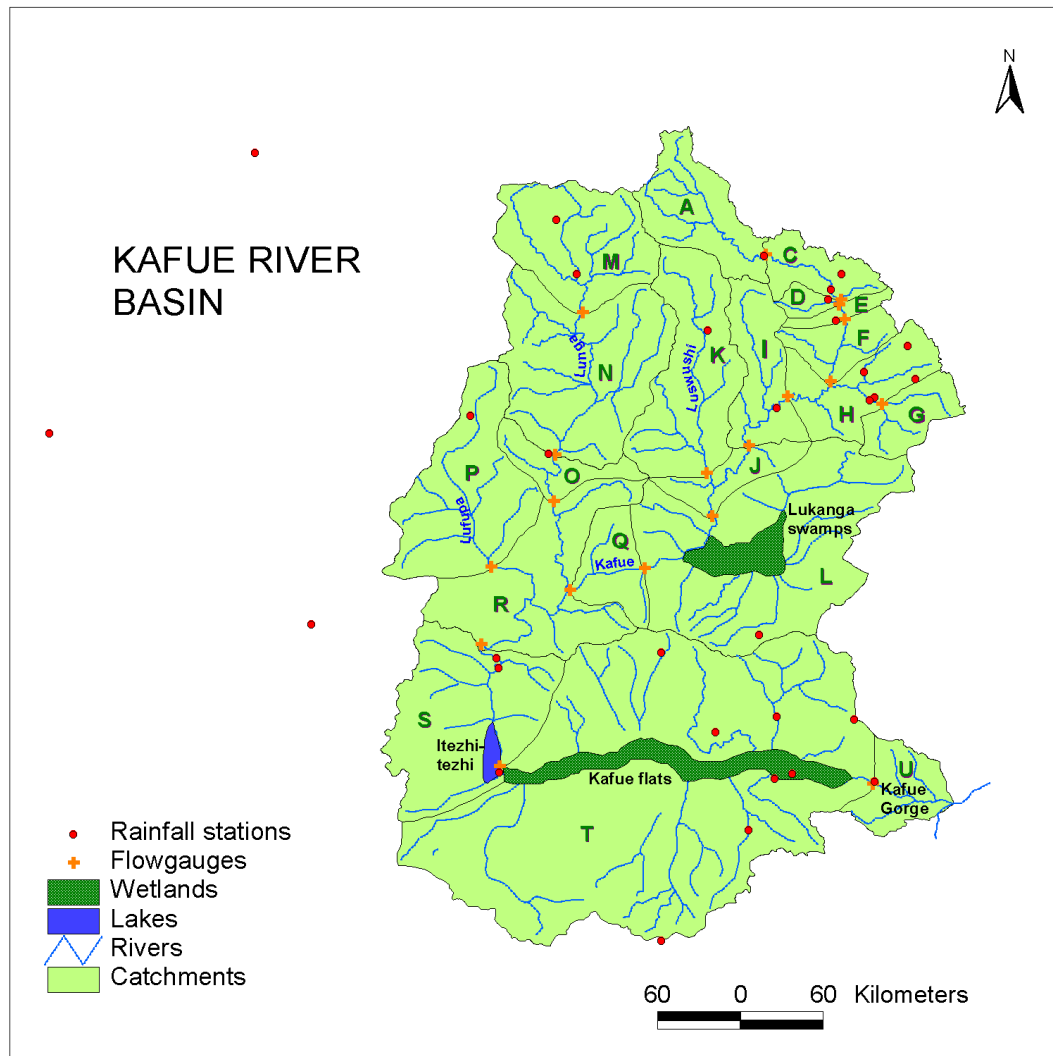


Figure 6.1 Kafue basin showing the sub-catchments used for model calibration.

This type of approach cannot be used for the spillage from the main Kafue channel into the swamps and therefore a more complex and multi-step approach had to be adopted. The first step was to calibrate the outflows from J without a dam against the observed data at that point and then edit the simulated flows at the outlet of J, decreasing all the monthly flows with volumes greater than 800 Mm^3 to a value of 800 Mm^3 . A relatively small ‘dummy’ reservoir ($1\,000 \text{ Mm}^3$; Dam A in Figure 3.11) was then established at the outlet of J and the edited time series generated by the first step used as a high priority downstream flow requirement on this

dam. The surface area to volume ratio of the reservoir was set to a low value to minimise simulated evaporative losses, such that the downstream requirement would always be met. An ‘abstraction’ demand ($1\,000\text{ Mm}^3$) was then established to represent the outflow from the channel into the swamps. The ‘operating rules’ were set such that the reservoir would have to be 98% full for the complete demand to be met, while progressively lower demands were established for 90%, 80%, 60% and 40%. The effect of this conceptual design is that during inflows of less than 800 Mm^3 the downstream requirement is the same as the inflows, the reservoir remains relatively empty and there are no abstractions. During higher flows the reservoir starts to fill and the abstractions increase. The objective of the calibration exercise was to set the different demand levels to values that gave a satisfactory pattern of spill volume. These are then added to the downstream requirement plus any outflows from L and Q to generate an acceptable time series of flows at the outlet of Q (calibrated against observed flows at this point). The calibration exercise involved two iterative steps, as the ‘abstractions’ from the reservoir at the outlet of J become transfer inflows into L. The modelling process is illustrated in Figure 6.2

The calibration process effectively prevents the observed flows at the outlet of L (which is on the main Kafue channel) from being used, as in the model these are only outflows from the swamps. However, after an examination of the observed flows at the outlets of J, L and Q, it appears that J and Q are more consistent with each other, while L appears to be somewhat anomalous. While there is no certainty that the model configuration is truly representative of the real processes, acceptable results have been obtained with parameter values that are consistent with calibrations for other parts of the Kafue catchment.

6.1.2 Itezhi-tezhi dam, Kafue Flats and Kafue Gorge dam

The configuration of the two dams is relatively straightforward. Itezhi-tezhi dam has been established at the outlet of sub-catchment S with a capacity of $4\,925\text{ Mm}^3$ and an area of 475 km^2 at full supply. The latter is higher than the stated area, as it was found that the evaporation losses appeared to be too low. The release estimates given in Table 5.3 (an annual total of about $7\,100\text{ Mm}^3$) did not seem to match the pattern of observed outflows and were reduced to give an annual total of $4\,925\text{ Mm}^3$. These were then reduced at dam volumes of 70% of capacity and lower.

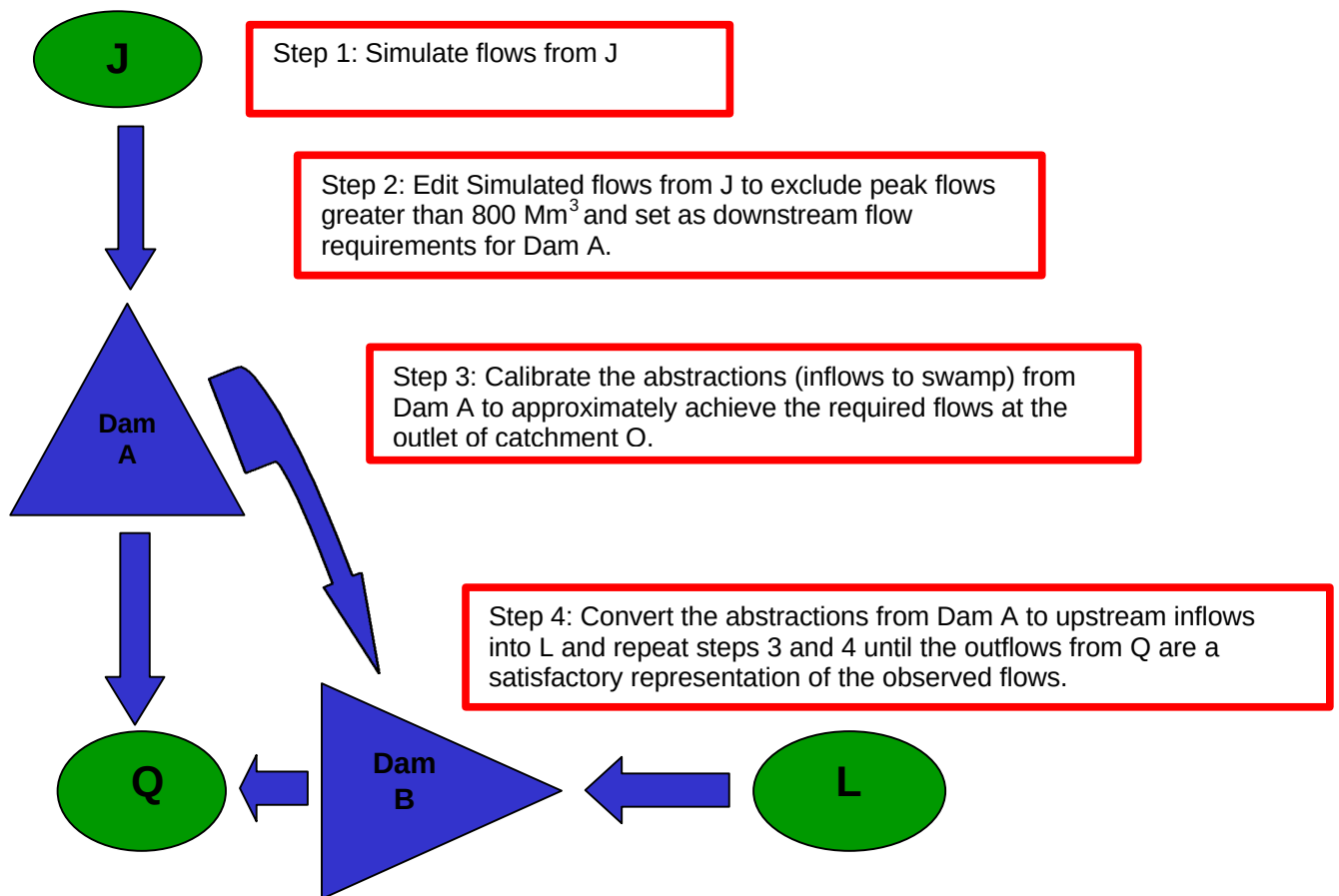


Figure 6.2 Diagrammatic representation of the model setup and calibration steps for sub-catchments J, L and Q.

Kafue Gorge dam has been established at the outlet of U with a capacity of 900 Mm³ and an area of 1 165 km² at full supply. This conforms with the known facts about the reservoir. The area of sub-catchment U was set at 15 000 km² (and the area of T reduced by the same amount) to represent that part of T that lies downstream of the main floodplain. This also allowed a separate ‘dummy’ dam to be placed at the outlet of T to represent the Kafue flats floodplain storage. The maximum release (at full supply) was set to 6 000 Mm³ y⁻¹ (or 190 m³ s⁻¹) and reduced when the dam reached 50% of capacity and lower.

The ‘dummy’ dam representing the Kafue flats has been established with a capacity of 6 500 Mm³ and an area of 3 250 km² at full supply, decreasing linearly with volume. As this ‘dam’ is required to have continuous outflow and yet its volume and area should fluctuate seasonally, it is not possible to simulate downstream flows as spillage. It was therefore necessary to assess (using the observed outflows from the Kafue Gorge dam during wet years) the likely outflows from the floodplain in advance of modelling and set these as

‘releases’ for different storages in the ‘dam’. Table 6.1 lists the levels at which the different releases apply and it was found to be sufficient to establish the same ‘release’ volume for all months. This is because the reduced inflows during the dry season ensure that the ‘dam’ volume decreases and therefore the outflows decrease.

Table 6.1 Release operating rules for the dummy dam representing the Kafue flats floodplain.

Volume (% Capacity)	> 90	89-75	74-50	49-25	24-10	<10
Release (Mm ³ mnth ⁻¹)	2500	1995	1468	1012	744	506

Assessing the usefulness of these unusual approaches to simulating both the Kafue flats and the Lukanga swamps, without modifying the structure of the model, forms part of the assessment of its applicability to the Kafue basin. This issue will be discussed in more detail after the final calibration results are presented.

6.2 CALIBRATION PROCEDURES

6.2.1 Manual Calibration

The calibration exercise began with a number of trial model runs using the sub-catchments M to O, as well as A to E. The purpose of these initial runs was to try and establish fixed values for many of the parameter values and therefore exclude them from the more detailed calibration process covering all the sub-catchments. Those parameters that were fixed during the first part of these early trial runs were RDF (0.8 – see section 5.2.2), PI1 and PI2 (1.5 and 4.0), FF (1.4), SL (0), POW (4.0), R (0.2), TL and GL (0.25 and 3.0 or 4.0). It was then necessary to decide if the absorption rate parameters ZMIN, ZAVE and ZMAX could remain fixed.

South African experiences with the Pitman model suggest that in humid climates the absorption rate parameters should be set to high values such that runoff is not generated by this component of the model, regardless of the monthly rainfall total. This is based on the premise that vegetation cover is usually quite dense, soils well developed and infiltration rates relatively high. However, it was noted that many of the rainfall events in the early part of the Kafue wet season are characterised by high intensities and short durations (see Figures

5.12, 5.15 and 5.18). These can generate early wet season runoff responses before the dry season moisture deficits have been satisfied. This implies that the surface runoff functions of the model involving the absorption rate parameters do play a role. After a range of model tests were undertaken it was decided to fix these parameter values at ZMIN = 200, ZAVE = 500 and ZMAX = 1200. Table gives the results of the initial manual calibration for sub-catchments A, C, D, E and F.

Table 6.2 Initial manual calibration results for Sub-catchments A, C, D, E and F.

Sub – Catch.	Parameters						Normal CE	MM % Error	Ln CE	MM % Error
	ZMIN	ZAVE	ZMAX	ST	FT	POW				
A	200	500	1200	1200	105	4.0	0.738	8.1	0.631	11.8
C	200	500	1200	1200	105	4.0	0.786	8.2	0.757	5.8
D	200	500	1200	1200	105	4.0	0.515	6.5	0.476	12.3
E	200	500	1200	1300	55	4.0	0.827	-9.8	0.892	-1.3
F	200	500	1200	1300	55	4.0	0.852	0.5	0.893	1.5

6.2.2 Automatic Calibration

During the initial simulations the usefulness of the automatic optimisation procedure was also assessed. One of the problems is that the rainfall inputs to the model are known to be less than perfect as they are based on a limited number of gauges and it is highly unlikely that the true spatial distribution of rainfall is correctly represented in all months. This problem can be accommodated during manual calibration, in that single months can be largely ignored in favour of a generally acceptable correspondence between observed and simulated flows. The automatic calibration procedure cannot account for this and simply generates parameter values that are the best fit given the calculated objective function. The objective function used in the automatic calibration procedure is the mean of the coefficients of efficiency (CE) based on untransformed data and on log transformed data. This was established in the model to try and avoid a bias to either high or low flows. In manual calibration, efforts are made to obtain high values for both these coefficients as well as minimising differences in the observed and simulated monthly means and standard deviations. It was found that the automatic optimisation process could generate small improvements in the CE values, but at the expense of errors in the simulated means. This suggests that a more complex objective function might be required.

The automatic calibration tests were done on sub-catchments A to F in the Upper Kafue basin in order to assess the performance of an automatic optimiser and its usefulness in improving the simulation results and confirming parameter ranges. In this regard two sets of calibration experiments were undertaken.

Automatic Calibration – Experiment A

In this experiment, the parameters for all sub-catchments were optimised, but each run excluded some catchment observed flows to see how that would affect the quality of the simulation. In this regard the following runs were undertaken:

- A1: Optimisation based on observed flows for sub-catchment F.
- A2: Optimisation based on observed flows for sub-catchments F and E.
- A3: Optimisation based on observed flows for sub-catchments F, E and D.
- A4: Optimisation based on observed flows for sub-catchments F, E, D and C.
- A5: Optimisation based on all observed flows.

Table 6.3 Automatic calibration experiment A.

Exp. Runs	Sub – Catch.	Parameters					Normal CE	MM % Error	Ln CE	MM % Error
		ZMIN	ZMAX	ST	FT	POW				
A1	A	249	1437	1942	78	4.9	0.450	36.886	0.776	2.256
A2	A	35	1740	1926	48	4.8	0.280	48.833	0.744	6.639
A3	A	422	1379	1920	103	5.6	0.519	34.810	0.795	4.230
A4	A	84	1823	1994	103	5.4	0.532	31.336	0.813	0.872
A5	A	44	1955	1518	76	5	0.602	29.242	0.844	3.153
A1	C	373	819	562	247	5.6	0.807	4.523	0.870	2.125
A2	C	470	1528	712	292	5.6	0.791	14.139	0.865	3.821
A3	C	286	795	578	196	4.3	0.833	2.794	0.866	2.125
A4	C	67	1563	590	201	5.6	0.821	4.480	0.874	2.275
A5	C	35	1963	637	190	3.9	0.829	-0.145	0.858	1.739
A1	D	57	1947	1973	197	5.7	0.477	9.560	0.538	-4.217
A2	D	463	1188	1953	110	3.1	0.515	-6.476	0.476	-12.272
A3	D	17	1166	1408	78	3.8	0.699	6.070	0.806	-2.850
A4	D	42	1263	1563	112	5.2	0.632	13.834	0.777	0.722
A5	D	27	1125	1617	107	5.5	0.623	17.163	0.793	2.014
A1	E	375	836	1199	153	5.7	0.813	-1.815	0.811	2.218
A2	E	39	1431	1956	41	2.5	0.827	9.852	0.892	1.261
A3	E	27	1989	1945	108	3.2	0.844	-3.260	0.870	-0.264
A4	E	188	1907	1940	78	2.8	0.851	0.725	0.887	0.203
A5	E	96	1267	1218	60	3.3	0.809	-2.501	0.810	1.790
A1	F	21	1266	1973	91	6.0	0.864	1.279	0.896	-0.295
A2	F	150	1132	969	120	4.9	0.852	-0.502	0.893	-1.473
A3	F	41	1953	1309	40	5.9	0.851	1.699	0.890	-0.118
A4	F	373	1040	1282	158	5.8	0.855	-4.574	0.878	-2.141
A5	F	174	1442	1942	145	5.2	0.845	-3.882	0.879	-1.984

The optimisation of sub-catchment A shows poor results compared to manual optimisation. C generally shows a good and equal or better optimization than manual calibration. D has a generally good and equal or better calibration than manual calibration but shows high mean % errors even when observed data for D is used (A3 to A5). E shows better calibration and points to an improvement of parameter values obtained during manual calibration (ZMIN – 200, ZMAX – 1200, ST – 1300, FT – 55 and POW – 4; refer to Table 6.2).

