INTERNATIONAL HYDROLOGICAL PROGRAMME

Southern Africa FRIEND Phase II 2000-2003

United Kingdom Contribution to the International Hydrological Programme (IHP) of UNESCO

Edited by

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Foreword

It is increasingly apparent that technical advances alone cannot solve the world's water problems and that an interdisciplinary approach relating water and social issues is required. This view is reflected in the focus of the sixth International Hydrological Programme (IHP) of UNESCO (2002-2007) on "Water interactions: systems at risk and social challenges". The activities described in this report, conducted under the auspices of the Flow Regimes from International Experimental and Network Data (FRIEND) project (one of two "cross-cutting" themes in IHP-VI) are an important contribution to this Programme.

The cooperation between UNESCO and the UK Department for International Development (DFID) has enabled the United Kingdom to play a leading role in successive International Hydrological Programmes. The UK contribution has focused on FRIEND, an international regional hydrology project, which aims to improve the accuracy, consistency and ease with which water resources can be assessed through applied research addressing regional problems. A key element is the development of international cooperation leading to the exchange of data, knowledge and techniques between countries and regions. Over 100 countries now participate in eight regional FRIEND groups worldwide.

Southern Africa FRIEND was the first regional FRIEND project to be established outside Europe. It was initiated in 1992 and brought together hydrological agencies from eleven states of the Southern African Development Community: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe. Phase I of the project from 1992 to 1997 was successful in developing for the first time an extensive database of river flow and spatial data for the whole area. This and other activities in Phase I are described in a report published by UNESCO (Technical Documents in Hydrology Series No. 15). Phase II from 2000-2003 has built on the achievements of Phase I by focusing on providing hydrological agencies in twelve countries (Mauritius has recently joined FRIEND) with improved tools for water resources management and by building capacity through workshops and in-house training. A key component has been the development and dissemination of user-friendly software (and spatial data) to hydrological agencies, which should enhance their ability to monitor on-going droughts and to assess and manage water resources.

The Southern Africa FRIEND project provides a basis for hydrologists from within the region to participate actively in the IHP and a framework for a wide range of research. It has an important and continuing role in helping to improve the ability of national hydrological agencies in Southern Africa to manage their water resources in a more sustainable and effective way, which will in turn help to alleviate poverty.

Dr Alan Gustard
Chair, FRIEND Inter Group Coordinating Committee 1998-2002

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During Phase II of Southern Africa FRIEND, an initial strategic appraisal meeting was held at the University of Dar es Salaam, Tanzania, in August 2000 (1), followed by Steering Committee meetings in Blantyre, Malawi, in November 2000 (2), and Cape Town, South Africa, in March 2002 (3). National representatives to these meetings were:

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Abbreviations and symbols

ARIDA	Assessment of the Regional Impact of Drought in Africa
BFI	baseflow index
BGS	British Geological Survey
c_{max}	maximum capacity of the soil moisture store (saturation capacity)
CGCM1	GCM of the Canadian Centre for Climate Modelling and Analysis
CEH	Centre for Ecology & Hydrology, Wallingford, UK
CRU	Climatic Research Unit, University of East Anglia, UK
DWAF	Department of Water Affairs and Forestry, South Africa
Echam4	GCM of the German Climatic Research Centre
ESRI	Environmental Systems Research Institute, Inc.
f_c	field capacity of the soil
FAO	Food and Agriculture Organisation of the United Nations
FRIEND	Flow Regimes from International Experimental and Network Data
GCM	Global Climate Model
GIS	Geographical Information System
GWAVA	Global Water Availability Assessment model
HABITAT	United Nations Centre for Human Settlements
HadCM2	GCM of the UK Hadley Centre for Climate Prediction and Research
HYCOS	Hydrological Cycle Observing System
I	water availability index (in the GWAVA model)
IHP	International Hydrological Programme (of UNESCO)
IPCC	Intergovernmental Panel on Climate Change
IWR	Institute for Water Research (Rhodes University, South Africa)
IWRM	Integrated Water Resources Management
MA	moving average
MAP	mean annual precipitation
MAR	mean annual runoff
NDVI	Normalised Difference Vegetation Index
NHA	national hydrological agency
NOAA-EPA	National Oceanographic and Atmospheric Administration – Environmental Protection Agency, USA
PDM	Probability Distributed Model
PDS	partial duration series
Q_x	flow that has an exceedance probability of X%
SADC	Southern African Development Community
SPATSIM	Spatial and Time Series Information Modelling package
t_d	averaging interval (for MA method)
TPTC	Tripartite Permanent Technical Committee: Kingdom of Swaziland, Republic of Mozambique, Republic of South Africa
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNEP-GRID	United Nations Environment Programme – Global Resource Information Database
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WHO	World Health Organization
WRC	Water Research Commission, South Africa
WRI	World Resources Institute
ZESCO	Zambia Electricity Supply Corporation

Executive summary

This report presents the results of the second phase of the Southern Africa FRIEND (Flow Regimes from International Experimental and Network Data) programme, covering the period August 2000 to March 2003. FRIEND is a contribution to the International Hydrological Programme of UNESCO. The participants in the Southern Africa programme are twelve of the states of the Southern African Development Community: Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe. The region covered is very large, having an area of about 6.8 million km^2 and a population of almost 150 million people. In terms of water resources, the region can be characterised as one of water scarcity. It includes some of the poorest countries in the world; with increasing population and lack of infrastructure, many people have inadequate access to water, and suffer from the severe impacts on livelihoods and health which this brings. This situation is exacerbated by the uneven distribution of water resources and their extreme variability, with recurrent drought and devastating floods. Much of the water resources are found in international basins shared between several countries, emphasising the need for co-operation to ensure effective management and response to problems. Throughout most of the region, hydrological data are scarce and essential monitoring networks are under-funded and poorly maintained. National water departments and research organisations alike suffer from a low level of funding, leading to difficulties in retaining staff, and low capacity to manage resources and to investigate improved solutions. Development of the water resources of Southern Africa in a sustainable manner, through the application of a range of technical, economic and institutional measures, is essential for optimal and efficient usage.

The Southern Africa FRIEND programme takes a demand-driven approach to tackling some of these issues, which can be seen as a step towards the overall goal of making an effective contribution to the sustainable management of regional water resources and poverty alleviation. The main objectives of the programme are: to promote and provide facilities for the free exchange of data for hydrological and water resources studies in the region; to promote co-operation between water resources managers and researchers, and provide a channel for the exchange of expertise, information and ideas; and to develop improved operational hydrological methods based on knowledge of flow regimes and to establish them in hydrological agencies in the region. The first phase of Southern Africa FRIEND was generally thought to have been successful, and the second phase was designed to build upon its achievements, focussing on the needs for capacity building and improved tools for water resources management in the region.

On this basis, a series of components of the project were defined, and these form the basis of this report. They are as follows:

- **Regional water resources and river flow modelling** (Chapter 2). The overall aim was to improve the abilities of the countries to make surface water resources assessments based on information and approaches that are reliable and mutually acceptable within the region. The approach was based on the WR90 water resources modelling system which was developed, and is very widely used, in South Africa. The system provides flow estimates that are valuable to water resource planners for the assessment of water availability at any site for preliminary project design and determining environmental flow requirements. The approach was applied in Zambia and Botswana, and this has shown the way towards improved assessment of resources; it is a step towards the extension of this technique to the entire region, an objective which has been adopted as a long-term aim of the Southern African Development Community.

- **Implementation of drought assessment and monitoring software** (Chapter 3). Recognizing the importance and potentially massive impacts of drought in Southern Africa, especially for the poor, the objectives were to enhance the abilities of the countries to analyse historic water resources droughts and to monitor ongoing droughts, using approaches that are appropriate to the particular hydrological characteristics of the region. This was done using the previously-

developed ARIDA approach (Assessment of the Regional Impact of Drought in Africa), focussing on software development – with the national hydrological agencies participating in improving the software for their needs – as well as training and dissemination.

- **Development and implementation of GIS water resources software** (Chapter 4). The objectives were to strengthen the abilities of the Southern African countries to assess, plan and manage surface water resources. This is similar to some of the other components, but it is useful to take a variety of approaches in order to address these issues effectively. This component focuses on improved decision support systems, using the latest GIS-based approaches. Software suitable for application in Southern Africa has been developed, including a new methodology to estimate flow characteristics and account for artificial influences for a part of the region. The software can be used to estimate flow characteristics at ungauged sites and determine the impact of upstream developments on the flow regime. It has been implemented and tested in the region, with training in its use and dissemination to all the hydrological agencies. This work has provided an advanced and powerful tool that is also very accessible and easy to apply. So far, it has been implemented in Malawi, but it has great potential for further application across the region, and there is considerable demand for wider dissemination.

- **Water resources and climate change in Swaziland** (Chapter 5). This component is again concerned with improving the ability to make surface water resources assessments, but it concentrates on examining the long-term impacts of future changes in climate and in water demands, an increasing concern in the region. There is a clear need to improve the abilities of the countries to carry out such assessments themselves. The work was carried out as a case study for Swaziland, using a grid-based approach which has shown how rapid assessments of the water resources impacts can be made in an integrated manner. The work included training and dissemination of the results.

- **Improving GIS capability** (Chapter 6). With the aim of providing an improved regional database and better knowledge on flow regimes, the spatial data sets developed in the first phase of the project were distributed to hydrological agencies and other organisations. Such datasets provide valuable information for water resources planning and the development of decision support tools for water resources management. Besides the datasets themselves, a specially developed piece of software was distributed to provide easy access to the data and documentation on its origin and interpretation, supplemented by enhancement of the GIS skills that are needed to make effective use of these data.

- **Capacity building** (Chapter 7). Transfer of technology and capacity building were important aspects of the project, with the involvement and participation of water resources professionals in the region being integral to each of the components. Support for a post-graduate student at a university in the region led to the application of the WR90 water resources assessment approach in Zambia. Specific training activities were also carried out through regional workshops to disseminate the work done in each component.