Automatic Calibration – Experiment B

In this experiment, optimisation was done with only observed flows for F while excluding some catchments from optimisation by fixing the parameter ranges to those obtained during manual calibration, as illustrated in Table 6.4, for sub-catchment C. In this regard the following runs were undertaken:

- B1: All catchments were optimised using observed flows of sub-catchment F as in A1.
- B2: Sub-catchment A was excluded by fixing its parameters.
- B3: Sub-catchments A and C were excluded by fixing their parameters.
- B4: Sub-catchments A, C and D were excluded by fixing their parameters
- B5: Sub-catchments A, C, D and E were excluded by fixing their parameters and only F was optimized using F observed flows.

Table 6.4 Fixed parameter values ranges for C.

Parameter	Inner Parameter ranges		Outer Parameter ranges	
	Inner Minimum	Inner Maximum	Outer Minimum	Outer Maximum
ZMIN	199.90	200.10	199.80	200.20
ZMAX	1199.90	1200.10	1199.80	1200.20
ST	1199.90	1200.10	1199.80	1200.20
FT	109.90	110.10	109.80	110.20
POW	4.99	5.01	4.98	5.02

Table 6.5 Automatic calibration experiment B.

Exp. Runs	Sub – Catch.	Parameters					Normal CE	MM % Error	Ln CE	MM % Error
		ZMIN	ZMAX	ST	FT	POW				
B1	A	249	1437	1942	78	4.9	0.450	36.886	0.776	2.256
B2	A	200	1200	1200	100	4.0	0.743	-5.322	0.824	-5.947
B3	A	200	1200	1200	100	4.0	0.743	-5.322	0.824	-5.947
B4	A	200	1200	1200	100	4.0	0.743	-5.322	0.824	-5.947
B5	A	200	1200	1200	100	4.0	0.743	-5.322	0.824	-5.947
B1	C	373	819	562	247	5.6	0.807	4.523	0.870	2.125
B2	C	222	1893	597	15	5.9	0.674	-1.794	0.714	4.722
B3	C	200	1200	1200	110	4.0	0.793	-1.689	0.857	-0.300
B4	C	200	1200	1200	110	4.0	0.793	-1.689	0.857	-0.300
B5	C	200	1200	1200	110	4.0	0.793	-1.689	0.857	-0.300
B1	D	57	1947	1973	197	5.7	0.477	9.560	0.538	-4.217
B2	D	108	1904	1804	98	5.6	0.372	32.049	0.546	9.309
B3	D	16	1620	402	41	4.7	0.244	33.030	0.507	18.655
B4	D	200	1200	1200	110	4.0	0.550	-7.070	0.704	-4.635
B5	D	200	1200	1200	110	4.0	0.550	-7.070	0.704	-4.635
B1	E	375	836	1199	153	5.7	0.813	-1.815	0.811	2.218
B2	E	324	1672	1902	36	1.6	0.768	0.762	0.824	2.157
B3	E	304	1295	1084	14	5.8	0.708	-6.055	0.700	2.950
B4	E	98	1047	560	12	4.8	0.706	-10.136	0.757	1.282
B5	E	200	1200	1500	50	4.0	0.744	-2.306	0.795	0.855
B1	F	21	1266	1973	91	6.0	0.864	1.279	0.896	-0.295
B2	F	22	1319	1856	79	5.4	0.844	3.283	0.890	-0.255
B3	F	16	1442	1985	28	1.9	0.819	-0.385	0.883	-1.454
B4	F	15	1389	1979	25	2.4	0.820	-1.705	0.880	-1.356
B5	F	10	850	1984	58	5.8	0.792	0.824	0.862	-1.179

From Table 6.5, it can be observed that the optimiser improves the simulation for F, but frequently does this at the expense of other sub-catchments, refer to B1 (A), B2 (C), B1 and 2 (D). These experimental runs also produce a very confusing pattern of parameters with very little regional consistency in parameter values or explanation for differences. However, the results for F are fairly consistent within the following parameter ranges:

ZMIN	10 – 22
ZMAX	850 – 1442
ST	1856 – 1985
FT	28 – 91
POW	1.9 – 6.0

The automatic optimiser did help to provide some insight into the most appropriate range of parameter values to use, but manual calibration procedures were considered to be the most efficient approach to use for the final calibrations covering all sub-catchments. The final calibrations focused on parameters ST, FT and GW, started with the upstream catchments

and moved progressively downstream. The standard period used for the input rainfall generation was October 1960 to September 1997. Wherever appropriate, the period up to 1980 was used for calibration purposes, while 1981 onwards was considered as the parameter validation period. These periods varied slightly between gauged sites depending upon the observed data availability.

The preceding sections have outlined the background information to the calibration of the Pitman model for the Kafue River basin. This section discusses the results of the model calibration process, including the variation in model parameter values and corresponding simulated flows and the degree of success with which the model has been able to simulate flows comparable to the observed flows. The spatial variations in parameter values are illustrated using tables and maps (which are scale correct, but no scale has been included for simplicity – see Figure 5.1 or 5.2 for scales). The correspondence between simulated and observed flows are illustrated by tables of statistics, time series plots and scattergraph screen images from the TSOFT program).

While the period used for simulation varied with each sub-catchment, dependent upon the available rainfall data, all sub-catchments cover the common period of October 1963 to September 1986. Reference to section 5 suggests that over this period the water use for agricultural and domestic/industrial purposes has changed. However, the parameter values for water use within the simulations have been fixed at values representative of the 1980 development condition. The changes over the simulation period are mostly small in relation to the mean annual runoff (MAR), but could have some impact on the low flow regimes at certain sub-catchment outlets. For example, the domestic/industrial use in sub-catchment E has varied between approximately 50 to 80 $\text{m}^3 * 10^6 \text{ y}^{-1}$ over the simulation period, which represents some 1% of the observed MAR. The variation in monthly water use over the simulation period represents approximately 7.5% of typical observed low flows during the dry season. While these factors have to be considered in the interpretation of the results, it was considered that the water use data were not sufficiently accurate to warrant including a facility to account for changes in water abstraction during the simulation period. The simulations therefore represent the best available representation of the 1980 development condition and this needs to be considered when comparing the simulated flows during the 1960s and early 1970s with the equivalent observed flows. This point will be followed up during the later part of this Section when the time series of observed and simulated flows are presented and discussed in detail.

7.1 THE PITMAN MODEL PARAMETERS

The major task in the model calibration process is to find a set of parameter values, which are able to simulate flows with a good correlation to the observed flows. A secondary consideration, related to the future possibility of transferring parameter values to ungauged areas, is that the spatial variation of the parameter values should be explicable with respect to variations in catchment characteristics. This section therefore discusses the parameter values that were found to produce acceptable simulated flows for each sub-catchment. Tables 7.1 and 7.2 list the calibrated parameter values for all the Kafue River basin sub-catchments identified by letters A to T. The nine main parameters that are discussed are the rainfall distribution factor (RDF), the percentage area of vegetation type 2 (AFOR), annual pan evaporation (PEVAP), the three absorption rate parameters (ZMIN, ZAVE and ZMAX), the maximum storage capacity (ST), the runoff rate at maximum storage capacity (FT) and the power of the soil moisture-runoff curve (POW).

7.1.1 Rainfall distribution factor (RDF)

Three rainfall distribution factors were assessed to try and account for the various daily rainfall distributions related to monthly rainfall amounts (section 5). The three RDF values are 0.6, 0.8 and 1.28. From the daily rainfall distribution analysis it was found that as the monthly rainfall total increased, the value of the most suitable RDF value decreased. There did not appear to be any evidence to suggest that this parameter is spatially variable. Since the RDF parameter value is fixed for all months within the model it became necessary to adopt a value that can be considered reasonably representative of the full range of monthly rainfalls. As the moderate to high rainfalls are more important from a runoff generation point of view, a compromise value of 0.8 for the RDF parameter was selected for all the sub-catchments of the Kafue River basin. This parameter was therefore not calibrated.

7.1.2 Percentage area of vegetation type 2 (AFOR)

The values for the percentage area of vegetation type 2 can have a substantial impact on the quantity of water lost to evapotranspiration within the model. The values have

been determined from a limited knowledge of the areas of forest and dense bush that occur in the sub-catchments taking into account the main land-use. Notable distinctions are made between the sub-catchments with a relatively high proportion of urban land-use, such as sub-catchment E (AFOR=5%) and the dominantly rural sub-catchments such as I (AFOR=40%). The values for the various sub-catchments range from 0 to 40%. The lower sub-catchments are mainly covered by wetland type of vegetation and also have low values for this parameter. The values (see Figure 7.1) for this parameter were therefore established *a priori* and not calibrated.

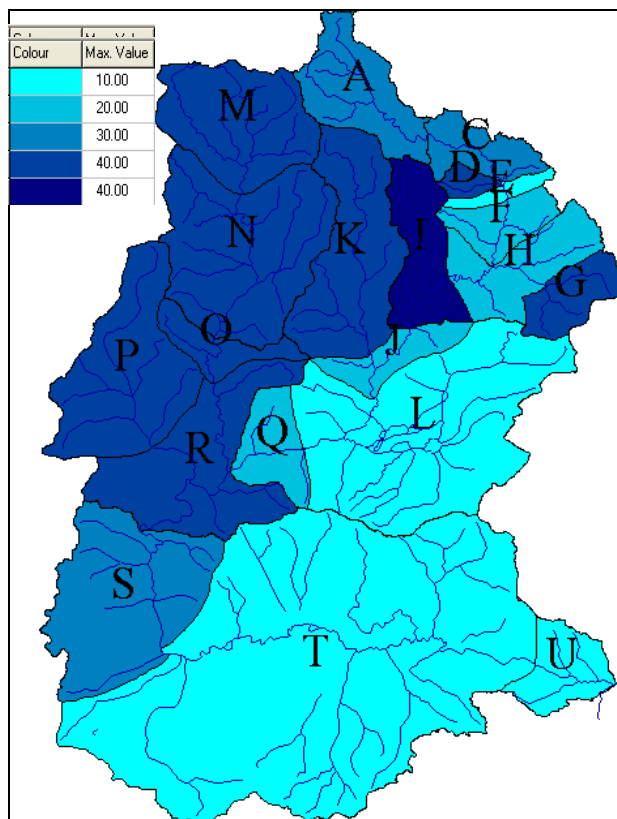


Figure 7.1 Geographical distribution of Percentage of Vegetation 2 cover.

7.1.3 Annual pan evaporation (PEVAP)

PEVAP values range from 1464 mm in the upper Kafue River basin sub-catchments to 1671 mm over the Kafue flats. Although evaporation data is an important input to the Pitman model, the available data are based on insufficient measuring points with a very sparse spatial distribution and incomplete time series. Individual sub-catchment values were therefore extrapolated from the nearest station in each case (see section

5). The annual evaporation values are distributed into monthly values using a fixed seasonal distribution for each sub-catchment. There is therefore no temporal variation of evaporative demand allowed for in the model at this stage. There is little doubt that the lack of evaporation time series data represents a potentially serious limitation to successful modelling. This is especially the case given the substantial evaporation losses that are expected to occur from the sub-catchments dominated by seasonally submerged wetlands (L and T).

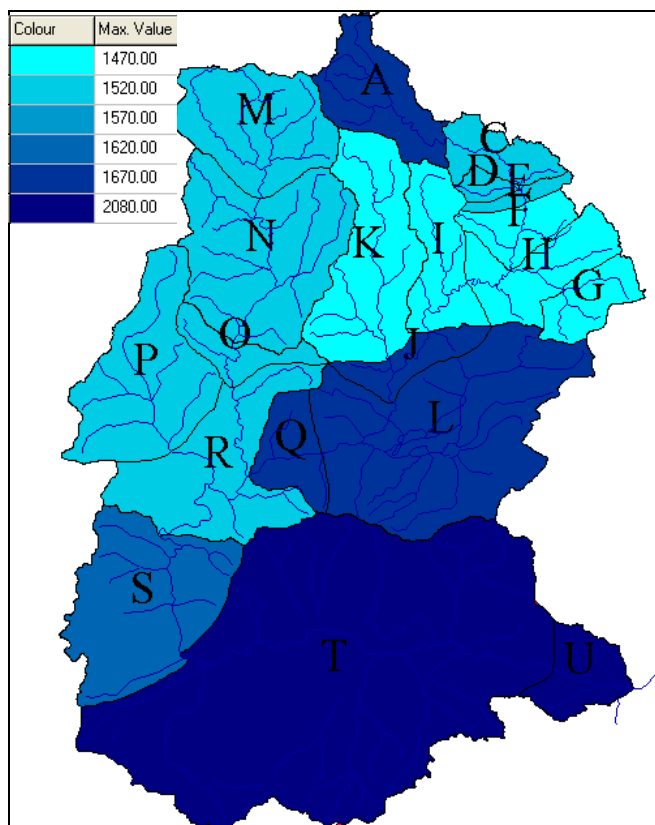


Figure 7.2 Geographical distribution of annual pan evaporation (mm). Refer to Tables 7.1 and 7.2 for the actual values for each sub-catchment.

7.1.4 The absorption rate parameters - ZMIN, ZAVE and ZMAX

The spatial distribution of absorption or infiltration rate of any sub-catchment is highly influenced by the geology, soil type and vegetation. The distribution of the calibrated values of the three parameters does suggest that the Kafue River has relatively homogenous characteristics. One physical feature in the Kafue river which may contribute to high absorption rates is the occurrence of head water storage

features known as dambos which in some areas form quite extensive swamps and flood plains (see section 5).

The South African experiences with the Pitman model (Pitman, 1973) suggest that in humid climates such as that of the Kafue River basin, the absorption rate parameters could be set to high values such that very little runoff is generated by this component of the model, regardless of the monthly rainfall total. This is based on the premise that vegetation cover is usually quite dense, soils well developed and infiltration rates relatively high. However, it was noted that many of the rainfall events in the early part of the Kafue wet season are characterised by high intensities and short durations, as can be seen from the RDF analysis in section 5.2.2. These rainfall events can generate early wet season runoff responses before the dry season moisture deficits have been satisfied. This implies that the surface runoff functions of the model involving the absorption rate parameters do play a role in the Kafue basin. After a range of model tests were undertaken it was decided to fix these parameter values at $ZMIN = 200$ mm/month and $ZMAX = 1200$ mm/month. Slight variations were introduced in the $ZAVE$ values within a range of 500 – 700 mm/month to account for apparent spatial differences in the runoff response to early wet season rainfall events of high intensities that occur before the soil moisture deficits have been satisfied. Table 7.1 and 7.2 provides the distribution of parameter values in the Kafue River basin

7.1.5 Maximum storage capacity (ST)

The parameter ST is important in regulating runoff response in several ways. It should also be noted that there is a high degree of interaction between the value of ST , FT , POW , as well as the evapotranspiration loss parameters. This makes it very difficult to isolate specific components of the flow regime to focus on when calibrating the ST values and is one of the reasons why automatic calibration in a regional context tends to fail. The higher the value of ST , the greater will be the rainfall required to satisfy moisture deficits at the beginning of the wet season and therefore initiate high levels of runoff. At the same time, high values of ST imply sustained moisture storage at the end of the wet season and therefore more sustained baseflow responses during the dry season. Perhaps the main influence, and the one that is frequently used to calibrate the values of ST in areas where wet season rainfalls are very high (typically 300 mm or

higher), is the extent to which the maximum value of moisture storage is exceeded during the peak of the wet season. If this occurs, all of the rainfall exceeding that peak becomes runoff, which can generate very high flow responses if the value of ST is too small.

The adopted parameter ST values range from 1200 to 1800 (see Figure 7.3). Topographically, the whole basin is very similar with gently undulating terrain, but with slightly steeper areas in the northern and upper catchment tributaries (mostly A, C and D). The flattest areas are in the Lukanga swamps (L) and the downstream areas R, S and T, however the ST value assigned to sub-catchment L is not very relevant in the regional context as simulated runoff from this area is dominated by the parameters of the dummy dam introduced to try and account for the wetland processes occurring between and within sub-catchments J and L (discussed in section 6.1.1).

In general terms, it would be expected that ST would increase from the steeper headwater areas to the flatter downstream areas and the results follow this general pattern. The frequent occurrence of dambos which are pan-like topographical features which act as subsurface flow storage areas may account for the low runoff yield of the Kafue River basin and may provide a possible explanation of some apparent anomalies, such as the relatively high ST values for sub-catchments K, I and P.

The values for sub-catchments J, L and T are difficult to determine as the calibrations of these areas are substantially influenced by the model configurations of the ‘dummy’ dams to simulate the complex hydrological systems of wetlands as discussed in sections 6.1.1 and 6.1.2. In addition, there are outstanding questions about the quality of the observed records at G and K and the parameter values for these areas are difficult to confirm. G has 30 years of record with 144 missing months, while K has 29 years of record with 157 missing months (table 5.25). It is necessary to further emphasise that errors in the observed data, seriously inhibit the estimation of parameter values with physical relevance.

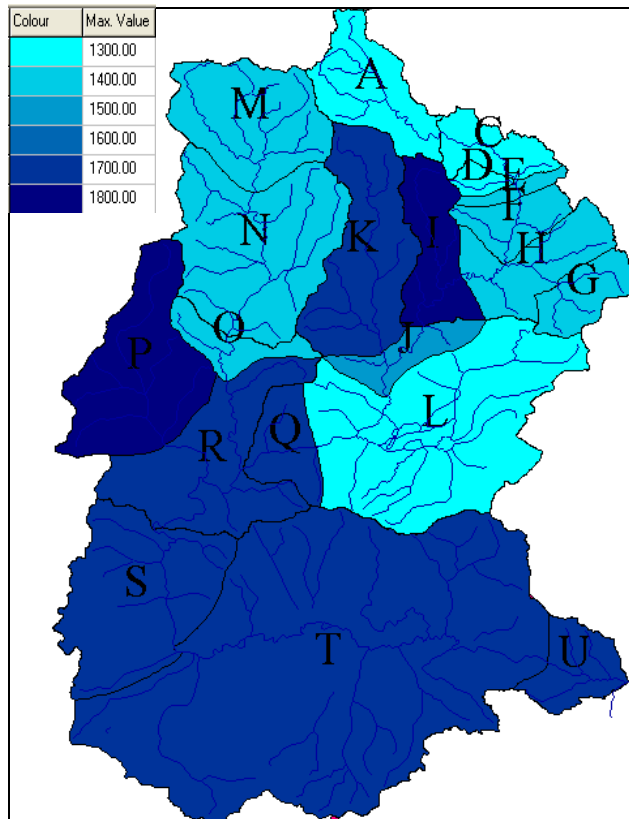


Figure 7.3 Geographical distribution of parameter ST, refer to tables 7.1 and 7.2 for the actual values for each sub-catchment.