In the final part of the report (Chapter 8), the key achievements of the project are summarised, and some recommendations are made for future work to help in meeting the needs of Southern African countries for improved water resources management, as a contribution towards improving the livelihood options of the people.

1 Introduction

J.R. Meigh

Background to the Southern Africa region

The Southern Africa FRIEND region is vast, covering approximately 6.8 million km^2 and stretching from one degree south of the equator, across the Tropic of Capricorn, to the Cape of Good Hope at 35°S. It is home to almost 150 million people, although its population density is relatively low. The region is one of diverse geography and climate. Much of it is lowland plains and plateaux at elevations of 1000 m or more, but there are also substantial mountain ranges in the east. The climate is mostly tropical, and semi-arid conditions predominate over large areas. There are also significant areas of extremely arid climate, including the Namib Desert, one of the world's driest places, characterised by huge sand dunes and practically zero rainfall. In the east a variety of much more humid climates are found, with small areas of rainforest on some of the eastern mountains. Rainfall is typically highly seasonal, with the rainy season in the austral summer, but ranges from an equatorial pattern of two rainy seasons per year in northern Tanzania to a Mediterranean type of climate in the extreme southern Cape where the main rains occur in winter. This wide range of climates produces a complex water balance, characterised by high spatial, seasonal and inter-annual variability. These factors have very significant implications for water resource availability, as well as for the frequency of floods and droughts across the region.

One of the most important hydrological characteristics of Southern Africa is the large number of international river basins. Major basins shared by two or more countries, include the Okavango, Limpopo, Orange and Zambezi. Shared basins account for a substantial proportion of the water resources in all countries. This degree of interdependence highlights the need for regional co-operation. At the government level, there is an existing agreement on water resources across the region and a revised agreement is currently in the process of ratification (SADC, 1995; 2000). However, there remains a strong need for enhanced co-operation at a wide range of other levels in hydrological studies and research in order to effectively address the water resources problems of the region.

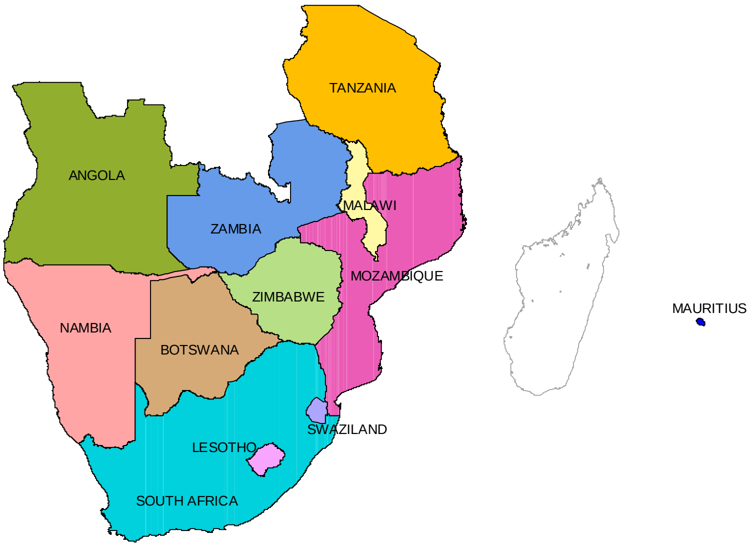


Figure 1.1 *Extent of the Southern Africa FRIEND project*

Main hydrological issues in the region

The Southern African region is characterised by water scarcity, exacerbated by the uneven distribution of resources, recurrent drought and devastating floods. Development of the water resources of Southern Africa in a sustainable manner, through the application of a range of technical, economic and institutional measures, is essential for optimal and efficient usage. Some of the main issues are:

- **Water scarcity.** Increasing population and lack of infrastructure, in a region that includes some of the poorest countries in the world, means that many people have inadequate access to water, with severe impacts on livelihoods and health.

- **Extreme variability of water resources.** Droughts are common, and extreme events (such as the current major drought (2002-03), and previous ones in 1992 and 1995) lead to widespread hardship, with the economic consequences felt at all levels from the individual right up to the national level. Floods can have similar consequences; the Mozambique floods in January 2000 led to widespread loss of life and required an international emergency response.
- **Shared resources.** Much of the water resources come from international basins shared between several countries, emphasising the need for co-operation to ensure effective management and response to problems.

- **Scarce hydrological data and under-funded, poorly maintained gauging networks.** National water departments and research organisations alike suffer from a low level of funding, leading to difficulties in retaining staff, and low capacity to manage resources and to investigate improved solutions.

Participation and organization of the project

Southern Africa FRIEND has twelve member countries, each represented by the national hydrological agency. They are Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe (Figure 1.1). These are all member countries of the Southern African Development Community (SADC) except for Democratic Republic of Congo and Seychelles, who have not yet participated in FRIEND. In addition to the national hydrological agencies, three research institutions participate in the project: the University of Dar es Salaam, Tanzania; Rhodes University, South Africa; and the Centre for Ecology and Hydrology, Wallingford, UK (CEH). From an administrative point of view the project is organised at four levels: the UNESCO/IHP umbrella; the Steering Committee; the Co-ordination Centre at the University of Dar es Salaam; and project groups who are responsible for specific activities. From a technical viewpoint, organisation of the project comprises a flow of information from countries to databases to research projects and finally back to countries as scientific outputs.

The first phase of Southern Africa FRIEND took place from 1992 to 1997. The activities and achievements were published in UNESCO (1997). Very briefly, these were:

- **River flow database.** Daily river flows for the whole region were assembled on a common database, held at the Co-ordination Centre at the University of Dar es Salaam.
- **Spatial database.** A wide variety of spatial information relevant to hydrology and water resources was assembled on a common database, covering the whole region.
- **Surface water resources and drought assessment.** A region-wide investigation directed towards: the spatial variability of mean annual runoff and flow regimes; the temporal variability of runoff; baseflow contributions to river flow; flow duration characteristics and estimation; and regional drought assessment.
- **Rainfall-runoff modelling.** An evaluation of: the performance of rainfall-runoff models in simulating river flow at a Southern African scale; the scope for regionalising model parameters for future applications; and model applicability for land use change studies.
- **Flood frequency analysis.** Development of regional flood estimation procedures for use in the design and appraisal of civil engineering structures.

- **Capacity building and training.** The project provided short courses on relevant topics and stimulated collaboration between the national hydrological agencies and research groups.

General objectives of the project
Southern Africa FRIEND has the following main objectives:

- To promote and provide facilities for the free exchange of data for hydrological and water resources studies in the region.
- To promote co-operation between water resources managers and researchers, and provide a channel for the exchange of expertise, information and ideas.
- To develop improved operational hydrological methods based on knowledge of flow regimes and to establish them in hydrological agencies in the region.

The project takes a demand-driven approach which is seen as a step towards the overall goal of making an effective contribution to the sustainable management of regional water resources and poverty alleviation.

Specific components and outputs of the project
The first phase of Southern Africa FRIEND was generally thought to have been successful, and it was agreed to continue into a second phase in order to build upon those achievements, focussing on the needs for capacity building and improved tools for water resources management in the region. The project was carried out from August 2000 to March 2003. The general objectives remained as listed above, with the project purpose being defined as:

- To establish in the hydrological agencies improved operational hydrological methods and knowledge in flow regimes, which are demand driven and thematically co-ordinated.

On this basis, a series of sub-projects and outputs was developed at an initial strategic appraisal meeting (August 2000). They were amended and then agreed by the Steering Committee at their meeting in November 2000. These various components of the project form the basis of this report. In outline, they are as follows:

- **Regional water resources and river flow modelling.** The overall aim was to improve the abilities of the countries to make surface water resources assessments based on information and approaches that are reliable and mutually acceptable within the region. The approach was based on the WR90 water resources modelling system which was developed, and is very widely used, in South Africa. The system provides flow estimates that are valuable to water resource planners for the assessment of water availability at any site for preliminary project design and in connection with environmental flow requirements. The immediate objectives of this work were to modify the approach as necessary and apply it to selected areas outside South Africa. The extension of the WR90 approach to cover the whole Southern Africa region has been adopted as a project by the SADC Water Sector. However, this will be a major long-term exercise, while the work discussed here has produced initial results quickly, helping to illustrate the validity of the approach and acting as a pilot study for the region-wide project. See Chapter 2.

- **Implementation of drought assessment and monitoring software.** Recognizing the importance and potentially massive impacts of drought in Southern Africa, especially for the poor, the objectives were to enhance the abilities of the countries to analyse historic water resources droughts and to monitor ongoing droughts, using approaches that are appropriate to the particular hydrological characteristics of the region. This was done using the previously-developed ARIDA approach (Assessment of the Regional Impact of Drought in Africa), focussing on software development – with the national hydrological agencies participating in improving the software for their needs – as well as training and dissemination (Chapter 3).

- **Development and implementation of GIS water resources software.** The objectives were to strengthen the abilities of the Southern African countries to assess, plan and manage surface water resources. This is similar to some of the other components, but it is useful to take a variety of approaches in order to address these issues effectively. This component focuses on improved decision support systems, using the latest GIS-based approaches. Software suitable for application in Southern Africa has been developed, including a new methodology to estimate flow characteristics and account for artificial influences for a part of the region. The software can be used to estimate flow characteristics at ungauged sites and determine the impact of upstream developments on the flow regime. It has been implemented and tested in the region, with training in its use and dissemination to all the hydrological agencies (Chapter 4).

- **Water resources and climate change in Swaziland.** This component is again concerned with improving the ability to make surface water resources assessments, but it concentrates on examining the long-term impacts of future changes in climate and in water demands, an increasing concern in the region. There is a clear need to improve the abilities of the countries to carry out such assessments themselves. The work was carried out as a case study for Swaziland, using a grid-based approach which provides a rapid overview of the situation, and included training and dissemination of the results (Chapter 5).

- **Improving GIS capability.** With the aim of providing an improved regional database and better knowledge on flow regimes, the spatial data sets developed in the first phase of the project were distributed to hydrological agencies and other organisations. Such datasets provide valuable information for water resources planning and the development of decision support tools for water resources management. Besides the datasets themselves, a specially developed piece of software was distributed to provide easy access to the data and documentation on its origin and interpretation, supplemented by support and training in GIS at an introductory level (Chapter 6).

- **Capacity building.** Transfer of technology and capacity building were important parts of all the components of the project. In addition, specific training activities were carried out through regional workshops which helped to disseminate the work done in the other components, and through post-graduate studies by a student at a university in the region. The training workshops and general aspects of capacity building are discussed in Chapter 7, while the work of the post-graduate student forms the core of the results presented in Chapter 2.

2 Regional water resources and river flow modelling

D.A. Hughes, E. Mwelwa, L. Andersson and J. Wilk

2.1 Introduction

During the first phase of Southern Africa FRIEND one of the main themes was rainfall-runoff modelling, with the Institute for Water Research at Rhodes University, South Africa, acting as the lead research organisation for this theme. The focus was on testing existing models (both monthly and daily time-step) with samples of the available data in the region to determine their broad applicability. The outputs included a contribution to the UNESCO final report (Hughes, 1997a), a more detailed report to the Water Research Commission of South Africa who funded the research (Hughes, 1997b), as well as other publications (Hughes, 1995; Hughes and Metzler, 1998).

As the project moved into phase II, it became apparent that the FRIEND programme in Southern Africa should be contributing more to the solution of practical problems in the region. Rainfall-runoff models were identified as potentially useful tools that could provide a vital component in the regional assessment of water resources availability. However, it was recognized that there is a lack of experience within the region in the use of such tools, as well as inadequate access to the software required to apply models, little common understanding of the benefits of different models and their results, and a lack of a common database required for setting up and running models.

In a parallel development, the need for an assessment of regional surface water resources was identified by the Southern African Development Community (SADC). Project Concept Note (PCN) 14 was conceived as a project proposal that would enhance the surface water resources assessment capabilities in the region (SADC, 2001; Hughes *et al.*, 2002). PCN 14 was the first step taken by the SADC Water Sector to spearhead the process of assessing and quantifying the surface water resources of the whole of Southern Africa in a coordinated and unified manner, as well as building capacity within the region to make site-specific water resources assessments. PCN 14 highlighted the following areas of concern:

- The absence of 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.
- 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.
- The need to produce and make accessible a SADC-wide Surface Water Resources Assessment, in a manner that builds capacity in implementing institutions and promotes confidence in assessment products amongst member states

The justification for the project at the regional level was that:

- An assessment of available surface water resources is 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.
- 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.
- Confidence amongst member states in assessments of available water within a whole river basin was identified to be more important than the assessment itself.

- The sharing of information among riparian states on cross border flows and geographic information is of paramount importance to enable them to generate the necessary assessments in an environment that has sparse data and information.
- A country-by-country basis of assessment is not sufficient to manage water in international river basins.

The overall aim of the long-term PCN 14 project 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 that is based on information and approaches that are reliable and mutually acceptable within the region. A strong emphasis has been placed on capacity building, without which it is considered unlikely that this aim will be met. The aim is supported by five primary objectives:

- To generate monthly time series of naturalised river flow at the sub-catchment spatial scale (100 to 2500 km^2), as well as at major river and basin scale.
- To develop and distribute databases of the generated river flow and associated information (spatial data, rainfall, evaporation, water use, etc.).
- To develop and distribute tools for accessing and applying the information within the databases.
- To build capacity within the SADC water resources community to make use of the developed information and tools.
- To improve inter- and intra-country, as well as international, networking and to improve the ability of SADC member states to develop water sharing programmes in a sustainable and equitable manner.

One of the motivations for the long-term assessment study are the benefits that South Africa has derived from the WR90 reports and database (Midgley *et al*., 1994). 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 regionalized model parameters based on calibration against naturalised observed streamflows.

It can be seen that the ideas of Southern Africa FRIEND in the area of rainfall-runoff modelling and of PCN 14 have much in common. However, FRIEND is smaller in scale and can achieve results much more rapidly than the long-term PCN 14 project. Bearing this in mind, the FRIEND work programme was designed as a contribution to the larger long-term study, focussing on providing some initial pilot results and helping to move towards the larger, eventual aims of that project. The following three focus areas were identified as being of value and achievable in the available time:

- A contribution to the development of the models and software tools required to undertake a regional water resource assessment study within SADC, coupled with a limited programme of training in the use of such tools.
- A regional application of the Pitman model in Zambia, designed to assess the model and the capabilities of associated software tools, identify problems related to data availability and build capacity in the use of the model (through a postgraduate study programme, see Chapter 7).
- The integration of other ongoing applications of the Pitman model within the SADC region (outside South Africa, where it is used on a regular basis) into the SA FRIEND project. A case study of its use in the Okavango basin is included here (Section 2.4).

The work was led by the Institute for Water Research at Rhodes University, South Africa, in collaboration with a number of other organisations. It is described more fully in Hughes *et al*. (2003).

2.2 Development of models and supporting software tools

2.2.1 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 here is based upon modifications added during the application of the model for Phase I of the Southern Africa FRIEND programme (Hughes, 1997b). This version has now been incorporated, together with a reservoir water balance model, into the SPATSIM (SPatial and Time Series Information Modelling) package developed at the IWR (see Section 2.2.2).

Figure 2.1 illustrates the structure of the model, while Table 2.1 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, irrigation water demand, other water demands and monthly parameter distribution factors. Optional data requirements include optimisation ranges for some parameters, 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, monthly distributions of drafts for up to five reserve supply levels, monthly distributions of normal compensation flow requirements and distributions of compensation flow for up to five reserve supply levels.

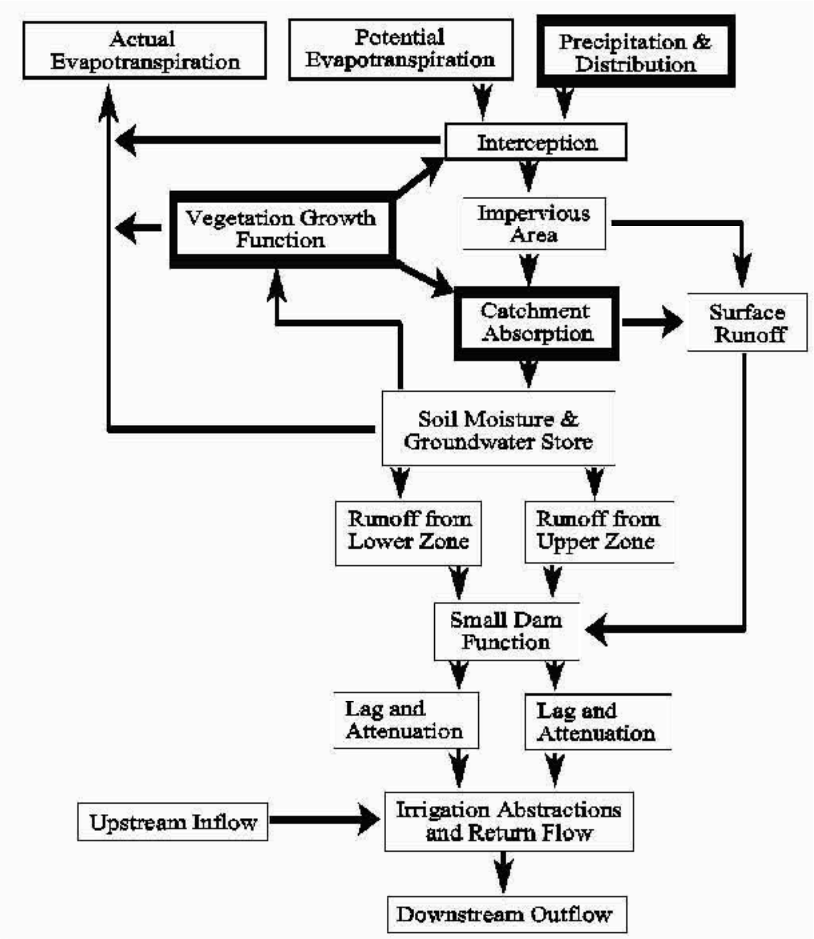


Figure 2.1 *Flow diagram representation of the Pitman model (bold boxes indicate modifications made during Phase I of SA FRIEND)*

Table 2.1 *Pitman and reservoir model parameters*

Parameter	Units	Description
Pitman model		
RDF		Rainfall distribution factor; controls the distribution of total monthly rainfall over four model iterations
AI		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 vegetation type 2 relative to type 1
PEVAP	mm	Annual catchment evaporation
ZMIN	mm/mth	Minimum catchment absorption rate
ZAVE	mm/mth	Mean catchment absorption rate
ZMAX	mm/mth	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/mth	Runoff from moisture storage at full capacity (ST)
GW	mm/mth	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		Irrigation water return flow fraction
EFFECT		Effective rainfall fraction
RUSE	Ml/y	Non-irrigation demand from the river
MDAM	Ml	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		
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

Note: Additions to the original version are highlighted in bold type

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.

Reference can be made to the original report (Pitman, 1973) for a full description of the model algorithms, and more details are also provided in Hughes *et al*. (2003).

Calibration procedures

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 predominantly affected by changes in 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 in catchments with good vegetation cover, temperate to humid climates and naturally perennial flow systems. It is usually necessary to adjust ST, POW and FT to 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 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.
- 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 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.

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 above, 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.

2.2.2 SPATSIM – Spatial and time series information modelling software

SPATSIM is a software package, developed at the Institute for Water Research (Hughes, 2002), which is designed as a database, data analysis and modelling system specifically for hydrological and water resource applications. Figure 2.2 provides an example of the main SPATSIM window, while Figure 2.3 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 design is such that it is straightforward to create generic database table structures that can be used to store virtually any type of information relevant to hydrological or water resources studies.