7.1.6 Runoff rate at maximum storage capacity (FT)

As with ST, the parameter FT is also of prime importance in the calibration process. In combination with the parameters POW and ST, FT controls the rate of runoff from the catchment for any given moisture storage state. As FT is increased, runoff is increased at the expense of catchment evapotranspiration. Consequently the total yield of the catchment is increased as is the reliability of runoff and the baseflow response in the dry season. It should be noted that the value of FT has a smaller effect on runoff during the peak wet period months when the moisture storage is full and runoff is determined largely as rainfall minus potential evapotranspiration.

The characteristic of the parameter FT, of playing a role in determining the balance between evaporation and runoff, is the reason why it is difficult to relate it to physical catchment characteristics (Pitman, 1973). However, in general terms it would be expected that ST would increase and FT decrease from the steeper headwater areas to

the flatter downstream areas and the results for both parameters follow this general pattern as can be seen from Figure 7.4. The parameter FT values for the Kafue River basin range from 25 mm/month to 110 mm/month

Apparent anomalies in the distribution pattern of parameter FT are detected mainly in sub-catchments J, L and, to a certain extent, O. These cannot be justified with respect to known physical features of the sub-catchments. For sub-catchment O, the geology and the land-use are the same as sub-catchments N and M and the quality of observed data, as discussed in Section 5.3.1, may be of relevance. Parameter FT values for sub-catchments J, L and T (as in the case of parameter ST), are difficult to determine as the model calibrations of these areas are substantially influenced by the model configurations of the dummy dams representing the complex hydrological interactions of the wetland areas (see Sections 6.1.1 and 6.1.2). It is also difficult to be certain that optimum values of FT have been developed for sub-catchments G and K due to the quality of observed data used in the calibration process.

ST and FT are the parameters which were generally the most sensitive and can therefore be considered as key parameters. The spatial variation of their values requires further investigation and a better understanding of the spatial dynamics of processes controlling runoff generation would assist in the future regionalization of parameters. The degree to which parameter values may be generalized for different catchments depends largely on the sensitivity of the simulated runoff to changes in the parameter values. As previously mentioned, the spatial variation in the frequency of dambos can be expected to be important

7.1.7 Power of soil moisture-runoff curve (POW)

The parameter POW determines the rate at which runoff diminishes as the moisture storage is decreased. This has a significant effect on both the seasonal distribution and reliability of flows as well as the total yield of a catchment. The lower the value of POW, the higher will be most flows when the moisture storage is not full. For the Kafue River basin, which has generally well drained and deeply weathered soils, it would be justifiable to expect higher POW values. The assumption is that drainage out of storage at the end of the wet season would be initially rapid, after which the

baseflows would be sustained by relatively slow releases from the low topography valley bottom Dambos. After a number of calibration runs, it was decided to fix all POW values at 4.0 and to focus the calibration effort on the FT and ST parameters.

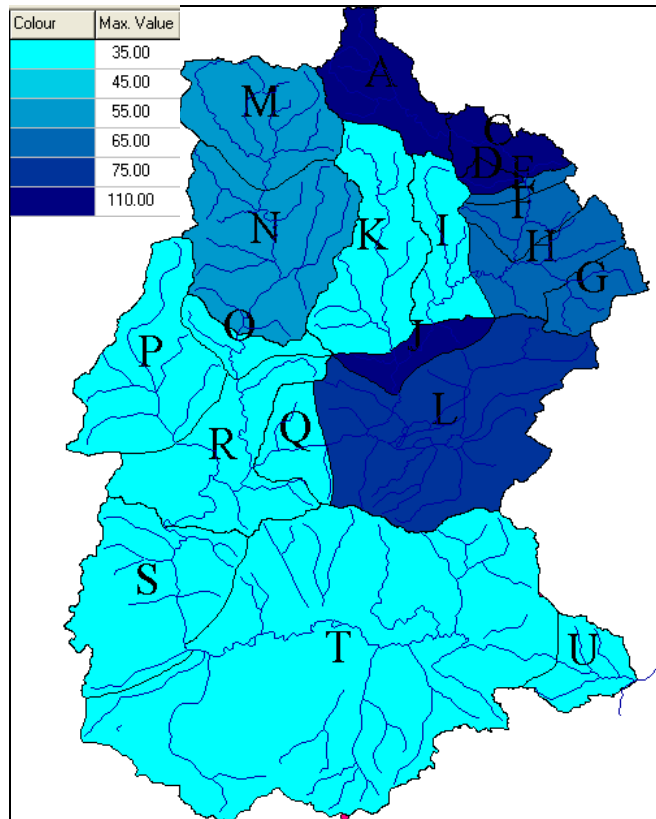


Figure 7.4 Geographical distribution of parameter FT (dark colour indicates high values up to 110) refer to tables 7.1 and 7.2 for the actual values for each sub-catchment.

7.1.8 General observations

Overall, as can be seen from Tables 7.1 and 7.2, there is a reasonable degree of consistency in the calibrated parameter values. This agrees with the generally homogeneous nature of the Kafue River basin. Many of the spatial differences in rainfall-runoff response are dominated by the two major wetland areas (in sub-catchments L and T), which have not been simulated through parameter value differences, but through differences in the model configuration. This is an important concept that suggests that simple model calibration principles would be difficult to apply in establishing a regional semi-distributed model for the Kafue basin. The range

of parameters values does provide a good starting point for any future work in the Kafue basin and possibly the whole Zambezi basin. However, there is not enough information about the real differences in basin characteristics to be able to confidently justify the parameter value differences from sub-catchment to sub-catchment. Further details about the distribution of Dambos is considered to be of particular importance, as it is speculated that these may play a substantial role in runoff generation processes and the ‘physically appropriate’ values of several parameters. While it is clear that spatial variations in the quality of the observed flow data (together with the representativeness of the rainfall and evaporation input data) can play a major role in any calibration process, it is almost impossible to account for these in situations of limited data availability. Some of these issues will be further discussed in the later sections.

7.2 ASSESSMENT OF QUALITY OF CALIBRATION RESULTS

The calibration process involved a standard set of statistical comparison criteria between observed and simulated streamflows, which is presented in Table 7.3. The measurement criteria (objective functions) used to check the comparison are: observed and simulated monthly means, the coefficient of determination R^2 , the coefficient of efficiency CE and the mean monthly percentage error between the simulated and observed flows. Two sets of data types are used, one test on the normal data and the other on natural log transformed data. While the tests on normal data are strongly influenced by high flow extremes, the tests on log transformed data are less influenced by extremes and therefore provide a better indication of the degree to which the model has simulated low to moderate flows. The TSOFT facility of SPATSIM is designed to automatically generate these measures of comparison when the X-Y scatterplot option is selected.

Table 7.1 Calibrated Pitman Model Parameters for Sub-catchments A to K.

Pitman Model Parameters	Kafue River Basin Sub-Catchments									
	A	C	D	E	F	G	H	I	J	K
Rain Distribution Factor (RDF)	0.80	0.80	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800
Proportion of impervious area (AI)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Summer interception capacity (Veg1) (PI1s)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Winter interception capacity (Veg1) (PI1w)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Summer interception capacity (Veg2) (PI2s)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Winter interception capacity (Veg2) (PI2w)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Percentage Area of Veg2 (AFOR)	20.00	20.00	35.00	5.00	10.00	30.00	10.00	40.00	15.00	35.00
Veg2/Veg1 Potential Evapotranspiration Ratio (FF)	1.40	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400
Power of Veg. recession curve	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Annual Pan Evaporation (mm) (PEVAP)	1640.00	1504.00	1604.00	1504.00	1464.00	1464.00	1464.00	1464.00	1658.00	1464.00
Summer minimum absorption rate (mm/month) (ZMINs)	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
Winter minimum absorption rate (mm/month) (ZMINw)	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
Mean absorption rate (mm/month) (ZAVE)	500.00	500.00	500.00	500.00	600.00	600.00	600.00	600.00	600.00	600.00
Maximum absorption rate (mm/month) (ZMAX)	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00
Maximum storage capacity (ST)	1200.00	1200.00	1200.00	1300.00	1300.00	1300.00	1300.00	1700.00	1400.00	1600.00
No runoff below storage (SL)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Power: storage-runoff curve (POW)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Runoff rate at ST (mm/month) (FT)	105.00	105.00	105.00	55.00	55.00	55.00	55.00	26.00	110.00	30.00
Maximum groundwater flow (mm/month) (GW)	10.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00	0.00
Evaporation-storage coefficient (R)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Surface runoff time lag (months) (TL)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Groundwater time lag (months)	3.00	3.00	3.00	3.00	3.00	0.00	3.00	3.00	3.00	3.00
Irrigated area (km^2) (AIRR)	0.00	0.00	0.00	0.00	0.00	0.00	91.300	0.00	0.00	0.00
Irrigation return flow fraction (IWR)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Irrigation Direct Demand (ML/year)	0.00	58000.00	0.00	78000.00	13000.00	0.00	21000.00	1000.00	0.00	0.00

Table 7.2 Calibrated Pitman Model Parameters for Sub-Catchments L to T.

Pitman Model Parameters	Kafue River Basin Sub-Catchments								
	L	M	N	O	P	Q	R	S	T
Rain Distribution Factor (RDF)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Proportion of impervious area (AI)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Summer interception capacity (Veg1) (PI1s)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Winter interception capacity (Veg1) (PI1w)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Summer interception capacity (Veg2) (PI2s)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Winter interception capacity (Veg2) (PI2w)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Percentage Area of Veg2 (AFOR)	0.00	30.00	30.00	30.00	30.00	10.00	30.00	20.00	5.00
Veg2/Veg1 Potential Evapotranspiration Ratio (FF)	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Power of Veg. recession curve	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Annual Pan Evaporation (mm) (PEVAP)	1658.00	1471.00	1471.00	1471.00	1471.00	1658.00	1471.00	1576.00	1671.00
Summer minimum absorption rate (mm/month) (ZMINs)	200.00	200.00	200.00	200.00	200.000	200.00	200.00	200.00	200.00
Winter minimum absorption rate (mm/month) (ZMINw)	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
Mean absorption rate (mm/month) (ZAVE)	600.00	700.00	700.00	700.00	700.00	700.00	700.00	700.00	700.00
Maximum absorption rate (mm/month) (ZMAX)	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00	1200.00
Maximum storage capacity (ST)	1200.00	1300.00	1300.00	1300.00	1800.00	1600.00	1600.00	1600.00	1600.00
No runoff below storage (SL)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Power: storage-runoff curve (POW)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Runoff rate at ST (mm/month) (FT)	70.00	45.00	45.00	30.00	25.00	30.00	30.00	30.00	30.00
Maximum groundwater flow (mm/month) (GW)	60.00	5.00	5.00	5.00	5.00	5.00	5.00	0.00	0.00
Evaporation-storage coefficient (R)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Surface runoff time lag (months) (TL)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Groundwater time lag (months)	12.00	3.00	3.00	3.00	4.00	3.00	4.00	4.00	4.00
Irrigated area (km^2) (AIRR)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	815.50
Irrigation return flow fraction (IWR)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Irrigation Direct Demand (MI/year)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	117800.00

7.2.1 The coefficient of determination (R^2)

The coefficient of determination is the objective function defined as the square of the correlation coefficient (R^2) and is calculated by the following equation:

$$R = \frac{\sum \{(Obs. - ObsMean)(Sim. - SimMean)\}}{n.S_o.S_s}$$

Where: S_o is the standard deviation of observed data

S_s is the standard deviation of simulated data

R^2 is not sensitive to systematic errors and a high value close to 1.0 can be achieved despite the fact that simulated values generally over- or under-estimate the observed flows. For the purposes of this study, a value of better than 0.75 can be considered a successful simulation. The range for the Kafue River basin sub-catchments is 0.46 to 0.85 for the normal values and 0.41 to 0.89 for the log-transformed values (refer to Table 7.4).

7.2.2 Coefficient of efficiency

The objective function CE (also referred to as the Nash-Sutcliffe criterion after Nash and Sutcliffe, 1970) is defined as:

$$CE = 1 - \frac{\sum (Obs. - Sim.)^2}{\sum (Obs. - ObsMean)^2}$$

The coefficient of efficiency CE is sensitive to systematic error and is a much better statistic of one-to-one fit. This then supplements the objective function R^2 and the two together provide one of the best methods of comparing two sets of time series data. Successful simulations would be indicated by values of better than 0.75 and no more than about 0.05 less than the equivalent R^2 value. The range for the Kafue River basin sub-catchments is 0.29 to 0.85 for the normal values and 0.26 to 0.89 for the log-transformed values (refer to Table 7.4).

7.2.3 Mean monthly percentage error

This provided the measure of deviation in estimation of simulated monthly means from the observed flows. A realistic objective for successful modelling would be within 5% of the observed monthly mean. The mean monthly % error range is -9.8% to 34.1% for normal values while the range is -2.3% to 17.3% for the log-transformed data (refer to Table 7.4).

7.3 VALIDATION OF CALIBRATION RESULTS

Calibrated model parameters can result in simulations that satisfy goodness-of-fit criteria over the period used for the calibration, but may not be satisfactory for other time periods that experience somewhat different climatological conditions. This makes it necessary to test if the parameter values can be considered useful for simulating other periods, not used in the calibration process. In this study the initial calibrations were based on a comparison with a sub-set of the available observed data and then the parameter values assessed using the remaining observed data.

For the Kafue basin it was not possible to split the observed data into two equal periods as the data are not sufficiently long for many sub-catchments and for those with a longer record, the period from the late 1980s had a lot of missing gaps. The calibration and validation periods are therefore based on unequal length data periods. The calibration period used data prior to 1980, while the validation period covers years of available data after 1980. In most cases, the pre 1980 period covers a wide range of climatological conditions (wet and dry years), while the post 1980 period was generally drier with less variation.

The calibration/validation results for selected sub-catchments (Table 7.3) suggests that there is no consistent difference in the performance of the model over the two periods and that the calibrated parameter values are generally equally suitable for both periods. This gives some reasonable degree of confidence that the results obtained in the calibration process are representative of the full observed record for the Kafue river basin. Further detailed discussion of the simulation results will therefore cover the whole period.

Table 7.3 Summary of the calibration and validation results for selected sub-catchments in the Kafue river basin.

Site	Period	Months	Normal		Ln values		Mean Monthly % Error	
			R ²	CE	R ²	CE	Normal	Ln
F	Calib.	223	0.783	0.762	0.862	0.833	9.2	3.6
	Valid.	81	0.717	0.707	0.806	0.793	4.1	1.8
O	Calib.	224	0.511	0.470	0.647	0.572	12.0	4.4
	Valid.	171	0.652	0.502	0.670	0.514	25.8	5.1
Q	Calib.	217	0.671	0.643	0.778	0.683	8.6	5.7
	Valid.	68	0.772	0.756	0.820	0.794	-2.3	2.3
T	Calib.	86	0.495	0.479	0.478	0.456	-4.7	1.9
	Valid.	216	0.344	0.334	0.308	0.203	2.3	1.8

7.4 DISCUSSION OF SIMULATION RESULTS

Simulation results for selected sub-catchments are discussed to provide further details about the quality of simulations that have been achieved for the Kafue River basin and the problems faced in achieving better and acceptable goodness-of-fit for the simulated flows in comparison with the observed data. A complete summary of the simulation results for all sub-catchments is provided in Table 7.4. Examples of time series comparative plots and X-Y scatterplots (for A, F, N, R and T) are presented in Figures 7.5 to 7.8

7.4.1 Kafue River at Raglan Farm - sub-catchment A

The Kafue River at Raglan Farm is the first sub-catchment in the Kafue river basin and a reasonably good simulation in comparison with the observed flows has been achieved. It can be seen from Figures 7.5 and 7.6 that the simulated flows are quite consistently over estimating the dry season flows and this is reflected in the relatively large difference between the R² and CE values based on log-transformed data (Table 7.4). The problem appears to be more evident during dry years and it is possible that further calibration could improve the simulation.

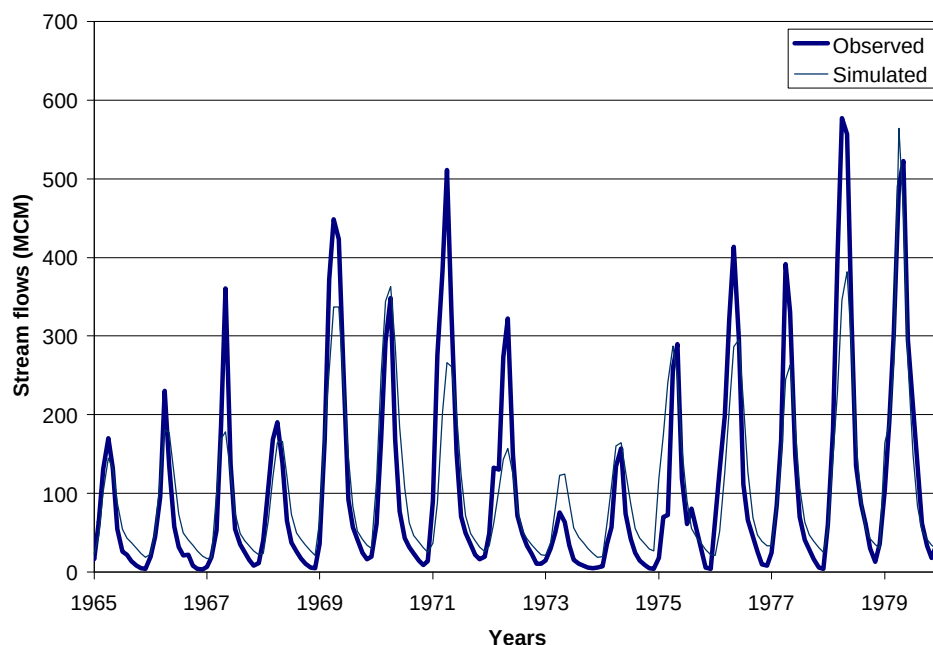


Figure 7.5 Graphical results of comparison between observed and simulation flows for sub-catchment A.

Table 7.4 Summary of statistical measure of goodness-of-fit between the simulated flows and the observed flows.

Sub-catch	Months	Normal		Ln values		Mean monthly % error		Normal mean		Ln value mean	
		R ²	CE	R ²	CE	Normal	Ln	Obs.	Sim.	Obs.	Sim.
A	306	0.744	0.738	0.816	0.631	8.1	11.8	104.6	113.1	3.901	4.362
C	299	0.794	0.786	0.856	0.757	8.2	5.8	171.6	185.7	4.659	4.929
D	309	0.522	0.515	0.624	0.476	6.5	12.3	21.2	22.6	2.632	2.955
E	303	0.845	0.827	0.896	0.892	-9.8	-1.3	212.4	191.5	4.915	4.853
F	304	0.853	0.852	0.898	0.893	0.5	1.5	270.9	272.2	5.090	5.165
G	226	0.415	0.017	0.415	0.247	34.1	17.3	26.0	34.8	2.548	2.988
H	324	0.759	0.733	0.821	0.779	10.0	3.7	352.1	387.3	5.395	5.597
I	406	0.774	0.769	0.850	0.767	7.5	4.6	367.5	395.0	5.376	5.625
J	248	0.744	0.708	0.845	0.795	-6.8	2.9	509.7	475.1	5.700	5.866
K	191	0.742	0.516	0.742	0.627	26.4	8.7	50.2	63.4	3.560	3.869
N	285	0.708	0.703	0.703	0.663	-2.2	-0.5	260.3	254.4	5.228	5.204
O	359	0.767	0.663	0.691	0.570	26.6	5.6	216.8	274.5	4.986	5.264
Q	285	0.752	0.745	0.760	0.671	8.2	5.2	530.2	573.6	5.699	5.995
R	288	0.812	0.807	0.839	0.728	2.3	-2.3	821.3	840.6	6.134	5.995
S	232	0.457	0.289	0.414	0.257	13.8	2.6	657.4	748.5	6.282	6.445
T	302	0.500	0.497	0.469	0.400	4.2	2.8	744.5	776.2	6.352	6.528

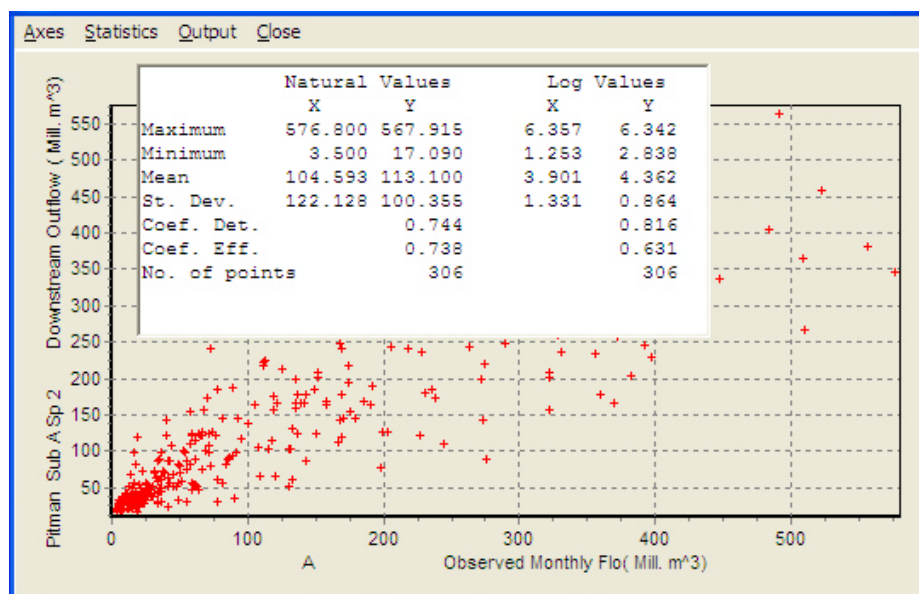


Figure 7.6 X-Y scatter plot and statistical results of comparison between observed and simulated flows for sub-catchment A.

7.4.2 Kafue River at Mpatamato - sub-catchment F

The Kafue River at Mpatamato is a sub-catchment just below the copper mining towns with the town water abstractions and mine dewatering discharge being added to the river. This sub-catchment therefore represents the main downstream point below the industrialised part of the Kafue basin. As such this was a major focus point of the calibration process. It can be seen that the simulated flows compare very well with the observed flows over the full range (Figures 7.7 and 7.8, Table 7.4). The over-simulation of low flows that was noted for sub-catchment A has therefore not been translated downstream. This further suggests that there is scope for adjustment of some of the parameter values within the upstream sub-catchments (A to F) to try and achieve an improvement in the spatial distribution of generated runoff (especially in the low flow regime).

The low flow simulations are satisfactory and the shape of the simulated recessions is generally very good. The high flow months are frequently over- and under-simulated, which is partly a reflection of the less than satisfactory representation of the spatial rainfall distribution and this aspect recurs in the results for all the sub-catchments. This is a typical problem when simulating large catchments with limited

representation of the spatial rainfall variations. The problem is also related to the fact that the sub-catchment response to high rainfalls is being represented in a lumped manner, when in reality there will be substantial spatial variations. The fact that the recession shapes and low flows are well simulated suggests that the catchment drainage dynamics have been reasonably well represented by the model.

Given that the simulations are based on fixed values for the water abstraction parameters, there is no clear indication that actual changes in these amounts over time have affected the simulation results. This may be because the real changes have been less than suggested by the available data presented in section 5, or that simulation errors are masking these changes.

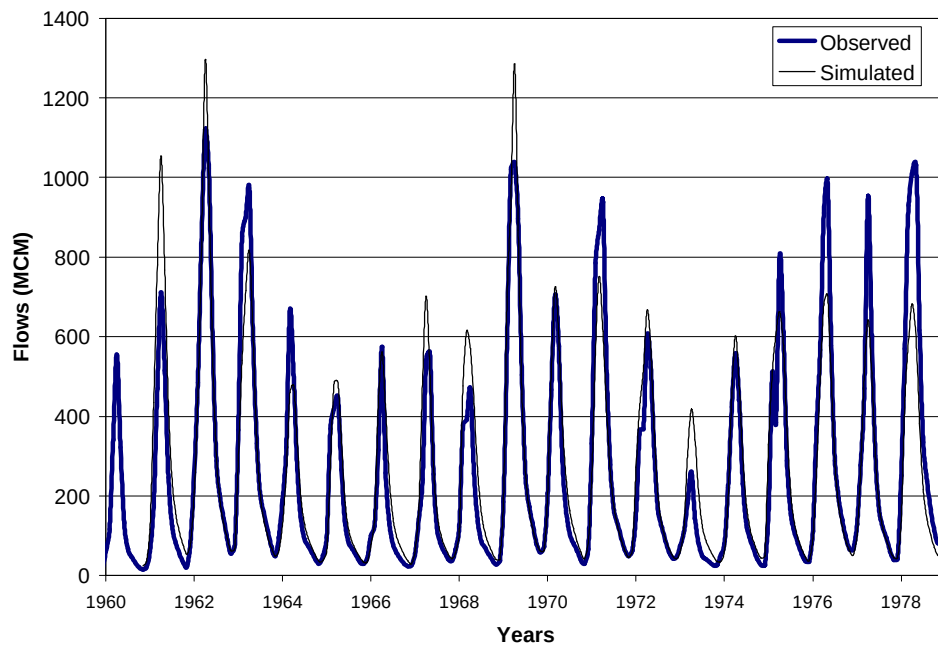


Figure 7.7 Graphical results of comparison between observed and simulation flows for sub-catchment F.

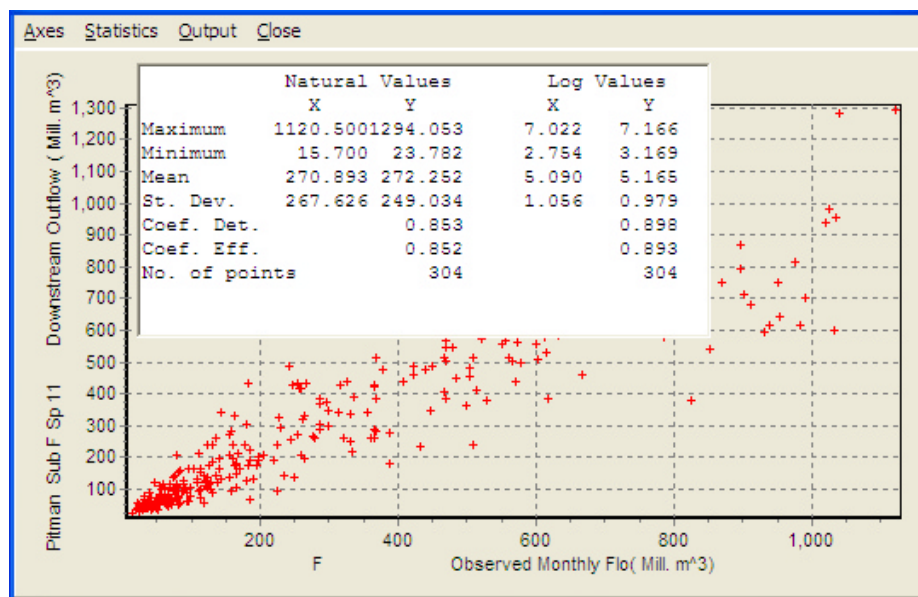


Figure 7.8 X-Y scatter plot and statistical results of comparison between observed and simulation flows for sub-catchment F.

7.4.3 Lunga River at Kelongwa - Sub-Catchment N

The Lunga river (sub-catchments M, N and O) is one of the major tributaries of the Kafue river and therefore was used for initial calibration of the Pitman model. The quality of the data for sub-catchments N and O has been questioned. However, the calibration process has indicated that the simulation is consistently providing better comparison with observed flows for N than O. Pitman model simulated flows compare fairly well with the observed flows at this station (Figure 7.9). The statistical comparison gives an R^2 for normal values of 0.708, while for natural logs a value of 0.703. The corresponding CE values are 0.703 for normal values and 0.663 for natural log values. The monthly mean error values of -2.2% for normal values and -0.5% for natural log values suggest acceptable volumetric simulations.

This tributary sub-catchment N result has shown better simulation results than at the other tributary sub-catchments of D (R^2 of 0.5 for normal values) and G (R^2 of 0.4 for normal values). This may be indicating a better quality of observed data for this particular sub-catchment than some of the other tributary sub-catchments.

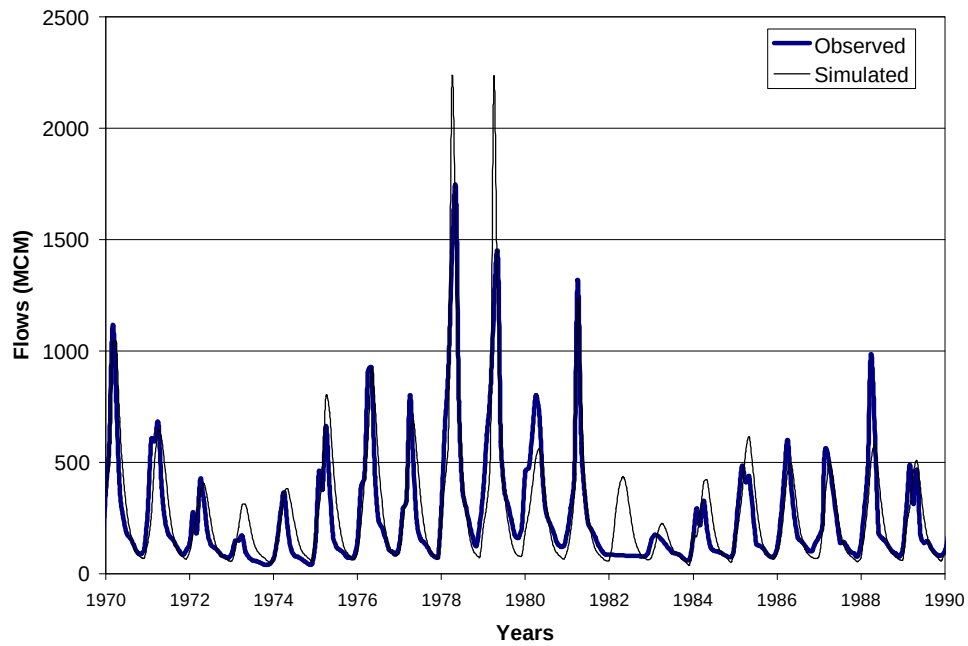


Figure 7.9 Graphical results of comparison between observed and simulated flow hydrographs of Sub-catchment N.

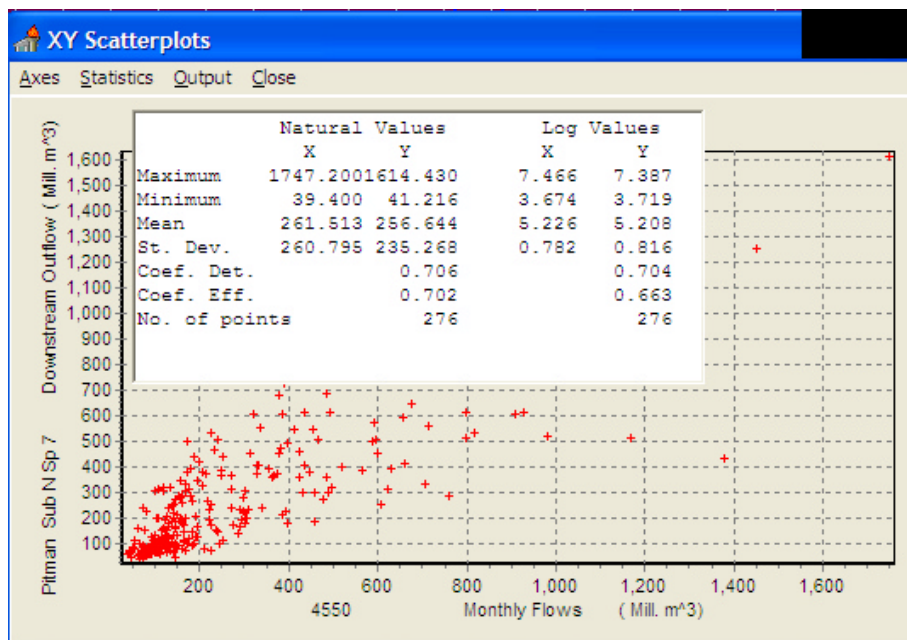


Figure 7.10 X-Y scatter plot and statistical results of comparison between observed and simulation flows for sub-catchment N.

7.4.4 Kafue River at Kafue Hook Bridge - sub-catchment R

Historically, the Kafue River at Kafue Hook bridge is considered to be a key station both for water resources management and for the monitoring of inflows for the Kafue hydropower scheme which lies downstream of this sub-catchment. This station also marks the end point for testing of rainfall-runoff models with largely unregulated flows. In addition, the hydrologic complexity increases downstream due to the presence of the Itezhi-tezhi dam (and associated operating rules) and the complex hydrological processes associated with the extensive Kafue flats wetlands. Both pose additional challenges to hydrological modelling. This site is therefore critical to an assessment of any model for simulating the water resource availability in the Kafue River basin. The confidence in the observed data is very high because, of all the stations in the Kafue basin, the observed flow data at Kafue Hook bridge can be considered to be of the best quality with very few missing gaps. In a record of 28 years (1973-2001) there are only 6 missing data months (refer to Table 5.25) and the rating curve is well established (refer to Table 5.24).

From the results presented in Figures 7.11 and 7.12, it can clearly be seen that in spite of some poor relationship between simulated flows and observed flows in some upstream sub-catchments, the simulated flows compare very well with the observed flows at this station. The statistical comparison gives an R^2 for normal values of 0.812, while for natural logs a value of 0.839. The corresponding CE values are 0.807 for normal values and 0.728 for natural log values. The monthly mean error values of 2.3% for normal values and -2.3% for natural log values suggest acceptable volumetric simulations.

It should be noted that this sub-catchment is downstream of the Lukanga Swamps and that the methods used for simulating the outflows through and from this area are relatively simplistic. While there is clearly scope for an improvement in the approach to simulating the effects of this large wetland area, the simulation results at R suggest that the approach adopted has been effective.

The worst aspect of the simulations at R is the less than satisfactory CE value based on log-transformed flows, suggesting that the low to moderate flows have not been

adequately simulated. Part of this problem may be related to the fixed water use parameters, while the available data suggest quite substantial changes in parts of the basin (notably agricultural water use in sub-catchment H). From the well-simulated low flows in the 1980s, there is a distinct trend toward over-simulation of the low flows in the mid-1990s (Figure 7.11). This supporting evidence is somewhat offset by the fact that the late 1970s also demonstrate an over-simulation of low flows, although to a lesser extent. The results for this sub-catchment highlight the need for accurate and reliable information, not only for the natural components of the hydrology (rainfall, evaporation, observed streamflow data, etc.), but also for the anthropogenic influences of abstractions and water use.