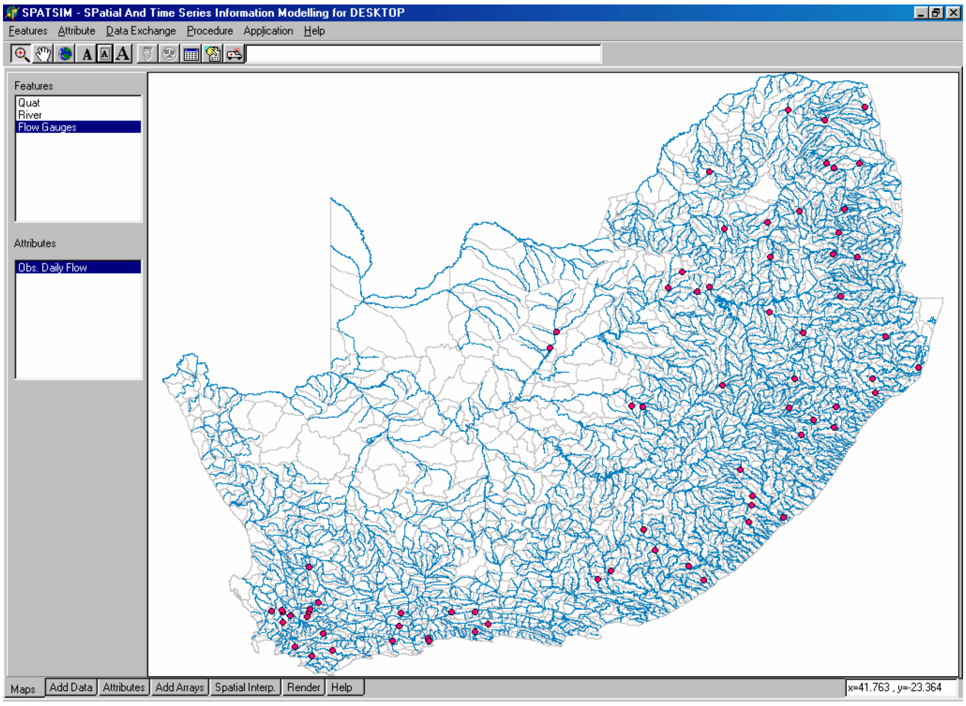


Figure 2.2 *Main window of SPATSIM*

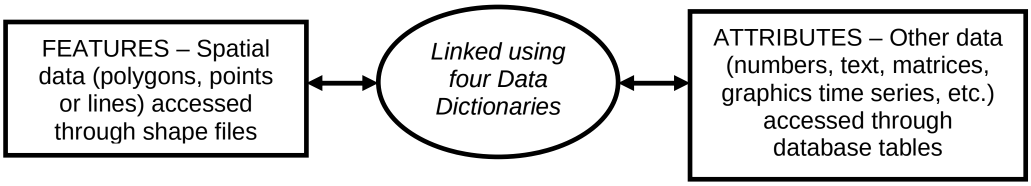


Figure 2.3 *Basic data access design in SPATSIM*

The facilities that are included in SPATSIM to enable data to be stored, displayed and processed can be divided up into internal facilities, which are not specific to any application, and external processes, which include a wide range of hydrological, water resource and eco-hydrological models. Help facilities are available within the program, while a more complete description of the system is available through the 'Hydrological Software' link on the IWR website (http://www.ru.ac.za/institutes/iwr). Although full details of the database structure and available facilities are not provided here, a brief summary of the range of facilities is outlined.

Internal SPATSIM facilities

The internal SPATSIM facilities are mainly designed to allow data of various types to be imported and exported, associated with spatial data, and 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.

External SPATSIM utilities

These 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. One of these is a generic time series data display and analysis program (TSOFT; Hughes *et al*., 2000), which has been established as a flexible tool for various types of time series data. 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.

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.

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 are displayed and the user selects SPATSIM attributes, which will satisfy the model requirements. 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, 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.

2.3 Regional calibration of the Pitman model for the Kafue basin, Zambia

2.3.1 Water resources use in Zambia

Zambia’s largest non-consumptive user of surface water resources is the hydroelectricity industry, which produces over 95% of Zambia’s electrical energy. Zambia has a hydroelectric power potential estimated at 6000 MW of which only about 1625 MW have been tapped. To conduct feasibility studies for all potential hydropower sites will require reliable water assessment and quantification methodologies, as some of the potential sites occur in ungauged catchments and catchments with short and/or poor streamflow records. Some of the most feasible project sites occur within the Kafue River basin.

A major consumptive user of water, with a high potential for expansion, is the agricultural sector. In the wake of the food shortages in Zambia in the last few years, which have been due to droughts and floods, investigations are needed to assess the feasibility of expanding irrigation and growing irrigated winter crops to supplement the rain-fed summer crops. The irrigation potential can only be assessed successfully with long-term quantitative water resource data relating to both surface and ground water.

There is little doubt that improved water resource assessment capability within Zambia should represent a high priority from a social and economic point of view. Although limited in scope to the Kafue basin, the results of this project, combined with some of the initial model assessments undertaken during the first phase of the Southern Africa FRIEND programme (Hughes, 1997b) on other Zambian catchments, could provide a sound basis for further national scale assessments.

2.3.2 Available data

One of the pre-requisites to any modelling study is an assessment of the data that are available to setup and calibrate the model. No model results can be better than the quality of the available data and it is therefore extremely important to appreciate the limitations that the quality of available data place on the reliability of the results. This is especially true of parts of the Southern African region, where warfare and past and present economic limitations have largely precluded the collection of spatially and temporally representative water resource information.

Rainfall

The Department of Meteorology in the Ministry of Transport and Communication is responsible for the collection of rainfall and meteorological data in Zambia. The earliest rain gauges (1905 to 1910) were associated with the early missionary stations. There are currently a total of 36 main meteorological stations with 825 registered voluntary stations, operated by farmers, railway stations, power stations, mines and foresters. The operational stations have been dwindling since 1976 and by 1991 only 340 of the voluntary stations were actually operating (Yachiyo, 1995).

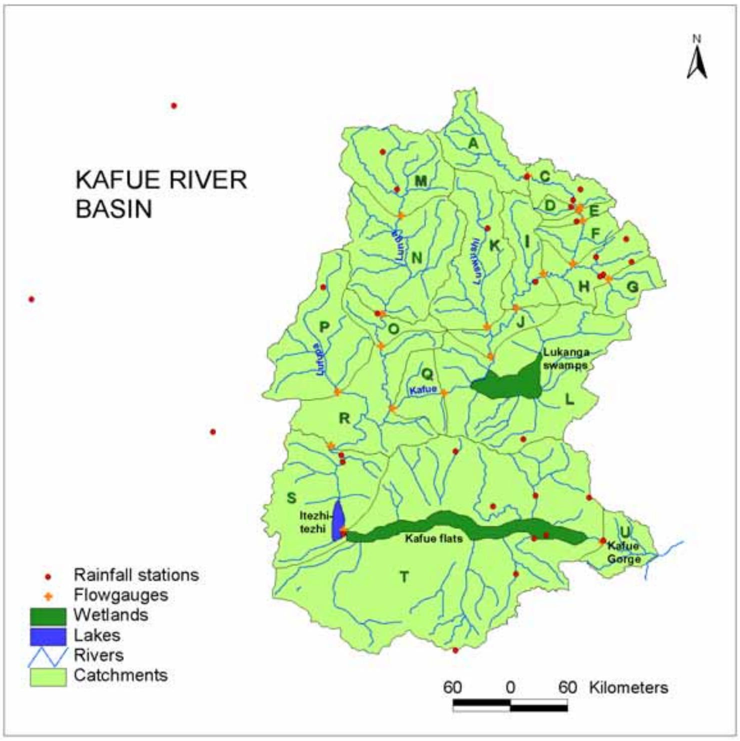


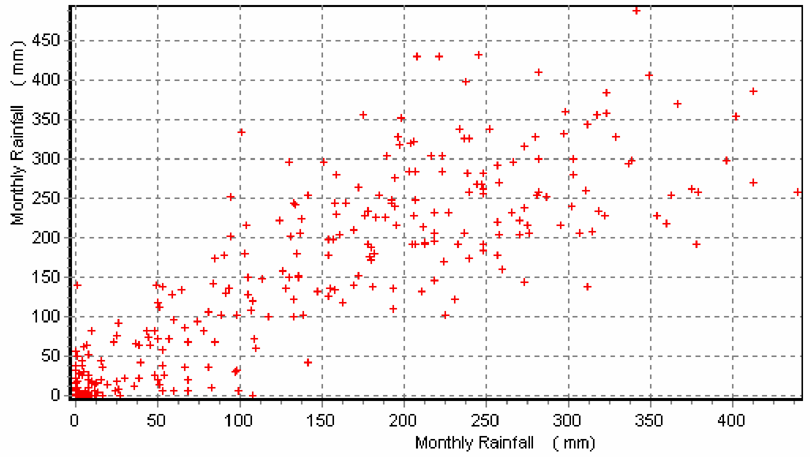
Figure 2.4 *Raingauges and gauged sub-catchments in the Kafue basin (capital letters are labels for the sub-catchments, see Table 2.3)*

To simulate the streamflows of the Kafue catchment, 28 rainfall stations, reasonably evenly distributed over the entire catchment, were selected (Figure 2.4). Three of these rainfall stations are outside the Kafue catchment, but within the Zambezi catchment. The rainfall record lengths range from 14 years to 62 years, however, most stations with longer records also have a larger number of missing data months. In general, raingauges located in mining towns, agricultural centres and main provincial towns have better records than rural and remote stations, since some of these stations are manned by full time employees while others are manned by volunteers.

Suitability of available rainfall data for streamflow simulation

To investigate patterns of spatial variability and to assess whether the rainfall data from the 28 stations was representative, pairwise correlation analysis was undertaken for all possible station pairs. Mean annual rainfall decreases from north to south in the Kafue catchment and rainfall stations in the northern part of the catchment are well correlated with each other (R^2 values of 0.8 and greater), even with separation distances of over 200 km. North-south correlations are much worse (R^2 values of 0.6 and lower). For the rainfall stations in the western part of the upper Kafue catchment, which is a high rainfall region (1200 to 1300 mm/y), the general trend is that better relationships occur for months with rainfall below 300 mm, while monthly rainfalls of more than 300 mm show poor relationships (Figure 2.5a). The rainfall stations in the eastern part of the upper Kafue catchment, which is also a high rainfall area (1200 to 1300 mm/y), show more consistent relationships over the full range of monthly rainfalls (Figure 2.5b). The lower Kafue catchment (800 to 900 mm/y) raingauges also demonstrate more consistency.