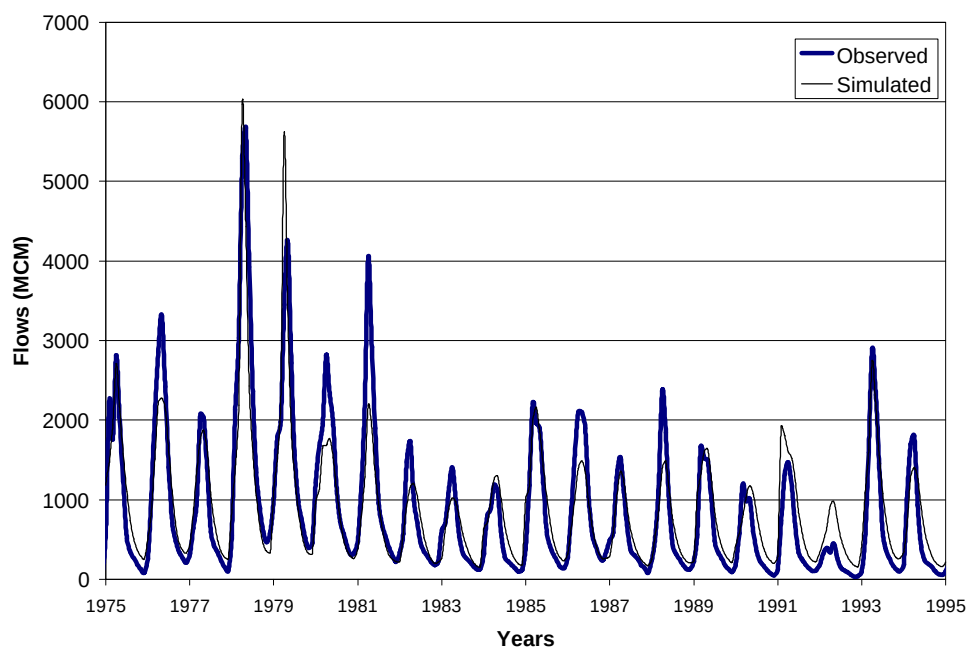


Figure 7.11 Graphical results of comparison between observed and simulated flow hydrographs of Sub-catchment R

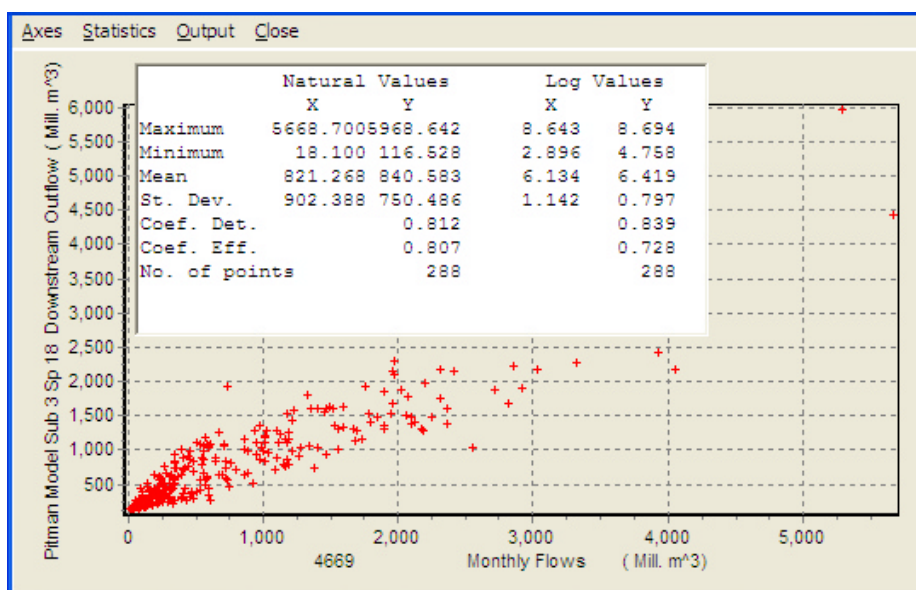


Figure 7.12 X-Y scatter plot and statistical results of comparison between observed and simulation flows for sub-catchment R.

7.4.5 Kafue River at Kafue Gorge Dam – sub-catchment T

Given the lack of information to adequately define the operating rules of the two reservoirs, Itzhi-tezhi and Kafue gorge, as well as the difficulties of configuring the model to represent the effects of the Kafue Flats, the results of the simulated outflows and the actual regulated outflows are reasonably good (Figures 7.13 and 7.14, Table 7.4). It can be noted that the correspondence in individual months is not very good (and the R^2 and CE statistics are less than satisfactory), however the effect of the drier years after 1982 to 1989 are very clear with few periods of spills from Kafue Gorge reservoir. This lack of spills may mean that the water regulators were preferring to keep the reservoir at full capacity and therefore not following the laid down operating rule curve. It can be reasoned that the measure of departure between the simulated flows and the observed outflows may also be a measure as to what extent the operations of the two reservoirs follow the operating rule curves.

There is little doubt that part of the reason for the overall poor performance of the model at this point is also due to the lack of complete understanding of the dynamics of flow transference through the Kafue flats wetland, coupled with the lack of suitable model components to simulate these effects. While this point is of major concern and

would need to be addressed if the model were to be used for practical water resource management purposes in the future, the comparison between the simulations for the 1970s and early 1980s (a generally wet period) and the drier mid to late 1980s is encouraging.

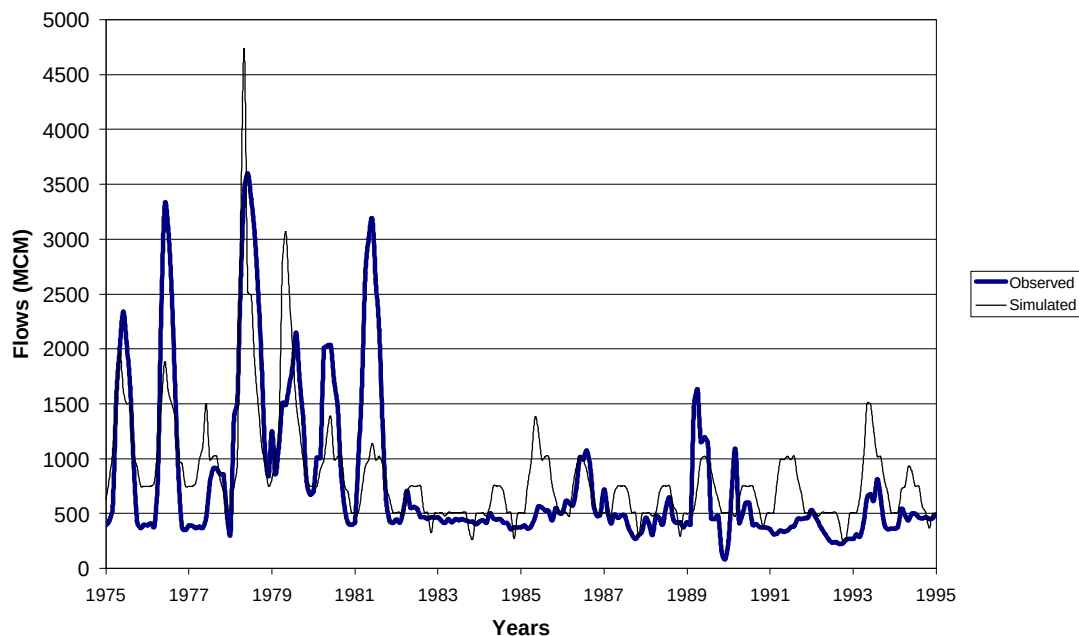


Figure 7.13 Graphical results of comparison between observed and simulated flow hydrographs of Sub-catchment T.

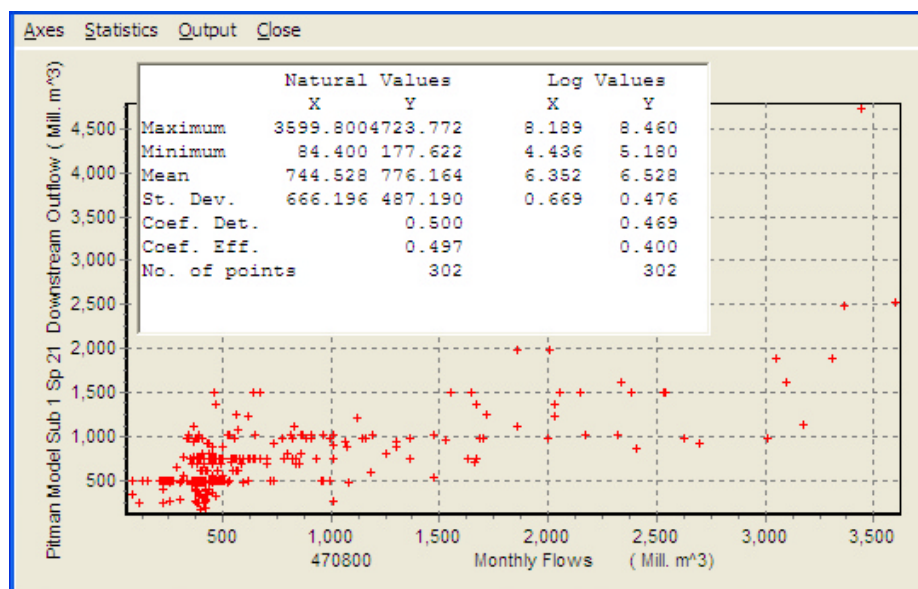


Figure 7.14 X-Y scatter plot and statistical results of comparison between observed and simulation flows for sub-catchment T.

7.4.6 Kafue flats floodplain storage in sub-catchment T

To simulate the hydrological processes in the Kafue flats wetland, a natural flood control and flow attenuation reservoir was assumed. Figure 7.15 illustrates the simulated volume in the ‘dummy’ reservoir used to represent the Kafue flats floodplain storage (maximum storage of 6 500 Mm³). While this pattern appears to generate reasonable inflows into the Kafue Gorge reservoir, there is no available information to confirm the results and they are highly dependent upon an accurate representation of the controlled releases from Itzhi-tezhi reservoir (especially during drier years). If further information were available on the real patterns of inflows to the Kafue Gorge reservoir, it may be possible to modify the model configuration and re-calibrate the lower parts of the basin. Therefore the absence of a flow measuring station in the Kafue flats made it difficult to calibrate the parameters of the main model and the dummy reservoir to represent the situation in the Kafue flats floodplain. The simulated pattern of stored volume on the floodplain roughly conforms to non-quantitative information that is available in the Strategic Environmental Impact Assessment report on the observed extent of flooded areas for the same period (Scott Wilson, 2003a, b).

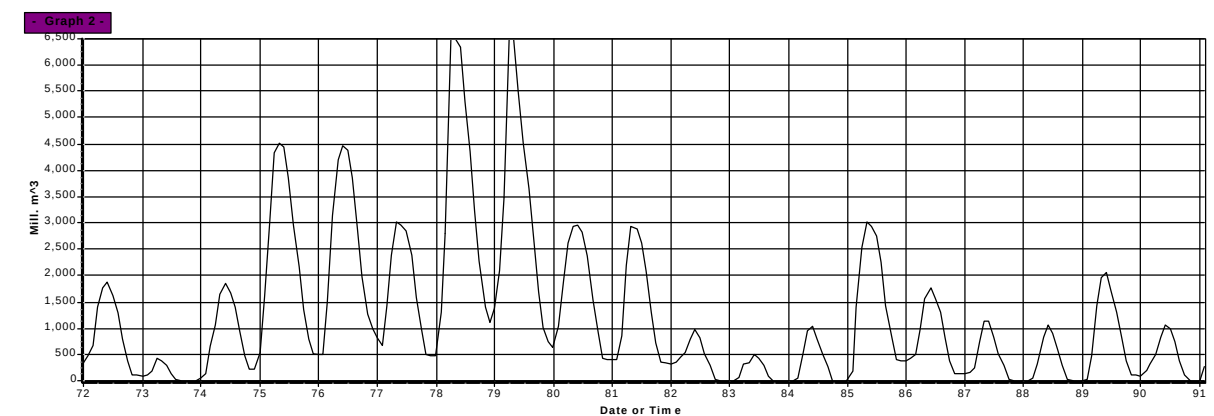


Figure 7.15 Simulated volume of the dummy reservoir representing storage on the Kafue flats floodplain.

7.5 CONCLUDING REMARKS ON THE RESULTS

The Pitman model calibration and simulations were made using the 1980 development conditions for the Kafue river basin and the calibration periods for individual sub-catchments varied depending on the availability of rainfall and observed flow. However, all sub-catchments cover the common period of October 1963 to September 1986. It should be noted that the discussion on results centred around two main components, the calibrated / fixed model parameters and the simulated flows in comparison to the observed flows.

Based on the modelling experience, data analysis and catchment characteristics, the following parameters were fixed and not calibrated: RDF; AFOR; and PEVAP. On the other hand the parameters ZMIN; ZAVE; ZMAX and POW were initially calibrated and once ranges were established, they were fixed to specific values for all the sub-catchments. The calibration process was therefore dominated by parameters ST and FT. Parameters ST and FT are the parameters which were generally the most sensitive and can therefore be considered as key parameters for the Kafue river basin. However the spatial variation of their values requires further investigation and a better understanding of the spatial dynamics of processes controlling runoff generation would assist in the future regionalization of parameters.

Overall, as can be seen from Tables 7.1 and 7.2, it can be concluded that there is a reasonable degree of consistency in the calibrated parameter values. This agrees with the generally homogeneous nature of the Kafue River basin. The range of parameters values does provide a good starting point for any future work in the Kafue basin and possibly the whole Zambezi basin. However there is not enough information about the real differences in basin characteristics to be able to confidently justify the parameter value differences from sub-catchment to sub-catchment. Further details about the distribution of Dambos is considered to be of particular importance, as these features may play a substantial role in runoff generation processes and the ‘physically appropriate’ values of several parameters

From the calibration/validation results for selected sub-catchments (Table 7.3), it was seen that there is no consistent difference in the performance of the model over the

two periods of calibration and validation and that the calibrated parameter values are generally equally suitable for both periods. This gives some reasonable degree of confidence that the results obtained in the calibration process are representative of the full observed record for the Kafue river basin

From the three objective functions used to measure success of simulation, it was seen that most of the sub-catchments achieved the mark of reasonable and acceptable correlation of $R^2 \geq 0.75$, $CE \geq 0.70$ and mean monthly percentage error of $-5\% \geq 0 \leq 5\%$. The reasons for deviation from the acceptable correlations have been attributed to the following: the less than satisfactory representation of the spatial rainfall distribution (this aspect recurs in the results for all the sub-catchments); poor observed streamflow data; a lack of information on the changes in land-use and water demand that may have occurred since the 1980s; lack of information on the physical characteristics that may have an influence on the runoff generation of the sub-catchments and; little understanding of the complexity of hydrological processes occurring in some sub-catchments related to physical features of swamps, floodplains and dambos.

It has been observed that since the physical nature of Kafue river basin is characterised by extensive wetlands, application of the Pitman model has to be done with some modifications to simulate the effects of these wetlands on the rainfall-runoff generation. While there is clearly scope for an improvement in the approach to simulating the effects of large wetland areas, the simulation results at sub-catchment R suggest that the approach adopted has been effective. The approach to simulating effects of large wetland areas therefore requires to be developed further in future Pitman model applications.

Given the lack of information to adequately define the operating rules of the two reservoirs, Itezhi-tezhi and Kafue Gorge, as well as the difficulties of configuring the model to represent the effects of the Kafue flats, the results of the simulated outflows and the actual regulated outflows at the outlet of the Kafue river basin (sub-catchment T) are reasonably good. In future studies, further effort in obtaining more data and information on dam operating rules and some data on the observed extent of Kafue flats flooding for some key years is required to improve the model calibration in the

complex Kafue flats. There is little doubt that part of the reason for the overall poor performance of the model at this point is also due to the lack of complete understanding of the dynamics of flow transference through the Kafue flats wetland, coupled with the lack of suitable model components to simulate these effects. This point is of major concern and would need to be addressed if the model were to be used for practical water resource management purposes in the future.

8 DISCUSSION AND CONCLUSIONS

The main objective of this section is to critically evaluate the available input climate data for the Kafue River basin as well as any supplementary information that has been used for the calibration of the Pitman model. The critical evaluation of the data is used to form conclusions about the model results and the applicability of the model for use in the planning and management of the water resources of the basin. In addition, the SPATSIM package, through which the data were organized and the model applied, will be evaluated. The discussions in this section will refer frequently to sections 5 (study area and available data) and 7 (results).

The evaluation of the available data is made, given the background and understanding that the whole point of applying and developing rainfall-runoff models is to overcome the lack of data that exists and which inhibits sustainable water resources management in many Zambian river basins.

Based on the data presented in section 7, for most of the sub-catchments a measure of simulation success has been achieved and acceptable correlations between simulated and observed flows were obtained ($R^2 \geq 0.75$, $CE \geq 0.70$ and mean monthly percentage errors of between 5 and -5%). However, there are still many shortcomings in the simulations and the effects of less than satisfactory representation of the spatial rainfall distribution and poor observed flow data (in some sub-catchments) are highlighted.

It should be noted that poor simulation results generated by a model may be caused by several interrelated factors and that it is never a simple task to determine which factor may be dominant in a specific model application. The following list provides a summary of the factors that could be relevant to this study:

- Inadequate representation of the spatial variations in input rainfall data.
- Inadequate representation of the spatial variation of potential evaporation, as well as the lack of time series of evaporation data.
- Inadequate, or inappropriate model formulation to represent the real processes affecting the generation of runoff from rainfall.

- Errors in observed streamflow data that can lead to inappropriate calibrated parameter values. An example would be the inability of some flow gauges to adequately measure high flows and therefore inaccuracies in the representation of peak wet season runoff volumes.
- Inadequate spatial and temporal detail within the model. This point is associated with the ‘lumping’ of spatial and temporal variations that occur in models like the Pitman model. An example of this has already been referred to, where the RDF parameter has been set at a fixed value of 0.8, when a different value for different monthly rainfall totals would match the observed data better (see Section 5).
- Inappropriate calibration procedures. This point is related to the parameter interaction that occurs in conceptual rainfall-runoff models and the general non-uniqueness of solutions given by specific sets of parameter values.

All of these factors together can contribute to less than satisfactory simulation results, but more importantly they can also contribute to the development of inappropriate parameter value sets. This issue assumes even greater importance in a regional study, where it is important that variations in parameter values should reflect ‘real’ variations in sub-catchment response characteristics.

8.1 IDENTIFIED DEFICIENCIES IN THE MODEL RESULTS

It has been concluded that, overall, the model results are satisfactory and that the calibrated model is able to reproduce the observed spatial and temporal variations in streamflow characteristics in the Kafue basin. However, there are some deficiencies that require highlighting so that these may be addressed during future investigations into the use of hydrological models within the region.

The results presented in section 7 suggest that one of the most obvious deficiencies is the frequent over- and under-simulation of peak wet season flows. This may be caused by a combination of inadequate input data, as well as the inability of the model to satisfactorily represent the real processes that occur during the high rainfall months.

A potentially related deficiency is the fact that the model generally tends to simulate seasonal recessions that are slower (less steep) than observed, especially in some of the headwater sub-catchments. This is difficult to interpret as a potential input data problem, although deficiencies in the representation of evapotranspiration losses may be a contributing factor. It would appear more likely to be related to a problem in the model formulation, or the calibration scheme. The surface runoff routing parameter (TL) has been set at a constant value of 0.25, following standard practice in South African catchments (Midgley et al., 1994). Reducing this to 0 improves the recession simulations, but at the expense of dry season flow simulations in some sub-catchments. Other changes to the basic approach to calibration also did not yield any general improvement, or if they improved the recession simulations, they adversely affected the simulation of other observed flow characteristics.

It was considered possible that a separation of two of the main runoff generation processes in the model (surface and ground water runoff from storage) might lead to improvements and section 8.1.1 briefly discusses the application of the revised ground water recharge and discharge routines that were added to the model during the course of this study (see Hughes, 2004).

There are a number of deficiencies in the model results downstream of the primary artificial influences in the basin represented by the two major reservoirs. However, these deficiencies were anticipated due to the lack of detailed information about the month-to-month variations in the operation of the dams.

8.1.1 Application of the revised ground water routines to sub-catchments A to F

A new version of the Pitman model (Hughes, 2004) was calibrated for sub-catchments A to F. While the full details of the revisions are not repeated here, the modifications have focused on adding more explicit ground water recharge and discharge components which are now separated from the runoff from moisture storage routines of the original model. Ground water recharge is estimated from a similar function that determines runoff from moisture storage, while ground water discharge is based on a simple representation of sub-surface storage geometry and the drainage slope of a conceptual water table. Several new parameters have been introduced (Drainage

Density, Storativity, Transmissivity and GPOW – the power of the recharge-surface moisture storage relationship), while the parameter GW has been redefined as the maximum recharge rate per month. The GL delay parameter is no longer used, as the new ground water recharge component is effectively routed through a storage function.

One of the perceived advantages of the revised model is the additional flexibility that is allowed for in calibration (although at the expense of more parameters to calibrate) and the fact that two of the runoff generating components are now more independent of each other (part of the surface runoff component driven largely by parameters FT and POW and the ground water component). Table 8.1 provides a summary of the changes that were made to the original parameter values, as well as the values used for the new parameters. The ranges for FT and GW refer to differences within the sub-catchments A to F. The transmissivity, storativity and drainage density parameters were set at values considered acceptable given the geology of the region, while the others were determined through manual calibration. No validation tests were undertaken for this limited evaluation.

Figure 8.1 compares the observed and two simulated time series for sub-catchment F and the following observations and initial conclusions can be made:

- There is very little difference in the simulations of the wet season peak flows.
- The dry season baseflows are better simulated by the revised model.
- There is some slight improvement in the simulations of the recessions in some years.
- The effects noted at sub-catchment F are repeated for the upstream sub-catchments.
- The calibration effort was no greater than for the original version of the model, although further work could be undertaken to assess the effects of varying the values of the ground water parameters that were fixed for this simple test (storativity, transmissivity and drainage density).

Based on these observations, the inclusion of the revised ground water routines (Hughes, 2004) into the Pitman model are likely to provide advantages, particularly if

they could be combined with more knowledge of the ‘real’ runoff generation process occurring within the catchment, or a better understanding of the geohydrological characteristics. It was always quite difficult to interpret geohydrological knowledge and understanding and use it to assist with setting parameter values in the original version of the model. The new version offers more opportunities in this regard, although, as yet this type of information is not readily available for the Kafue basin.

Table 8.1 Parameter changes between the original and revised versions of the Pitman model.

Model Version	Parameter	Original	Change
Parameters in old version	POW	4.0	4.5
	ZMIN	200	100
	FT	55 to105	50 to100
	R	0.2	0.0
Parameters in new version	GPOW	-	3.0
	GW	5 to10	5 to 10
	Drainage Density	-	0.6
	Transmissivity	-	20
	Storativity	-	0.01

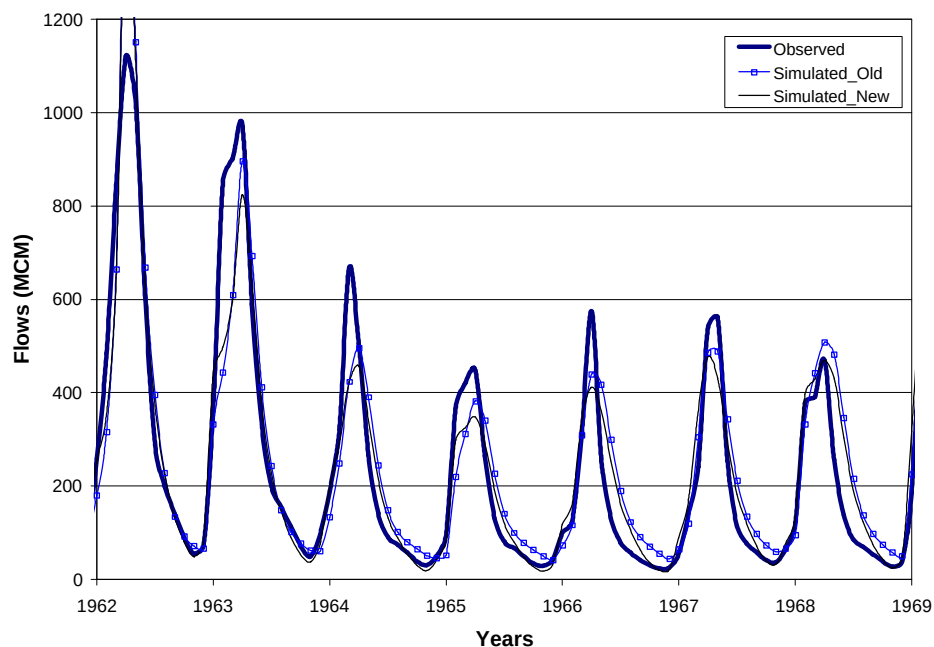


Figure 8.1 Comparison of observed and simulated flows based on the original (Old) version and the revised Pitman model (New) with ground water routines for sub-catchment F.

8.2 EVALUATION OF THE ZAMBIAN DATA FOR INPUT TO THE MODEL

The main input data required for the Pitman model is the monthly rainfall data and annual pan evaporation data. The observed flows are also critical to guide the model calibration process. Therefore the discussion in this section will be limited to these three data types and their impact on the model calibration and the quality of simulations.

8.2.1 Rainfall data

It should be pointed out that as regards the Pitman model, rainfall data is the single most important input in the simulation of runoff. One of the main reasons for use of rainfall-runoff models is the general understanding that collection of rainfall data is frequently more spatially representative than available flow measurements and that periods of observation are often longer for rainfall data than for streamflow data. The long rainfall records can be used as input into the model to generate streamflows for ungauged catchments and for the extension of streamflow data to sufficient lengths to allow for water resources planning and infrastructure designs.

Distribution of point rainfall data

The main requirement for successful simulations is that the distribution of point rainfall should be as representative as possible of the real variation of rainfall in a particular sub-catchment. Table 8.2 outlines the rainfall stations distribution per sub-catchment. .

The relatively sparse spatial distribution shown in Figure 5.2 and further summarised in Table 8.2, is likely to inhibit the generation of adequately representative catchment areal rainfall. Clearly the middle sub-catchments J, L, Q and R have a very poor distribution of rainfall stations. The anomalies in simulation that can be associated with a lack of representative rainfall data are mostly related to the under- and over-estimation of wet season high flows in individual years. This is a common phenomenon to varying degrees for all the sub-catchments. Low flows are less likely

to be affected to the same degree in this type of basin, where the representation of the moisture storage, evaporative loss and drainage characteristics of the basin will be more important.

Table 8.2 Number of rainfall stations per sub-catchment.

Map Label	Station Number	Sub-catch Area km ²	Cum. Catch Area km ²	Sub-catchment Name	Number of rainfall stations
A	4050	4 999	4 999	Kafue at Raglan Farm	1
C	4090	2 149	7 148	Kafue at Kafironda	2
D	4120	869	869	Mwambashi at Mwambashi	1
E	4150	1178	9 195	Kafue at Wusakile	1
F	4200	2 460	11 655	Kafue at Mpatamato	0
G	4205	2 499	2 499	Kafulafuta at Ibenga	1
H	4260	4 572	18 726	Kafue at Ndubeni	5
I	4280	4 194	22 920	Kafue at Machiya	1
K	4340	8 708	8 708	Luswishi at Kangondi	1
J	4350	2 534	34 162	Kafue at Chilenga	0
L	4307	16 317	50 479	Kafue at Mswebi	2
Q	4450	3 963	54 442	Kafue at Lubungu	0
M	1	8 100	8 100	Lunga at Chipembebe	2
N	4550	11 455	19 555	Lunga at Kelongwa	1
O	4560	1 890	21 445	Lunga at Chifumpa	1
P	2	9 450	9 450	Lufupa at Ntemwa Camp	1
R	4669	9 716	95 053	Kafue at Hook Bridge	0
S	460995	10 619	105 672	Itezhi-tezhi	3
T	470800	47 138	152 810	Kafue Gorge	9

From the analysis of the spatial variations in monthly rainfall patterns, it is apparent that rainfall stations at similar latitudes showed a better correlation (based on both monthly and daily time series data) and therefore were much better for filling missing data gaps than stations to the north or south, which may be geographically closer but have lower correlations. This north to south variation of rainfall distribution gives the Kafue River basin an advantage in that even if the rainfall station is further away from the sub-catchment, as long as it is at a similar latitude, it is likely to provide representative catchment areal rainfall, at least in terms of monthly depths. Therefore it can be said that the number of rainfall stations, though less than ideal, should be sufficient to permit reasonable model calibrations to be achieved. However, it is also evident that there are some periods within the total modelling period, when the existence of missing data at key stations means that less than ideally located gauges are used to generate areal rainfall inputs in some sub-catchments.

Record length and continuity

As the generation of streamflow depends on the rainfall data, it is desirable to have continuous data for at least 15 years to provide a meaningful length of simulated flows for statistical analysis. The shorter the record length, the less likely would the model be able to generate flows that would be comparable to a longer period of observed flows. This is largely because the period would not contain a sufficient number of calibration ‘signals’ to be able to develop a sufficiently representative parameter value set. For the Kafue basin, all the stations with less than 15 years of record were excluded from the list of inputs (Table 5.5). Given the acceptable results of the validation test, as presented in section 7.3 and Table 7.3, it can be concluded that the rainfall record lengths and their continuity were sufficient to provide a reasonably good set of input data for the generation of runoff.

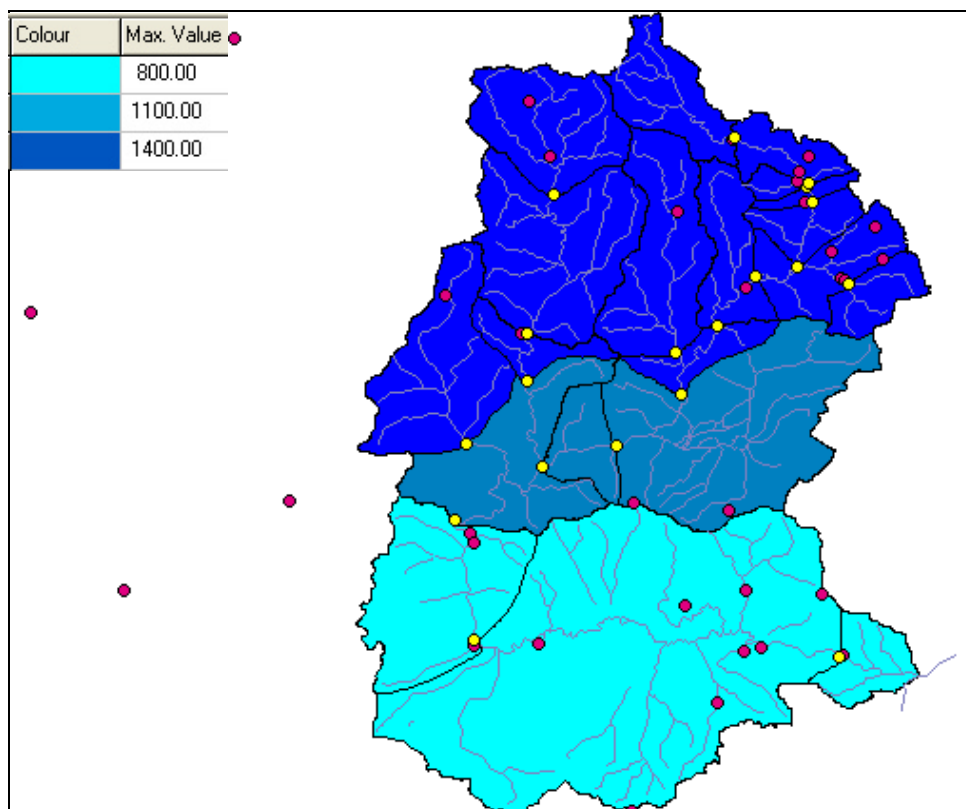


Figure 8.2 Spatial distribution of the rainfall stations and mean annual rainfall distribution (darker dots represent rainfall stations while the lighter dots represent streamflow stations).

8.2.2 Annual pan evapotranspiration data

While evaporation data are an important input into the Pitman model, the association between typically available evaporation data (either from pans, or from climate variable data and estimation equations) and the actual processes of evapotranspiration loss are less than clear. This is partly because there are generally no readily accessible and practical methods of measuring actual evapotranspiration losses at the catchment scale. The use of potential evaporation data as input to rainfall-runoff models is therefore a pragmatic, but generally inadequate, solution to an otherwise intractable problem.

The data available for the Kafue basin are based on insufficient measuring points with a very sparse spatial distribution and incomplete time series. Individual sub-catchment values were extrapolated from the nearest station in each case (see section 5). The model results are also based on mean monthly potential evaporation data with a fixed seasonal distribution and no inputs of likely time series variations. Given the generality of the evaporation input data used for the Kafue River basin, it is likely that this would account for some of the difficulties experienced in achieving satisfactory regional calibrations of the model.

The main reason for the lack of data is that there are few meteorological stations where pan evaporation measurements are taken. Table 8.3 indicates that sub-catchments C, D and E were assigned mean monthly values from Kafironda; F, G, H, I and K were assigned values from Ndola station; J, L and Q were assigned values from a boundary station Kabwe; M, N and O were assigned values from Kasempa; while P and R were assigned values from Kaoma, a station which is outside the basin.

For some sub-catchments with extensive wetlands and reservoirs, representative evaporation data is of key importance and the absence of, or lack of representative data, would account for some poor comparisons between the observed and simulated flows. Efforts are therefore needed in future studies to improve the representativeness of evaporation data over each sub-catchment.

During a similar study in the Okavango basin (Hughes et al., 2005), an attempt was made to improve simulations using satellite based surface temperature data to provide the time series signal of evaporative losses and to weight the mean monthly potential evaporation data that were available. While small improvements were evident, the use of these additional data did not make a substantial contribution to the success of the modelling exercise. This serves to illustrate the difficulty of providing satisfactory evaporation loss demand information to hydrological models.

8.2.3 Observed flows

From the extensive assessment undertaken for observed streamflows reported in section 5.3, it can generally be concluded that the observed streamflows used in the simulations, especially for periods before the late 1980s, are of reasonably good quality for model calibration purposes. However, there are a few exceptions where some sub-catchments have rather suspect quality observed flows. The model calibration exercise has highlighted these suspicions of poor quality, while conformation must be based on a detailed and thorough analysis of the records themselves.

From the calibration process, sub-catchment O appears to have a problem with the gauge rating curve, as it consistently shows lower peak flows than sub-catchment N, when it is 1 890 km² larger. This potential problem in the observed flows has been reflected in the consistently lower correlation between the simulated and the observed flows. Sub-catchment O also reflected a different FT value departing from the similarity that was seen for the M and N sub-catchments in the Lunga tributary catchment. From the CE values analysis, sub-catchment O has $R^2 = 0.69$ with CE = 0.57 (log values). This result indicates the presence of systematic errors and one of the major sources of systematic errors in observed flows is a poorly developed water level – discharge rating curve.

Sub-catchment G has one of the worst calibration results and the poor correlation between the simulated and observed flows could be attributed to questionable observed streamflow data. However, as sub-catchment G is a relatively small tributary catchment (area = 2 499km²), its response to specific rainfall events is more

pronounced and if there is lack of representativeness in the rainfall data used in the simulation, the differences would be even more evident and may also contribute to poor correlations between observed and simulated flows.

Table 8.3 Distribution of nearest Evaporation stations for sub-catchments.

Map Label	Sub-catchment Name	Nearest Meteorological station data used
A	Kafue at Raglan Farm	Solwezi
C	Kafue at Kafironda	Kafironda
D	Mwambashi at Mwambashi	Kafironda
E	Kafue at Wusakile	Kafironda
F	Kafue at Mpatamato	Ndola
G	Kafulafuta at Ibenga	Ndola
H	Kafue at Ndubeni	Ndola
I	Kafue at Machiya	Ndola
K	Luswishi at Kangondi	Ndola
J	Kafue at Chilenga	Kabwe
L	Kafue at Mswebi	Kabwe
Q	Kafue at Lubungu	Kabwe
M	Lunga at Chipembebe	Kasempa
N	Lunga at Kelongwa	Kasempa
O	Lunga at Chifumpa	Kasempa
P	Lufupa at Ntemwa	Kaoma
R	Kafue at Hook Bridge	Kaoma
S	Itezhi-tezhi	Magoye
T	Kafue Gorge	Kafue Polder
U	Zambezi-Kafue Conf.	Kafue Polder

The quality of observed flows cannot be underestimated in determining the measure of success of any calibration process, which may cause parameters to lose their relevance and association with catchment physical characteristics. However, in the Kafue river basin, it is evident that most of the observed flows are of a reasonably good quality to form the basis for sound model calibrations.

8.2.4 Water use data

Water use information has been allowed for in the model using fixed values for the whole modelling period, while available information suggests that quite substantial changes have taken place during that time. Many of the changes are relatively small compared to the volumes of flow from the basin, but could be significant locally (sub-catchment G, for example). The water use information is based on license permits to

abstract water, while the actual amounts of water abstracted are not readily available in most parts of the basin. This is a typical situation for many parts of southern Africa and make it very difficult to naturalise historical flow data, or to correct historical flow data to generate a stationary time series of flows, representing a constant level of water resource development.

Despite these comments, it has not been possible to identify such influences on the model calibration exercise in the Kafue basin. Either the water use variations are too small to be noticeable and are masked by variations in climatic inputs over the modelling period, or documented changes have not really occurred.

8.3 EVALUATION OF THE MODEL RESULTS

Overall, the simulation results can be said to be satisfactory and the calibrated model can be used with a reasonable degree of confidence for investigating water resource development options within the Kafue basin. However, as expected, the confidence in the results is affected by uncertainties relating to the quality of the available data.