(a)



(b)

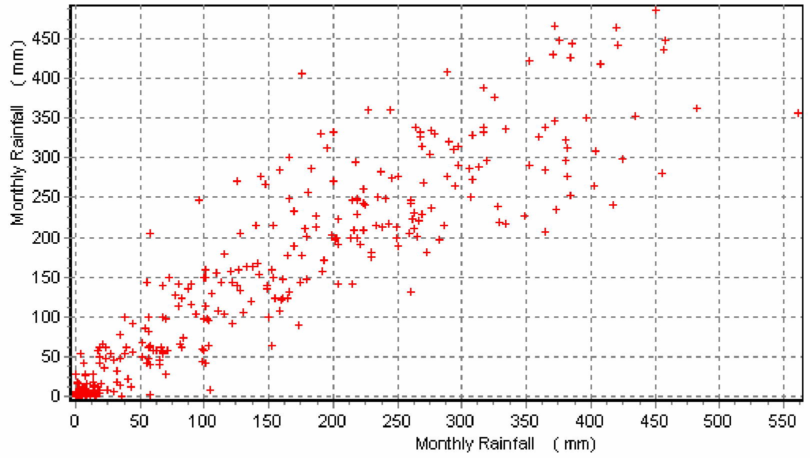


Figure 2.5 *Scatter plot of monthly rainfall: (a) Kasempa (x-axis) and St. Francis, 130 km apart with* $R^2 = 0.798$*, (b) Ndola (x-axis) and Roan, 39 km apart with* $R^2 = 0.878$

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 over the sub-catchments of the Kafue, it is necessary to use data from stations 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.

Monthly distribution of rainfall

The SPATSIM version of the Pitman model uses four iteration periods within each month and makes some assumptions about the distribution of rainfall over those four periods based on the parameter RDF (see Table 2.1). Observed distributions of daily rainfall were analysed using data from four rainfall stations, which were chosen from the upper, middle and lower catchment areas, and these were compared to the distributions assumed in the model for a range of values of the RDF parameter. It is apparent that the model assumes relatively low rainfall in the first and last iterations (days 1-7 and 24-30) and much higher rainfall in the middle two iterations (days 8-15 and 16-23). While the observed sequence of high and low rainfall periods within a month will affect the amount of runoff generated, the way in which the model distributes the amounts of rainfall in the four iterations is more important in the context of the Kafue basin. This is largely because high rainfalls occur seasonally and changes in storage during a single month are not critical. However, simulated maximum rainfalls can seriously affect the runoff generated by the model and the calibration of some of the parameter values.

From the analysis it was found that daily rainfall distributions for monthly rainfalls of 70 to 100 mm tended to relate most closely to an RDF value of 1.28, i.e. relatively extreme rainfall over short periods within the month. For monthly rainfalls of 150 to 180 mm the daily rainfall distributions tended to be more variable, and to relate to lower RDF values of 0.6 and 0.8. For monthly rainfalls of 220 to 280 mm and 300 to 490 mm, the daily rainfall was much more evenly distributed, suggesting RDF values of 0.6 or lower. Figure 2.6 shows the results for monthly rainfall of 220-280 mm for the St. Francis Mission station in the western part of the basin, compared to the model assumptions for RDF values of 0.6, 0.8 and 1.28. Unfortunately, the RDF parameter value is fixed for all months within the model and it is necessary to adopt a value that can be considered suitable for the full range of monthly rainfalls. As the higher rainfalls are more important from a runoff generation point of view, a compromise value of 0.8 for the RDF parameter was selected.

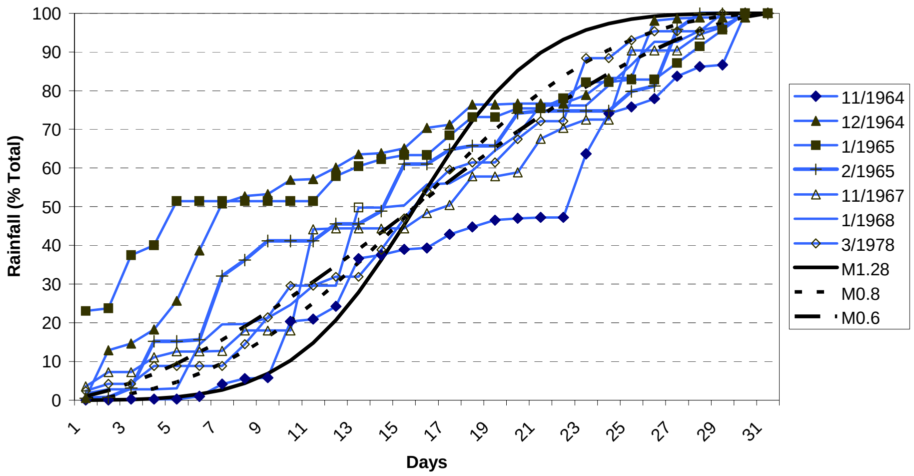


Figure 2.6 *Comparison of modelled and observed daily rainfall distributions for St Francis with monthly rainfall totals in the range 220-280 mm*

Observed streamflows

The Department of Water Affairs under the Ministry of Energy and Water Development has the responsibility to maintain the Zambian hydrometric network. There are also 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, while most of the important stations were opened during the 1950s. Currently, very little continual monitoring and station maintenance is being undertaken due to a lack of resources. The total number of registered streamflow stations in Zambia is 284, but only 127 (45%) stations are still operational, with some vital basins such as the Kafue having only 33% of the stations operational. Table 2.2 lists the status of the Zambian hydrometric network in June 2001.

Table 2.2 *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 are discharge measurement stations and therefore have established discharge rating curves. The discharge measuring stations use rated channel sections for discharge measurements. The water level information is collected by gauge readers employed by the Department of Water Affairs and data are stored both as daily water levels and as daily flows. A lack of regular maintenance since 1992 has resulted in many gauged records becoming unreliable. For the purpose of the Pitman model calibrations, the requirement for observed monthly streamflow data strongly influenced the sub-catchment delineation process and 17 gauging stations were available (Table 2.3). The available streamflow record lengths range from 24 to 43 years, but most have significant periods of missing data.

Table 2.3 *General information on the available monthly streamflow data*

Map label	Station number	Sub-catch. area (km^2)	Cum. catch. area (km^2)	Sub-catchment name	Record length (dates, years of record)	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	1,178	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	–	–

Suitability of observed streamflow data for Pitman model calibrations

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 pair-wise correlation analysis. The analysis shows that data from most station pairs are well correlated with coefficient of determinations of between 0.7 and 0.9. A few outliers exist and these can be mainly attributed to gauge plate errors before correction and maintenance. The tributary flows are less well correlated with the main river system flows due to differences in the hydrological response to rainfall events over the catchment. There is a very good correlation between stations on the same tributary streams.

There are some situations where there are unexpected inconsistencies between flows observed at two stations close to each other on the main channel. For example, there is a good correlation between the flows at Kelongwa and Chifumpa, but flows at the more downstream gauge (Chifumpa) are consistently less (up to about 1100 Mm^3) than at the upper gauge despite there being no evidence of significant abstractions (Figure 2.7). As the relationship between the two data sets is otherwise quite good, the problem is assumed to be a systematic error in one or both of the rating curves.

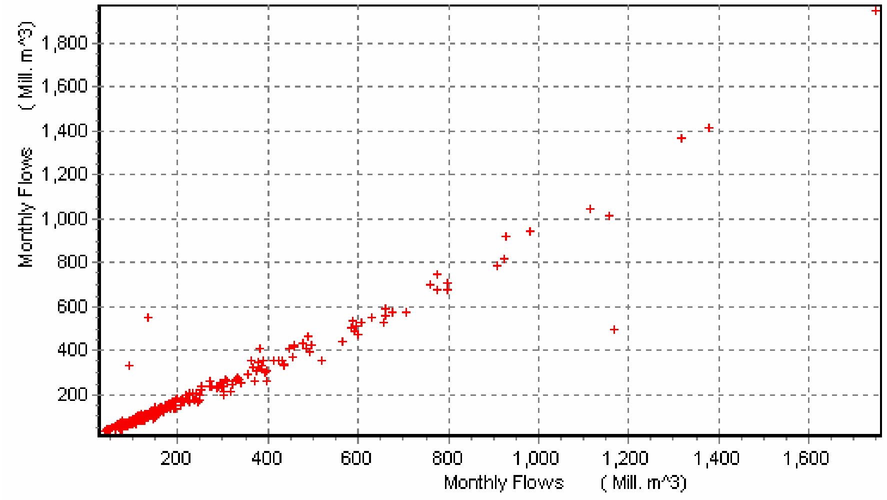


Figure 2.7 *Monthly flows for Lunga River: Kelongwa (x-axis) against Chifumpa (R^2 = 0.918)*

The regulated flow stations (reservoir outflows) have understandably poor relationships with other stations. The Itezhi-tezhi outflows at 1000 Mm^3 and above have a relatively high correlation with the peak flows of the upstream station at Hook Bridge, although outliers occur after dry years when the reservoir is filling. The Kafue Gorge reservoir outflows show a very poor correlation with all the stations, which can be explained by the complexities of the natural losses occurring over the extensive Kafue Flats wetland and the highly managed spills from the dam. The impact of wetland losses is also observed in the differences in peak flows at the stations upstream (Chilenga) and downstream (Mswebi) of the Lukanga swamps. Considerable losses are known to occur from the Kafue River during high flows into the Lukanga swamps. Figure 2.8 shows that there is a high degree of scatter in the relationship between the flows at these sites and that the downstream flows are generally lower when the upstream flows are 800 Mm^3 and greater. It is clear that special considerations are required when configuring the model for the sub-catchments including swamps and regulating reservoirs.