There are several outstanding issues that require further information and investigation for the degree of confidence in the use and application of the model to increase:

- The extent to which some of the differences in parameter values between sub-catchments reflect differences in the representativeness of the input rainfall data.
- The extent to which some of the differences in parameter values between sub-catchments reflect differences in the quality of observed flows and the accuracy of the rating curves for the streamflow.
- Whether inclusion of more representative evaporation data and time series of potential evaporation demand would improve the simulations.
- Whether more detailed time series information about the actual patterns of release from the two reservoirs would allow improved calibrations to be achieved;

- Whether information about the patterns of inundation in the Lukanga swamps and the Kafue Flats would allow improved calibrations to be achieved.
- Very little information is currently available about spatial variations in land use and vegetation cover and it has not been possible to accurately represent these (and consequently evaporation losses) in the model. Investigate whether additional information would improve the calibrations and would account for some of the differences in other calibrated parameter values.
- Whether the application of the revised model with new ground water simulation routines would improve the simulations throughout the basin.

Answers to the above questions would have the potential to increase the confidence with which the model is applied to the Kafue basin and would also help with regionalisation of the model parameters to ungauged catchments, which is one of the primary objectives of the calibration exercise.

It is clear that the model can be considered applicable in this region, the available data are adequate, if not ideal, for establishing the model and there is a reasonable degree of consistency across the various sub-catchments to suggest that regionalisation is possible to a certain degree.

8.4 EVALUATION OF SPATSIM AS A METHOD OF APPLYING THE MODEL AND STORING DATA

SPATSIM is a generic software package designed as a database, data analysis and modelling system, specifically for hydrological and water resource applications (Hughes, 2002). It has been developed using the Delphi programming language with links to Paradox database tables and uses ESRI Map Objects to provide the spatial data display and analysis facilities. (Refer to detailed description of SPATSIM in section 4.2).

The facilities that are included within SPATSIM to enable data to be stored, displayed and processed can be divided up into internal facilities that are not specific to any

application and external processes that include a wide range of hydrological, water resource and eco-hydrological models some of which are listed in the screen display in Figure 8.3. It is designed to be as user-friendly as possible with help facilities accessible within the software, or via the ‘Hydrological Software’ link on the Institute for Water Research web site (<http://www.ru.ac.za/iwr/software/spatsim.html>).

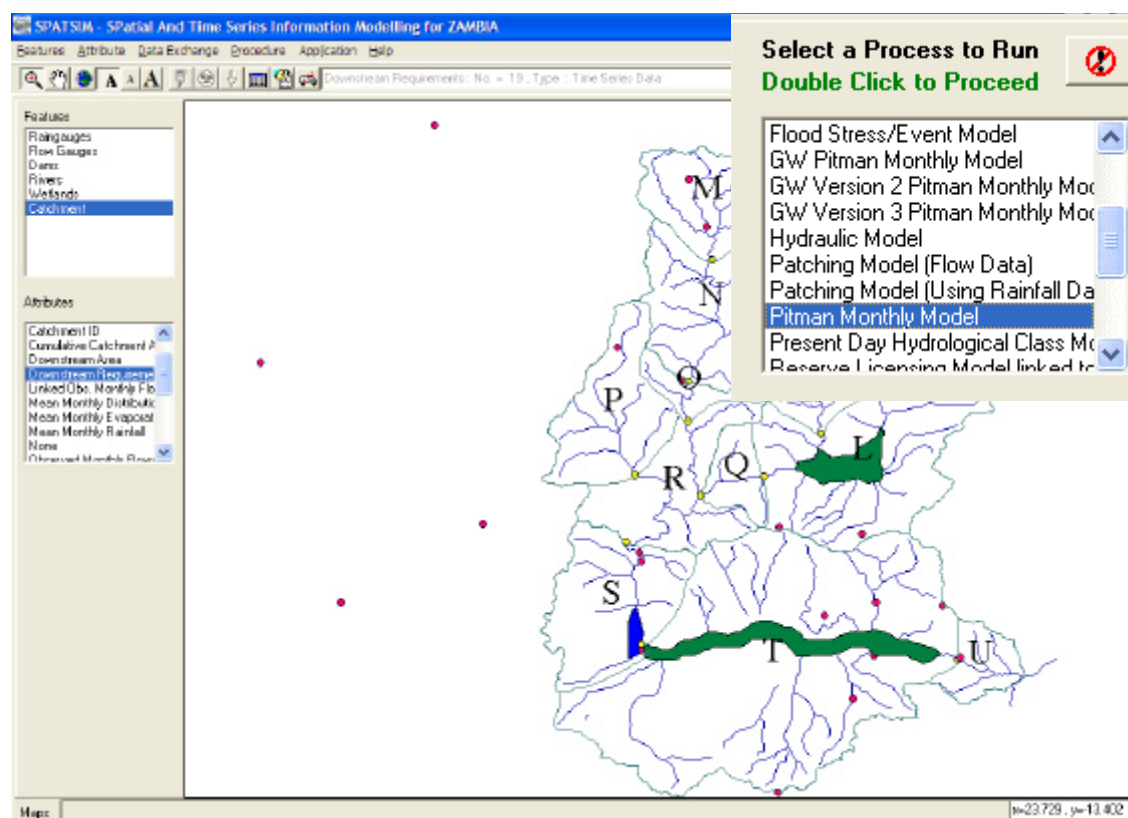


Figure 8.3: SPATSIM and some of the linked external processes

The SPATSIM package was developed with the needs of hydrological and water resource models in mind, and therefore it is designed to provide all the basic facilities needed (from data preparation to calibration process) to undertake model calibrations. In the assessment of the software as a method of applying the model and storing data, the successful calibration process for the Kafue River basin can be given as an example in that the whole process of Pitman calibration presented in this report was achieved with little use of other programs, the majority of the requirements being met by SPATSIM itself. One area where external programs are required is in the presentation of time series results. The output options from SPATSIM (specifically the graphics outputs from TSOFT) are somewhat limited and do not usually provide

‘report quality’ graphics. However, it is a relatively simple process to export the data and use the graphics capabilities of a spreadsheet program to produce the required diagrams (for example, Figure 8.1). While the GIS capabilities of SPATSIM are relatively limited, the rendering facility is very useful for displaying the geographic distribution of parameter values or summary indices of hydrology or climate (see Figure 8.2 for example). As SPATSIM makes use of shape files for the spatial data, it is a relatively simple matter to use one of several commercial GIS packages for any additional spatial analyses, or spatial data manipulations, that are required.

Since the software has been developed by a research and teaching organisation (Institute for Water Research), it is being continuously developed and upgraded in order to be responsive to the needs of the user group (now represented by some 30 individuals and groups within southern Africa, as well as a few in other parts of the world). In the last two years (2002 – 2004) the software has been upgraded from version 2.0.0.0 to 2.0.0.6.

With respect to its evaluation for use in the type of study referred to here, it should be further emphasized that it is not designed to apply only one model, but any of several models. This means that some of the user actions required are slightly more complicated than if the system was designed for a single purpose. This implies that the learning and familiarisation process is also somewhat longer. However, the advantages of being able to apply several linked models within the same data management environment should outweigh the disadvantages of spending more time learning how to use the package.

In general terms, many of the hydrology and water resource models that are available within the southern African region have been based on DOS operating systems that access their data from, and write results to text files. This implies that many users of hydrological models are less than familiar with the concepts of storing information in database tables. This can cause confusion for first time users of the SPATSIM system and takes some time to get used to. This is, however, a problem that is soon overcome as users become familiar with the package. The use of database tables certainly makes managing the large amounts of data associated with a modelling study of this type much more efficient in the long-term.

The concepts of referencing data through the SPATSIM ‘attributes’ and managing these, can also be somewhat difficult to learn at first. It is important to manage the names of these attributes properly, otherwise the user can become confused and easily forget where specific data are stored. It would be an advantage to have some kind of internal text ‘dictionary’ that could include user-entered explanations of what each attribute is and what type of data are stored. This is especially relevant if there are long gaps between using a specific application of SPATSIM.

The graphical display and time series comparison capabilities of TSOFT are particularly useful in the context of calibrating a rainfall-runoff model. The ability to visually examine, and statistically compare, a number of sets of results as parameters are changed is a great help in any manual calibration process. The methods available for summarising time series, such as flow duration curves and seasonal distributions are also very helpful.

8.5 CONCLUDING REMARKS

The discussions in this section have established a reasonable degree of confidence in the future application of the Pitman model in the Kafue River basin. The conclusions are based on the author’s experience in the application of the Pitman model as regards to the quality of input data, the efficiency of the Pitman model and the SPATSIM package for the application in water resources assessments.

The following broad conclusions have been made:

- The overall Pitman model results were found to be satisfactory and the calibrated model is able to reproduce the observed spatial and temporal variations in streamflow characteristics in the Kafue River basin.
- The deficiencies that have been observed in the simulation may be related to a combination of inadequate input data and the inability of the model to satisfactorily represent the real hydrological processes during high rainfall months.
- Some of the deficiencies suggest that modifications to the model could be beneficial. The addition of a more explicit ground water routine that has already

been added to the model (Hughes, 2004) was tested and there are indications that it could contribute to improving the simulations.

- Deficiencies in the input data can be identified using the model simulation results and assist in finding solutions that would lead to improved water resource estimations. However, some input data problems, such as inadequate rainfall stations are difficult to resolve and may suggest alternative sources of spatially distributed climate information through the use of satellite data. The investigation of such options is one of the objectives of the IAHS, PUB programme (Sivapalan, 2003).
- The SPATSIM package, with its associated internal and external utilities, has been assessed to be a package that is able to provide the basic facilities needed to undertake model calibration and therefore a useful tool to assist with the successful application of models in a region of this type.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 OVERALL CONCLUSIONS ON THE MODELLING EXERCISE

This modelling exercise for the Kafue River basin has confirmed many of the conclusions reached during Phase I of the Southern Africa FRIEND programme (Hughes, 1997). Despite the limitations of the data, there are clear indications that regionalised rainfall-runoff modelling of catchments in Southern Africa is feasible. The Kafue example has indicated that it is important to be able recognise, conceptualise and quantify special cases where natural runoff processes (Lukanga swamps and the Kafue flats) or man-made influences (the Itezhi-tezhi and Kafue Gorge dams) are complex. Without this information, calibration parameters will not be a true reflection of the runoff process and parameter transfer to ungauged areas is unlikely to generate realistic results.

The Pitman model is no different from most conceptual models in that there is rarely an optimum solution based on a unique combination of parameter values for a specific basin. This presents a real challenge with respect to the design of calibration, as well as parameter regionalisation procedures especially in the case where limited information is available on basin characteristics making it difficult to determine suitable relationships between the specific basin characteristics and calibrated parameter values.

The Kafue River basin is an important catchment where most of Zambia's national development activities such as mining, agriculture and hydropower generation and all major urban areas are concentrated and it therefore requires practical ways of ensuring an improvement in the understanding of available water resource potential and the development of user friendly hydrological assessment tools to aid water resource assessment.

It can be said that this study, with the results produced, has laid a foundation for further water resource assessments and appraisal using the Pitman model. It is therefore recommended that further studies be concentrated on generating information

on the physical characteristics of the sub-catchments in order to ascertain with confidence the association and relationships between certain parameter values and physical catchment characteristics. This aspect is very important for any future attempts to regionalise parameter values with confidence and for the successful application to ungauged catchments, which is one of the key reasons for development and application of the rainfall-runoff models.

The modelling exercise presented in this report may not be considered to be purely academic, but has been done in order to meet the aspirations of the institutions responsible for water resources management in the southern Africa region. These aspirations are also reflected in the objectives of the Southern African FRIEND programme which had the objective of enhancing the understanding and capacity in the use and application of rainfall-runoff models. SADC, through PCN 14, have also called for the enhancement of regional water resource assessments, improvement of knowledge and information for improved water resources management and the need to produce a regional surface water resource assessment mechanism. The modelling exercise has therefore attempted to contribute to these objectives, being used as a starting point (pilot) for the regional expansion of the application of rainfall-runoff models. It is therefore recommended that this pilot study on the Kafue River basin be expanded in scope to study the physical characteristics of the sub-catchments in greater detail, so that the application to other SADC regional catchments will be based on the comprehensive framework that would be developed.

This modelling exercise has been used to compile and generate a lot of useful information on the Kafue River basin which, at the local level has already been used in two important studies (Scott Wilson, 2003a,b; DHV, 2004). Given the absence of valuable hydrometric data, it is becoming increasingly important to use modelling tools to generate missing data for simulations and water resources planning. The Integrated Kafue River basin study (Scott Wilson, 2003a) used the data compiled from this study to gain a good understanding of the hydrological system in the basin and the Pitman model data for the estimation of tributary flow contributions to the Kafue flats. The Integrated Water Resources for Kafue Flats Study (DHV, 2004) used the data compiled by this study and included the Pitman model for the prediction of flows in the upper Kafue basin.

This modelling exercise has also brought to the fore the issues regarding quality of the input data, difficulties related to working with poor quality data in modelling and how some difficulties can be resolved. Associated with the data preparation for input, were data checking, correction and compiling. The result has been the generation of a cleaned up database that can be easily updated for future work in modelling application.

Specific recommendations in terms of the future application of the Pitman model are the need to re-evaluate the approaches to simulating the effects of the two main wetland systems and a more complete assessment of the new ground water version of the model. In terms of improving the availability of input data to the model, it is recommended that international trends in the use of satellite data for both rainfall and evaporative loss estimation are assessed and applied to the region.

9.2 CONCLUSIONS ON THE DEVELOPMENT AND APPLICATION OF SPATSIM

Great strides have been made in the development and application of SPATSIM with its associated models, within the South African context. It would be useful if this could now be replicated in other SADC countries. There is clearly a need for a practical training component to enable the transfer of this technology to be effective and sustainable. The development of SPATSIM has continued since the year 2000 and has now reached a stage where it is relatively free of critical errors and is being distributed to a wider group of users. It provides a very efficient method of storing and accessing the type of data used and generated within modelling studies, while it also seems to be relatively straightforward to learn how to use. The latter is an important conclusion if the software is to be considered as a candidate for wider use within the SADC region for water resource assessments.

The SPATSIM version of the Pitman model has been thoroughly tested and checked to ensure that it generates stable and repeatable results and is also relatively straightforward to set-up and use. The automatic optimizing function has been included and is a valuable addition to the available modelling facilities. One of the

advantages it provides is a check to ensure that the manually calibrated parameters for the headwater catchments were reasonably close to optimum values.

One important aspect of the development of SPATSIM is the ability of the developers to respond to future water resource management user needs. For the South African water resources sector, the software has been frequently updated to try and meet specific water resource assessment needs. In the last two years (2002 -2004) SPATSIM has been revised six times, each version provided with an update in order to meet the ever-changing needs of the water managers. The author would not hesitate to recommend that this tool be developed further for the SADC wide region to help with water resources assessment aspects. Outside South Africa it has already been applied (either by the Institute for Water Research or by collaborating partners) to the Okavango basin, catchments in Zimbabwe, Tanzania, Swaziland and Mozambique, while several southern African groups or individuals have received training.

9.3 RECOMMENDATIONS FOR FURTHER STUDIES IN ZAMBIA AND THE REST OF SADC

Sections 1 and 2 of this report refer to the background objectives that led to the conception of this study which was meant to be part of an initial step in establishing the proposed long-term study of water resource availability in the SADC region. Sufficient ground has been covered in this study and very interesting results generated. It is therefore recommended, in accordance with the SADC water sector and FRIEND aspirations, that this study be expanded to enable more detailed assessment to be made, especially with respect to the derivation and verification of relationships between parameters and physical catchment variations.

Such further studies and the expanded scope would allow for an improvement in the confidence of regional parameter transfer and estimation at ungauged sites. It is therefore recommended that the Kafue basin be studied to sufficient depth which will allow better replication to other basins in the region

For the sake of sharing information and building capacity, the author has benefited from the regional initiative and would therefore be willing to share the valuable

experience gained in working closely with the Institute of Water Resources to help build capacity and raise the interest and awareness of the benefits of applying models in water resources assessment.

REFERENCES

- Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Rasmussen, J., 1986a. An Introduction to the European Hydrological System – Système Hydrologique Européen, “SHE”, 1: History and Philosophy of a Physically-Based, Distributed Modelling System. **Journal of Hydrology**, 87: 45-59.
- Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Rasmussen, J., 1986b. An Introduction to the European Hydrological System – Système Hydrologique Européen, “SHE”, 2: Structure of a Physically-Based, Distributed Modelling System. **Journal of Hydrology**, 87: 61-77.
- Balek, J., 1971. **Water balance of the Zambezi Basin**. National Council for Scientific Research, TR 15/WR8, Lusaka, Zambia.
- Beater, A., 1989. **The Application of Two Simple Single Event Rainfall-runoff Models to Catchments with different Climate and Physiography**. Rhodes University, Grahamstown, South Africa.
- Beven, K., 1991. Spatially Distributed Modeling. Conceptual Approach to Runoff Prediction. In: D.S. Bowles and P.E. O'Connell (Editors), **Recent Advances in Modelling of Hydrologic System**. Kluwer Academic Publishers. The Netherlands, pp. 373-387.
- Beven, K.J., 1989. Changing ideas in hydrology – the case of physically-based models. **Journal of Hydrology**, 105: 157-172.
- Beven, K.J., 2001. **Rainfall-runoff modelling – The primer**. John Wiley & Sons, Chichester.
- Beven, K.J., and Hornberger, G.M., 1982. Assessing the effect of rainfall pattern of precipitation in modeling streamflow hydrographs. **Water Resour. Bull.**, 18 (5): 823-829.