Evaporation data for the Kafue Basin

Catchment monthly evaporation data, required for running of the Pitman model, is derived from the Class A pan evaporation data, measured at the 36 main meteorological stations countrywide. The data used in this study have been taken from the Water Resources Master Plan (Yachiyo, 1995). The mean annual A pan evaporation in Zambia ranges from 1666 mm to 2814 mm, and the Zambian average is 2061 mm. Annual pan evaporation is low (1700 to 2000 mm) in the north, very high (2200 to 2600 mm) in the east and moderate in the centre, west and south of the country. In general terms, there are insufficient data to be able to generate complete time series of evaporation for the various sub-catchments and mean monthly distributions have been used in the modelling studies. The Pitman model assumes S-pan evaporation values and therefore the mean annual evaporation (MAE) data were converted from A-pan values to S-pan values using the equation applied in South Africa and used in the WR90 reports (Midgley *et al.*, 1994).

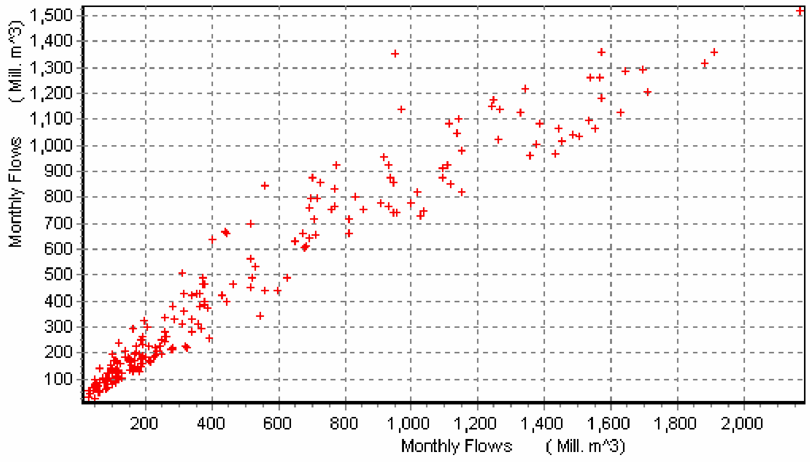


Figure 2.8 *Relationship between flow upstream (Chilenga, x-axis) and downstream (Mswebi) of the Lukanga Swamps*

Evaporation estimates for the Kafue Flats

The capacity of the main channel in the middle of the Kafue Flats around Lochinvar has been estimated to be approximately 170 m^3/s. Due to managed releases from Itezhi-tezhi Dam, this capacity is exceeded by at least 13 m^3/s most of the year, resulting in the formation of permanent lagoons where temporary aquatic habitats existed before. The increase in permanently flooded areas is reflected in higher evaporation, which is reported to be enhanced by weed proliferation (SLHP, 1990).

Water use information

This section is included to provide background on the information that is available to quantify both natural losses (through the influence of the Lukanga Swamps and Kafue Flats), as well as abstractions from, or return flows to, rivers and reservoirs for domestic, industrial and agricultural purposes.

- **Lukanga Swamps.** The Lukanga swamps cover an area of 2600 km^2 at peak water level when the average depth is 6.1m. The capacity of the swamp depression between its average low water level and maximum water level is reported to be about 7400 Mm^3. The swamp intercepts inflows from the headwater areas of sub-catchment L (see Figure 2.4), as well as acting as an off-channel reservoir for flood flows from the Kafue River (Balek, 1971). During most years there are negligible outflows from the swamps, but these do occur during wet years.

- **Kafue Flats.** These are the second biggest flood plain in Zambia, extending for about 353 km and covering an area of some 6500 km^2. For most of its length, the river meanders through a large flat grassland floodplain, with only a 15m height difference between Itezhi-tezhi Dam and Kafue Gorge (slope of 0.004%). The Kafue Flats operates as a natural reservoir that has continual outflows, considerable evaporation losses and a strong attenuation impact.

- **Itezhi-tezhi Reservoir.** The dam was constructed in 1977 to guarantee a flow of 120 m^3/s throughout the year to meet the needs of the Kafue Gorge power station. The reservoir has an area of about 300 km^2 and a live storage capacity of 4925 Mm^3, equivalent to 56% of the long-term mean annual inflow. The travel time of the water from Itezhi-tezhi to Kafue Gorge has been estimated to be two months due to the attenuation and delay effects of the Kafue Flats. During a dry year, the release requirements vary from 180 m^3/s in December and January to a maximum of 300 m^3/s in March.

- **Kafue Gorge Reservoir.** The dam was completed in 1971 and has a maximum storage of 900 Mm^3, at which the surface area is some 1180 km^2. The minimum storage of 218 Mm^3 results in a reservoir surface area of 460 km^2. The reservoir is therefore quite shallow and evaporation losses are high. The operating principles are to maintain the lowest possible level to reduce evaporation losses, given the constraints of the releases required for power generation and the expected inflows from the Kafue Flats. The normal operating rule is that the reservoir will be maintained at a storage of 218 Mm^3 over August to November, the level will rise from December onwards to the full storage of 900 Mm^3, which will be maintained until the following March/April from natural and controlled flows through the Kafue Flats. The power plant requires a minimum flow of 120 m^3/s to maintain its firm energy target of 450 MW. These relatively complex operating rules make it difficult to incorporate the dam into the model.

Water abstractions and return flows

About 283 water rights for direct water abstraction for both domestic/industrial and agricultural purposes exist within the Kafue catchment, totalling 1078 Mm^3/y. They vary widely in different areas, from only 0.02 Mm^3/y for domestic supply in sub-catchment G to 567 Mm^3/y for agricultural use in sub-catchment T. Figure 2.9 provides information about the changes that have occurred over time. The only known return flow exits in sub-catchment C and represents water pumped out of the mines in the Copperbelt region. It has been quantified as 110 Mm^3/y. The major non-consumptive water right, which is used for generating electricity, is held by ZESCO Ltd in the lower Kafue basin. It is 15,137 Mm^3/y (greater than the mean annual runoff).

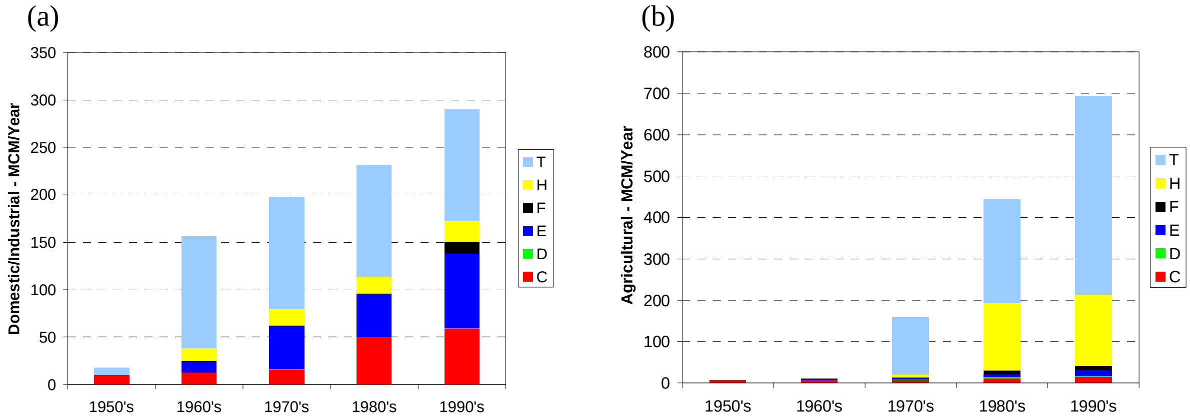


Figure 2.9 *Change in water abstraction in the Kafue basin over time: (a) domestic and industrial, (b) agricultural*

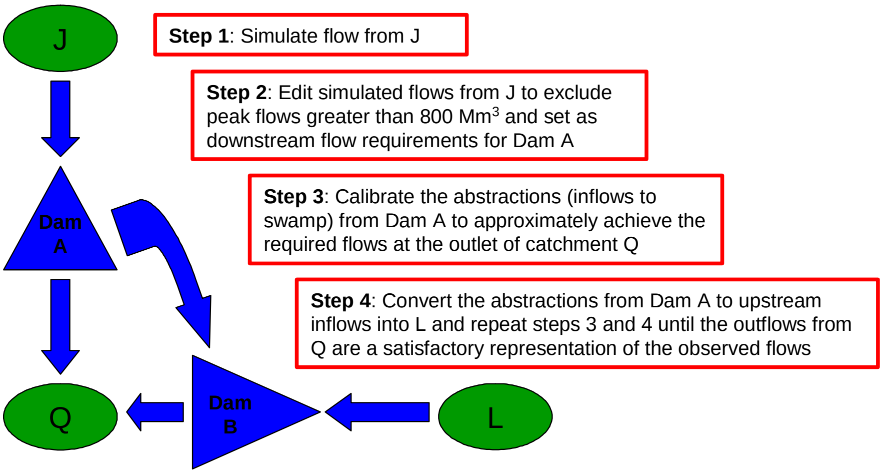
2.3.3 Configuration of the Pitman model for the Kafue basin

For most of the basin 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 (including the Kafue Flats).

Lukanga swamps

The physical setting of the Lukanga Swamps is described above, and can be seen in Figure 2.4. 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 Mm^3. There appears to be very little flow out of the swamps back into the Kafue channel and this only occurs during wet years.

There is no model component designed specifically to cater for this type of process, although ‘dummy’ reservoirs can be use to represent evaporative or channel bed seepage losses. To overcome this problem, the modelling process illustrated in Figure 2.10 was constructed. The storage and losses from incremental catchment L are simulated by Dam B (maximum volume 7400 Mm^3), with a large surface area to represent the swamp, through which all the runoff from catchment L is routed. However, not all the upstream flow should pass through the reservoir representing the swamps, so to more accurately represent reality, the outflows from J are re-routed into Q (bypassing L). In addition, the area of Q is increased and L decreased, so that the part of L that does not contribute to the swamps, bypasses the ‘dummy’ reservoir (Dam B). This approach cannot be used for the spillage from the main Kafue channel into the swamps and therefore a somewhat more complex, multi-step approach was adopted. The first step was to calibrate the outflows from J (without a dam) against the observed data at that point, and then to edit the simulated flows at the outlet of J, decreasing all monthly flows greater than 800 Mm^3 to that value. A relatively small ‘dummy’ reservoir (1000 Mm^3, Dam A) was then established at the outlet of J, with the edited time series generated by the first step used as a high priority downstream flow requirement on the 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 (1000 Mm^3) was 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 volumes. 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 involves two iterative steps, as the ‘abstractions’ from the reservoir at the outlet of J become transfer inflows into L.



Step 1: Simulate flow from J

Step 2: Edit simulated flows from J to exclude peak flows greater than 800 Mm^3 and set as downstream flow requirements for Dam A

Step 3: Calibrate the abstractions (inflows to swamp) from Dam A to approximately achieve the required flows at the outlet of catchment Q

Step 4: Convert the abstractions from Dam A to upstream inflows into L and repeat steps 3 and 4 until the outflows from Q are a satisfactory representation of the observed flows

Figure 2.10 *Model setup and calibration steps for sub-catchments J, L and Q*

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

Itezhi-tezhi Dam, Kafue Flats and Kafue Gorge dam

The configuration of the two dams is relatively straightforward. Itezhi-tezhi Dam was established at the outlet of sub-catchment S with a capacity of 4925 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 above (an annual total of about 7100 Mm^3) did not seem to match the pattern of observed outflows, and were reduced to give an annual total of 4925 Mm^3. These were then reduced at dam volumes of 70% of capacity and lower. Kafue Gorge Dam was established at the outlet of U with a capacity of 900 Mm^3 and an area of 1165 km^2 at full supply. This conforms to the known facts about the reservoir. The area of sub-catchment U was set at 15,000 km^2 (and the area of T reduced by the same amount) to represent the 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 6000 Mm^3/y (or 190 m^3/s) and reduced when the dam reached 50% of capacity and lower.

The dummy dam representing the Kafue Flats was established with a capacity of 6500 Mm^3 and an area of 3250 km^2 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’. The levels at which the different releases apply were as follows:

Volume (% capacity)	> 90	89-75	74-50	49-25	24-10	<10
Release (Mm^3/mth)	2500	1995	1468	1012	744	506

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. Assessing the usefulness of these rather 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.

Calibration procedures

The calibration began with a number of trial model runs using the sub-catchments M to O, as well as A to E, with the aim of trying to establish fixed values for many of the parameters so that they could be excluded 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, PI1, PI2, FF, SL, POW, R, TL and GL. It was then necessary to determine if the absorption rate parameters ZMIN, ZAVE and ZMAX could also remain fixed. South African experience with the Pitman model suggests that in humid climates these 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. 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 = 600 and ZMAX = 1200.

During the initial simulations the usefulness of the automatic optimization 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 minimizing differences in the observed and simulated monthly means and standard deviations. It was found that the automatic optimization 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.

Although automatic optimization tests did help to provide some insight into the most appropriate range of parameter values to use, manual calibration procedures were considered to be the most efficient approach 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.

2.3.4 Simulation results

Full details of the calibrated model parameters are given in Hughes *et al*. (2003). It was found that the values of parameters ST and FT dominated the calibration process: their geographical distribution is shown in Figure 2.11. Topographically, the whole catchment is very similar with slightly steeper areas in the northern tributaries (mostly A, C and M). The flattest areas are in the Lukanga Swamps (L) and the downstream areas R, S and T. 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 follow this general pattern. However, there are some anomalies that are difficult to explain and that cannot be accounted for by other influences (geology, soils, vegetation cover, etc.). The values for J, L and T are difficult to determine as the calibrations below these areas are substantially influenced by the model configurations of the dummy dams that cannot be confirmed. The gauged records at G and K do not appear to be very accurate and the parameter values for these areas are quite suspect. Overall there is a reasonable degree of consistency in the parameter values, but there is not enough information about the differences in basin characteristics to be able to justify the parameter value differences.

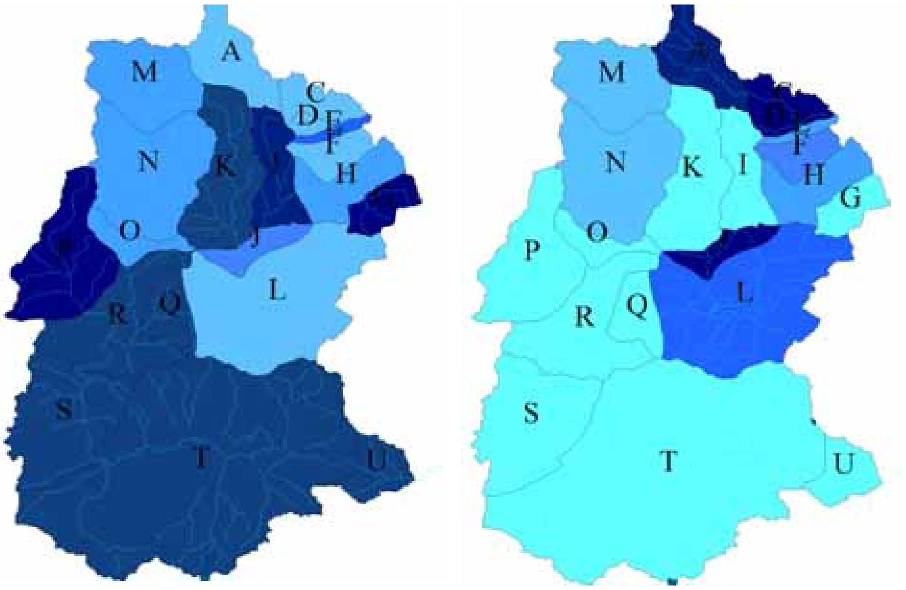


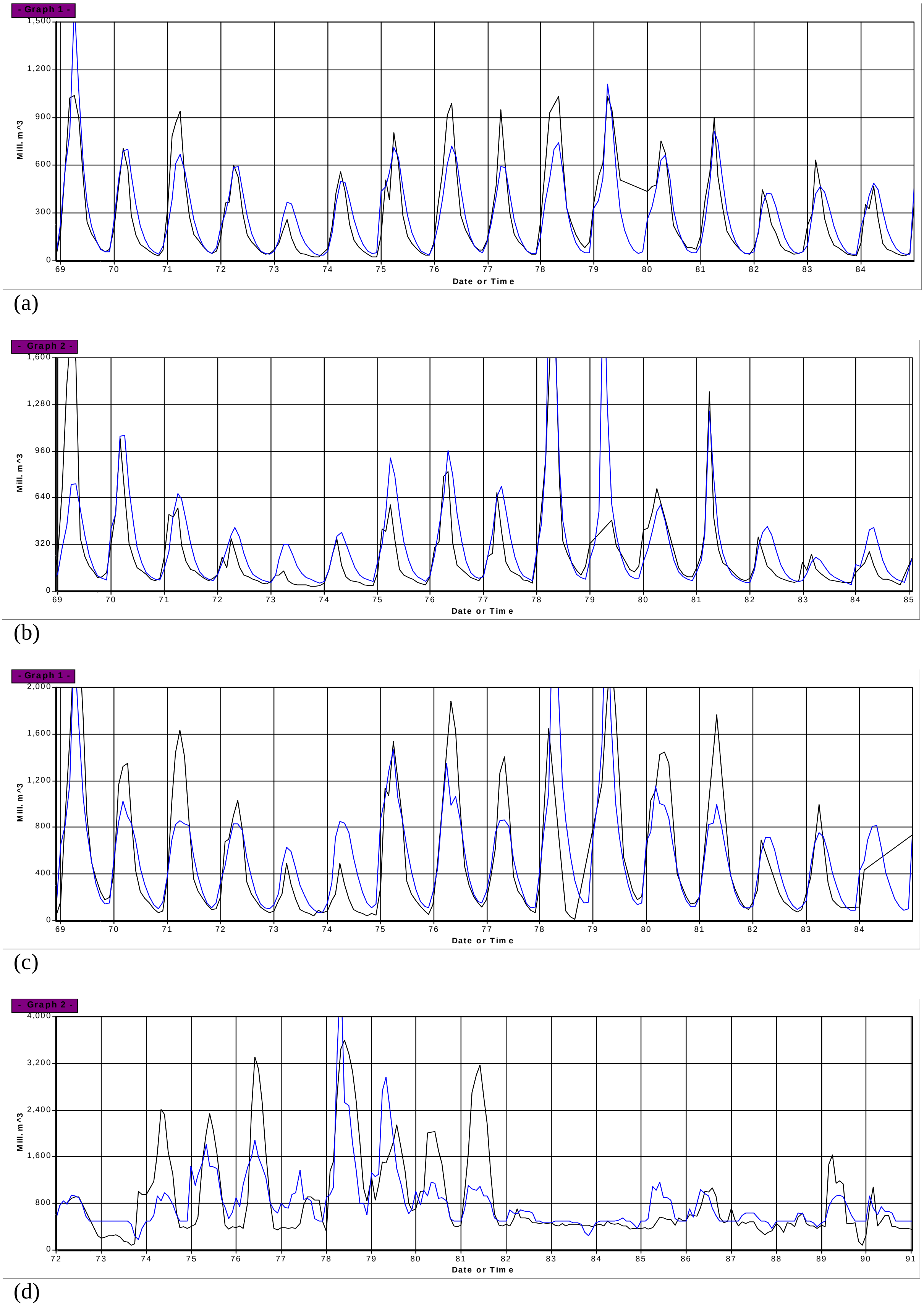
Figure 2.11 *Geographical distribution of parameters ST (left, dark colour indicates high values up to 1800mm) and FT (right, dark colour indicates high values up to 110)*