- Beven, K.J., and O'Connell, P.E., 1982. **On the role of physically-based distributed modeling in hydrology**. Report No. 81, Institute of Hydrology, Wallingford, United Kingdom.
- Beven, K.J., Wood, E.F., and Sivapalan, M., 1988. On Hydrological Heterogeneity: Catchment Morphology and Catchment Response. **Journal of Hydrology**, 100:353-375.
- Blöschl, G., and Sivalapan, M., 1995. Scale issues in hydrological modelling – a review. **Hydrolog. Process.**, 9: 251-290.
- Bonne, J. 1970. **Stochastic simulation of monthly streamflow by a multiple regression model**. Ph.D. Thesis, University of Nevada, University Microfilms, USA.
- Bosman (1990). Methods to convert American Class A pan and Symons tank evaporation to that of a representative environment, **Water SA**, 16 (4): 227-236.
- Burke, J.J., Jones M. J. and Kasimona, V., 1994. Approaches to integrated water resource development and management of the Kafue basin, Zambia. In: C. Kirby and W.R. White (Editors), **Proc. Integrated River Basin Development International Conference**. John Wiley & Sons, Chichester.
- Chapman, T.G., 1975. Trends in catchment modeling. In T.G. Chapman and T.X. Dunin (Editors), **International Association of Hydrological Sciences Publication**. 96: 126-144
- Chibanga, R., 2002. **Modeling of rainfall-runoff and streamflows in the Kafue catchment and optimisation of water resource allocation**. Ph.D. Thesis, Katholieke Universiteit Lueven, Belgium.
- Clarke, R.T. 1973. A review of some mathematical models used in hydrology, with observations on their calibration and use. **Journal of Hydrology**. 19(1973): 1-20

- Coats, J.S., Mosley, P.N., Mankelow, J.M., Mwale, M., Chikambwe, E.M., Muibeya, B., Ndhlovu, K.C., Nzabara, F., 2001. **The Geology and Mineral Resources of Zambia**. Memoir 6, Geological Survey Department, Lusaka, Zambia.
- Crawford, N.H., and Linsley, R.K., 1962. The syntheisi of Conitnuous Streamflow Hydrographs on a Digital Computer. **Technical Report No.12**, Department of Civil Engineering, Stanford University.
- Dawdy, D.R. and O'Donnell, T, 1965. Mathematical Models of Catchment Behaviour. **J. Hydraul. Div.**, Proc. Am. Soc. Civ. Engrs., 91 (HY4): 123-127.
- Dawdy, D.R. and Bergman, J.M., 1969. Effect of rainfall variability on streamflow simulation. **Water Resour. Res.**, 5: 958-969
- DHV Consulting Engineers, 1980. **Kafue Flats Hydrological Studies**. Final Report. Amersfoot, The Netherlands. For the Ministry of Agriculture and Water Development, Department of Water Affairs, Mulungushi House, P. O. Box 5028, Lusaka, Zambia.
- DHV Consultants, 2004. **Decision making system for Improved Water Resources Management for the Kafue Flats - Integrated Water Resources Management Project for the Kafue Flats – Phase 2 Final Report**. Report produced for WWF Partners for Wetlands Project, Lusaka, Zambia.
- Dobson, A. J., 1983. **An Introduction to Statistical Modelling**. Chapman and Hall, London, UK.
- Dunne, T., 1978. Field studies of Hillslope Flow Processes. In M.J. Kirkby, (Editor.), **Hillslope Hydrology**. John Wiley and Son, Chechester, United Kingdom.
- Eckhardt, K. and Arnold, J. G., 2001. Automatic calibration of a distributed catchment model. **Journal of Hydrology**. 251, 1-2: 103-109

- FAO., 1968. Multipurpose Survey of the Kafue River Basin. Final Report. **Volume III, Climatology and Hydrology**. UNDP, Rome.
- Fleming, G., 1975. Computer simulation techniques in hydrology. **Environmental Sciences Series**, Elsevier, New York
- Görgens, A. H. M., 1983. **Conceptual modelling of the rainfall-runoff process in semi-arid catchments**. Hydrological Research Unit, Report No. 1/83, Rhodes University, Grahamstown, South Africa.
- Gumbrecht, T., 2000. **Spatial data and applications for environmental studies in Africa**. Department of Geology, University of the Witwatersrand. South Africa.
- Gupta, V.K., and Sorooshian, S., 1985b. The automatic calibration of conceptual catchment models using derived-based optimization algorithm. **Water Resources Research** 21(4): 473-486
- Handlos, W. L., 1984. **Development of the Kafue Flats – the last five years**. Kafue Basin Research Committee, University of Zambia, Lusaka. Zambia.
- Herald, J.D., 1989. **Statistical modeling of rainfall and runoff in semi-arid areas of the eastern cape Province**. Hydrological Research Unit, Report 2/89, Rhodes University, Grahamstown, South Africa.
- Hewlett, J.D. and Hibbert, A.R., 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: W.E. Sopper and H.W. Lull (Editors.), **Forest Hydrology**. Pergamon, London.
- Horton, R.E., 1933. The Role of Infiltration in the Hydrological Cycle. **Trans. Am. Geophys. Union**, 14: 446-460.
- Hughes, D. A., 1985. Conceptual Catchment model parameter transfer investigations in the Southern Cape. In: **Water SA** Vol 11 No. 3 of July 1985

- Hughes, D.A., 1992. Variable time intervals in deterministic models. **Journal of Hydrology**, 143: 217-232.
- Hughes, D.A., 1995. Monthly rainfall-runoff models applied to arid and semiarid catchments for water resource estimation purposes. **Hydrological Science Journal**, 40(6): 751-769.
- Hughes, D.A., 1997. **Southern African “FRIEND” – The Application of Rainfall-Runoff Models in the SADC Region**. Water Research Commission Report No. 235/1/97, Pretoria, South Africa.
- Hughes, D.A., 2002. The development of an information modeling system for regional water resource assessments. In: H.J. van Lanen and S. Demuth (Editors), **FRIEND 2002 – Regional Hydrology: Bridging the Gap between Research and Practice**. Proc. 4th FRIEND Conf., Cape Town, March 2002. IAHS Publ. No. 274: 43-49.
- Hughes, D.A., 2004. Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. **Hydrological Sciences Journal**, 49(2) April 2004: 297-311
- Hughes, D.A., 2005. Three decades of hydrological modeling research in South Africa. **South African Journal of Sciences, Special Rhodes University Centenary Edition** (Accepted for publication), South Africa.
- Hughes, D. A. and Beater, A. B., 1989. The application of two single event models to catchments with different physical characteristics. **Hydrol. Sci. J.**, 34, 63-78.
- Hughes, D.A., Sami K. and Murdoch K. A., 1993. **Hydrological Models Development and application**. Report to the Water Research Commission by the Institute For Water Research, Rhodes University. WRC Report No. 235/1/93; IWR Report No. 2/93
- Hughes, D.A., and Sami, K., 1994. A semi-distributed, variable time interval model of catchment hydrology – structure and parameter estimation procedures. **Journal of Hydrology**, 155: 265-291.

Hughes, D.A. and Forsyth, D., 2002. **SPATSIM – Spatial and Time Series Information Modelling Software User’s Guide**. Institute for Water Research, Rhodes University, Grahamstown, South Africa.

Hughes, D.A., Görgens, A., Middleton, B. and Hollingworth, B., 2002. Regional water resource assessments in the SADC region. In: H.J. van Lanen and S. Demuth (Editors), **FRIEND 2002 – Regional Hydrology: Bridging the Gap between Research and Practice**. Proc. 4th FRIEND Conf., Cape Town, March 2002. IAHS Publ. No. 274: 11-18.

Hughes, D.A., Forsyth, D. and Watkins, D.A., 2000. **An integrated software package for the analysis and display of hydrological or water resources time series data**. Water Research Commission Report No. 867/1/2000, Pretoria, South Africa.

Hughes, D.A., and Metzler, W., 1998. Assessment of three monthly rainfall-runoff models for estimating the water resource yield of semiarid catchments in Namibia. **Hydrol. Sci. Journ.**, 43(2): 283-297.

Hughes, D.A., Mwelwa, E.M., Andersson L., and Wilk, J., 2003. Regional Water Resources and River Flow Modelling. In: J. Meigh and F. Matt (Editors), **Southern Africa FRIEND Phase II 2000 – 2003**. Centre for Ecology & Hydrology, Wallingford, UK

Hywel, D. D., 1971. **Zambia in Maps**. University of London Press, London. UK

Institute of Hydrology, 1994. **Hydrological Review of the Kafue River, Zambia**. Wallingford, United Kingdom

Ibbitt, R.P. and O’Donnell, T., 1971. Fitting methods for conceptual catchment models. **Journal of Hydraulic Division, American Society of Civil Engineering**, 97(HY9): 1331-1342

James, L.D., 1972. Hydrologic modeling, parameter estimation and watershed characteristics. **Journal of Hydrology**, 17: 283-307

- James, L.D., 1991. Hydrologic Modeling for Water Resources Planning. In Bowles D.S and P.E. O'Connel (Editors), **Recent Advances in the Modeling of Hydrologic Systems**. 559-570. Kluwer Academic Publishers. The Netherlands.
- Klatt, P., and Schultz, G.A., 1981. Improvement of Flood Forecasts by Adaptive Parameter Estimation. **Proc. International Symposium on Rainfall Runoff Modelling**, Water Resources Publications, Littleton, CO.
- Klemeš V., 1986. Operational testing of hydrological simulation models. **Hydrological Science Journal**, 31: 13-24
- Kovar K., and Nachtnebel, H.P., (Editors), 1993. Application of Geographic Information Systems in Hydrology and Water Resources Management. Proceedings of an international conference, Vienna, April 1993. **IAHS Publ.** No. 211.
- Krajewski, F.W., Lakshmi, V., Georgakakos, K.P. and Subhash, C.J., 1991. A Monte Carlo study of rainfall sampling effect on a distributed catchment model. **Water Resour. Res.**, 27 (1): 119-128.
- Linsley, R. K., 1982. Rainfall-Runoff Models: An overview. In, V. P. Singh (editor) **Rainfall-Runoff relationship**. Water Resources Publication, USA.
- Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. **Journal of hydrology**, 235, issues 3-4(2000): 276-288
- Mazvimavi, D. 2003. **Estimation of Flow Characteristics of Ungauged Catchments – Case Study in Zimbabwe**. Ph.D. Thesis, Wageningen University, The Netherlands.
- McCartney, M., 1998. **The hydrology of a headwater catchment containing a dambo**. Ph.D. Thesis, University of reading, United Kingdom.
- McCartney M.P., Daka A.E, and Laker M.C., 2001. **Water abstraction from dambos using treadle pumps**. Paper presented at the 27th WEDC Conference, Lusaka, Zambia.

- McLaughlin, D., 1995. Recent developments in hydrologic data assimilation. **Reviews Geophysics**, (Suppl.): 977-984.
- Meigh, J.R., McKenzie, A.A., Austin, B.N., Bradford, R.B., and Reynard, N.S., 1998. **Assessment of global water resources – phase II. Estimates of present and future water availability for Eastern and Southern Africa**. Report to DFID by the Centre for Ecology and Hydrology, Technology Development & Research Programme, DFID Report 98/4.
- Meigh, J.R., McKenzie, A.A., and Sene, K.J., 1999. A grid-based approach to water scarcity estimates for Eastern and Southern Africa. **Water Res. Management**, 13: 85-115.
- Midgley, D.C., Pitman, W.V., and Middleton, B.J., 1994. **Surface Water Resources of South Africa 1990**. A User Guide plus 6 volumes of Data Appendices and Map. Water Research Commission Reports 298/1/94 to 298/6/94, Pretoria, South Africa.
- Moore, R.J., 1985. The probability-distributed principle and runoff production at point and basin scales. **Hydrological Science Journal**, 30(2): 273- 297.
- Nash, J. E. (1959) A note on the Muskingum flood routing method. **J. Geophys. Res.**, 64(8), 1053–1056.
- Nash, J.E., 1960. A Unit Hydrograph Study with Particular Reference to British Catchments. **Proc. Institute of Civil Engineers**, 17: 249-282
- Nash, J.E., and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I – a discussion of principles. **Journal of Hydrology**, 10(1970): 282-290
- Ndiritu, J.G., and Daniell T.M., 1999. An improved genetic algorithm for continuous and mixed discrete-continuous optimization. **Eng. Opt.**, 31, 589-614.

- Obled Ch., Wendling J., Beven K., 1994. The sensitivity of hydrological models to spatial rainfall patterns: an evaluation using observed data. **Journal of Hydrology** 159(1994): 305 – 333.
- O’Connell, P.E., 1991. A historical perspective. In: D.S. Bowles and P.E. O’Connell (Editors), **Recent Advances in the Modeling of Hydrologic Systems**. 3030, Kluwer, The Netherlands.
- Paturel J. E., Servat E., and Vassiliadis A., 1994. Sensitivity of Conceptual rainfall-runoff algorithms to errors in input data – Case of the GR2M model. **Journal of Hydrology**, 168 (1995): 111 – 125.
- Penman, H.L., 1961. Weather, Plant and Soil Factors in Hydrology,. **Weather**, 16: 207-219
- Perrin, C., Michel, C., and Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. **Journal of Hydrology**, 279: 275-289.
- Pirt, J., and Bramley, E.A., 1985. The application of simple moisture accounting models to ungauged catchments. **Journal of Institute of Water Engineering Science**, 39: 169-177.
- Pitman, W.V., 1973. **A mathematical model for generating river flows from meteorological data in South Africa**. Report No. 2/73, Hydrological Research Unit, University of the Witwatersrand, Johannesburg, South Africa.
- Pitman, W.V., 1976. **A mathematical model for generating daily river flows from meteorological data in South Africa**. Report No. 2/76, Hydrological Research Unit, University of the Witwatersrand, Johannesburg, South Africa.
- Pitman, W.V., and Kakebeeke, J.P., 1991. **WRSM90, Water Resources Simulation Model, User’s Guide**. Stewart Scott Inc., Sandton.

- Roberts, P.J.T., 1978. **A comparison of the performance of selected conceptual models of the rainfall-runoff process in semi-arid catchments near Grahamstown.** Report No. 1/78, Hydrological Research Unit, Rhodes University, Grahamstown, 324pp.
- Rosenbrock, H.H., 1960. An automatic method for finding the greatest or least value of a function. **Computer Journal**, 4: 175-184
- SADC., 1999. Regional Strategic Action Plan. Integrated Water Resource Development and Management in SADC. **PROJECT CONCEPT NOTE 14**
- SADC., 2001. **Assessment of Surface Water Resources, PCN14 Terms of Reference.** Compiled for the SADC Water Sector Co-ordination Unit, by the Water Research Commission of South Africa. WRC Report No: 1112/1/01.
- Schulze, R.E., 1994. **Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System.** Water Research Commission, Report TT69/95, Pretoria, South africa.
- Schulze, R.E., 2000. Modelling hydrological responses to land use and climate change: A southern African perspective. **Ambio**, 29: 12-22.
- Scott Wilson Piésold, 2003a. **Integrated Kafue River Basin Environmental Impact Assessment Study – State of the Environment Report.** Report for ZESCO LIMITED, Lusaka. Zambia
- Scott Wilson Piésold, 2003b. **Integrated Kafue River Basin Environmental Impact Assessment Study – Strategic Environmental Assessment Report.** Report for ZESCO LIMITED, Lusaka. Zambia
- (SHP) Shawinigan Engineering & Hidrtecnica Portuguesa, 1990a. **Simulation of the Kafue Gorge Power Plant operation.** SADC AAA.3.4 Hydroelectric Hydrological Assisstance Project – Phase 1. ZESCO LTD. Lusaka, Zambia.

Shawinigan Engineering & Hidrtecnica Portuguesa, 1990b. **Review of River Basin Models in Use in the SADCC Region and Recommendations for Models and Studies Appropriate to the Zambezi Basin.** SADC AAA.3.4 Hydroelectric Hydrological Assisstance Project – Phase 1. ZESCO LTD. Lusaka, Zambia.

Shawinigan Engineering & Hidrotecnica Portuguesa, 1993. **Itezhi-tezhi / Kafue Gorge operating procedure.** SADC AAA.3.4 Hydroelectric Hydrological Assisstance Project – Phase 1. ZESCO LTD. Lusaka, Zambia.

Sikatali, C., 1994. **Geological and Mineral Occurrence Map.** Geological Survey Department, Lusaka, Zambia.

Sivapalan, M., 2003. **IAHS Decade on Predictions in Ungauged Basins (PUB): 2003 – 2012. PUB Science and Implementation Plan.** IAHS Press, Centre for Ecology and Hydrology, Wallingford, UK

Sorooshian, S., and Dracup, J.A., 1980. Stochastic parameter estimation procedures for hydrologic rainfall-runoff models: correlation and heteroscedastic error cases. **Water Resource Res.**, 16(2): 430 - 442

Sorooshian, S., 1983. Surface water hydrology: On-line estimation. **Reviews of Geophysics and Space Physics**, 21(3): 706-721

Sorooshian, S., 1991. Parameter Estimation, Model Identification, and Model Validation: Conceptual – Type Models. In: D.S. Bowles and P.E. O’Connell (Editors), **Recent Advances in the Modeling of Hydrologic Systems.** 3030, Kluwer, The Netherlands.

Sorooshian, S., Gupta, V.K., and Fulton J.L. 1983. Evaluation of Maximum Likelihood Parameter Estimation Techniques for Conceptual Rainfall-Runoff Models – Influence of Calibration Data Variability and Length on Model Credibility. **Water Resources Research**, 19(1): 251-259.

Stedinger, J.R., and Taylor, M.R., 1982. Synthetic streamflow generation. 1. Model verification and validation. **Water Resources Research**, 18(4): 900-918

- Tate, E., Meigh J., Prudhomme C., and McCartney M., 2000. **Drought assessment in Southern Africa using river flow data**. DFID Report 00/4(2000). Centre for Ecology & Hydrology. Wallingford, United Kingdom.
- Todini, E., 1988. Rainfall-runoff modelling – past, present and future. **Journal of Hydrology**, 100: 341-352.
- Todini, E., and Wallis, J.R., 1977. Using CLS for Daily or Longer Period Rainfall Runoff Modelling. In: Ciriani, T.A., Maione, U., and Wallis J.R. (Editors), **Mathematical Models for Surface Water Hydrology**. John Wiley and Sons, Chichester.
- UNESCO., 1997. Southern Africa FRIEND. IHP V., **Technical Documents in Hydrology, No. 15**, UNESCO, Paris.
- Wagener, T., McIntyre, N., Lees, M.J., Wheater, H.S., and Gupta, H.V., 2003. Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis. **Hydrolog. Process.** 17: 455-476.
- Ward, R.C., 1984. On the response to precipitation of headwater streams in humid areas. *Journal of Hydrology*, **74**: 171-189.
- Wilson, C.B., Valdes, J.B., and Rodriguez-Iturbe, I., 1979. On the Influence of the Spatial Distribution of Rainfall on Storm Runoff. **Water Resources Research**, 15(2): 321-328.
- Yachiyo, 1995. **The National Water Resources Master Plan in The Republic of Zambia**. Compiled by Yachiyo Engineering Co. Ltd for the Ministry of Energy and Water Development, Lusaka. Zambia.
- Yapo, P.O., Gupta, H.V, and Sorooshian S., 1995. Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. **Journal of Hydrology**, 181 (1996): 23-48