A statistical summary of the simulation results is provided in Table 2.4. For the whole period (calibration and validation periods together), and for most of the main channel sites, the correspondence between simulated and observed flows is acceptable. Examples of time series comparisons between observed and simulated flows at key points are provided in Figure 2.12, and Table 2.5 provides comparisons of the statistics for the calibration and validation periods separately for these sites. The following observations can be made about the simulation results:

- For sub-catchment F outflows (Figure 2.12a) the low flow simulations are satisfactory, while the high flow months are sometimes over-simulated and sometimes under-simulated. This recurs in the results for all sub-catchments and is partly a reflection of the less than satisfactory representation of the spatial rainfall distribution. The shape of the simulated recessions is generally quite good.
- For sub-catchment O outflows (Figure 2.12b) the recessions are poorly simulated except in one or two years. The results for N are substantially better and this may be a reflection of a poorly calibrated rating curve for the gauging station (see Section 2.3.2 where the stations are compared).
- The results at Q (Figure 2.12c) are very similar to those for many of the mainstream stations, illustrating generally acceptable results but with some poor simulations in several wet seasons. It was difficult to obtain good simulations for many of the intermediate years without adversely affecting the results for the dry and wet years. There are no model parameter combinations that were found that could address this problem. This site is below the Lukanga Swamps and the results are partly affected by the relatively simplistic method of representing the water exchanges between the swamp and the Kafue River.
- Given the lack of information to adequately define the operating rules of the two reservoirs in the lower parts of the basin, as well as the difficulties of configuring the model to represent the effects of the Kafue Flats, the results at the outlet of the basin (Figure 2.12d) are surprisingly good. While the correspondence in individual months is less than satisfactory, the effect of the drier years after 1982 are very apparent with few periods of spill from the Kafue Gorge Reservoir (the outflows are the controlled releases for hydropower generation).
- Figure 2.13 illustrates the simulated volume in the ‘dummy’ reservoir used to represent the Kafue Flats floodplain storage. While this pattern appears to generate reasonable inflows into the Kafue Gorge reservoir, there is no available information to confirm the results. If such information were available it might be possible to modify the model configuration and re-calibrate the lower parts of the basin.

Table 2.4 *Summary of simulation results for the Kafue basin*

Site	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	408	0.713	0.704	0.830	0.771	10.5	8.8	93.2	102.9	3.734	4.062
C	357	0.777	0.763	0.868	0.844	7.7	3.5	166.2	178.9	4.614	4.776
D	415	0.620	0.542	0.682	0.656	7.2	5.8	19.5	20.9	2.528	2.674
E	360	0.756	0.720	0.836	0.818	8.6	2.1	203.0	220.4	4.858	4.958
F	304	0.768	0.750	0.847	0.825	7.8	3.1	270.9	292.1	5.090	5.248
G	226	0.378	0.322	0.655	0.350	- 28.4	0.9	26.0	18.6	2.548	2.572
H	324	0.766	0.755	0.830	0.813	5.8	2.0	352.1	372.6	5.395	5.504
I	406	0.780	0.779	0.839	0.814	3.5	3.0	367.6	380.5	5.376	5.539
K	191	0.707	0.516	0.742	0.627	26.4	8.7	50.2	63.4	3.560	3.869
Q	285	0.678	0.661	0.777	0.703	6.2	4.9	530.2	563.3	5.699	5.977
N	285	0.704	0.699	0.700	0.656	- 2.2	- 0.5	260.3	254.4	5.228	5.204
O	395	0.544	0.486	0.656	0.557	16.8	4.6	237.2	277.1	5.040	5.274
R	288	0.815	0.808	0.836	0.730	1.5	4.5	821.3	833.6	6.134	6.412
S	232	0.460	0.309	0.416	0.269	13.0	2.5	657.4	743.0	6.282	6.441
T	302	0.506	0.506	0.450	0.416	- 0.8	1.8	744.5	738.8	6.352	6.466



(a)

(b)

(c)

(d)

Figure 2.12 *Simulation results for: (a) sub-catchment F, (b) O (c) Q and (d) T; observed monthly flows are shown in black, and simulated in blue.*

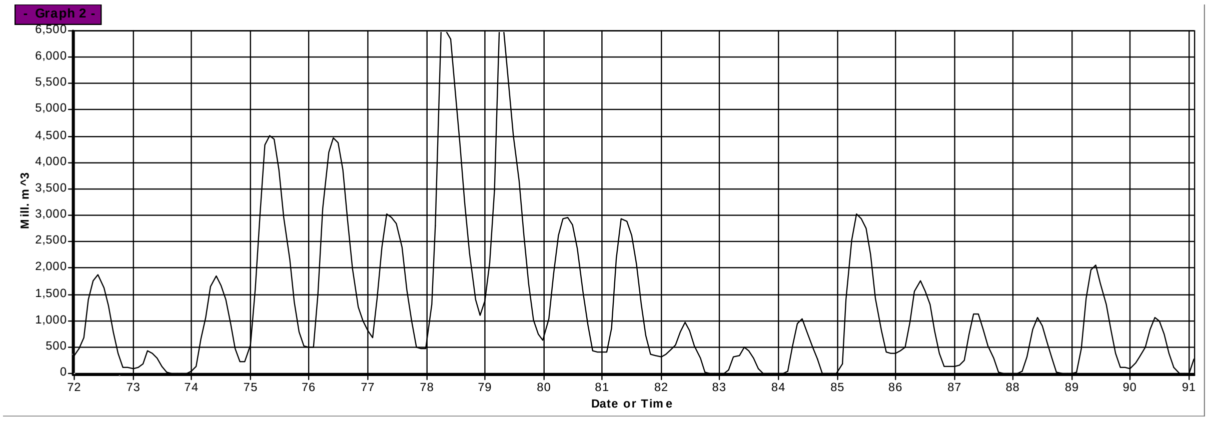


Figure 2.13 *Simulated volume of the dummy reservoir representing storage on the Kafue Flats floodplain*

Table 2.5 *Comparison of calibration and validation results for selected sites in the Kafue 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

2.3.5 Discussion and conclusions – Kafue basin

Overall the simulation results are satisfactory and the calibrated model could 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 questions that cannot be answered without further information:

- To what extent do some of the differences in parameter values between sub-catchments reflect differences in how well the available rainfall data represent actual rainfall inputs?
- To what extent do some of the differences in parameter values between sub-catchments reflect differences in the accuracy of the rating curves for the streamflow gauging stations?
- Would time series of potential evaporation demand improve the simulations?
- Would more detailed time series information about the actual patterns of release from the two reservoirs allow improved calibrations to be achieved?
- Would information about the patterns of inundation in the Lukanga Swamps and the Kafue Flats 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. Would additional information improve the calibrations and account for some of the differences in other calibrated parameter values?

One of the main objectives of the calibration exercise was to investigate the feasibility of regionalising the model's parameters. There are two main approaches to parameter regionalisation.

The first is to relate parameter values to measured physical basin characteristics and develop predictive equations for parameter values. This approach is currently of little relevance to this study as the physical basin data are not readily available with the required accuracy and resolution. The simpler alternative is to identify regions where calibrated parameter values are broadly similar. The latter was the approach used in the South African WR90 study (Midgley *et al.*, 1994). The problem with such an approach is that parameter differences between basins in the same parameter region are neglected. Ultimately, any complete regionalisation procedure should illustrate the effect on the model results of such parameter 'smoothing'. Difficulties in both cases occur when there is uncertainty about the extent to which the parameters represent 'real' catchment responses to rainfall rather than a combination of the response and the errors and inconsistencies in the data. A relatively simple test was carried out in which a common set of the key parameters ST, FT and GW were assumed for a region made up of sub-catchments A, C and D, and another common set was assumed for sub-catchments E to G. The results at the outlet of the whole area suggest only a slightly worse simulation with the R^2 and CE statistics deteriorating by 1 to 4% and the percentage errors in untransformed and log transformed means increasing to 10% and 3.8%, respectively.

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.

2.4 Regional calibration of the Pitman model for the Okavango basin

2.4.1 Introduction

The Okavango basin rises in Angola, flows through the north-eastern part of Namibia, and reaches its terminus in an inland delta in Botswana. The basin above Mohembo weir was sub-divided into 23 sub-catchments (Figure 2.14), of which 17 have gauging stations at their outlet. Of these, 10 are located in the north-west on sub-catchments of the Cubango River. A further 5 are located in relatively small headwater tributaries of the Cuito River and have very short records with a great deal of missing data. The remaining two are close to the inflow to the delta at Mukwe and Mohembo. The former has the longest and most complete record, while the latter only starts in 1975.

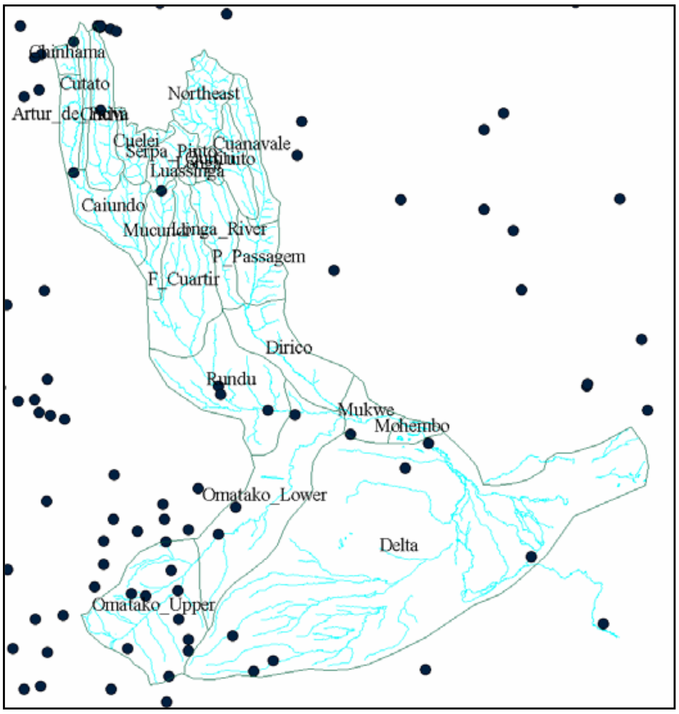


Figure 2.14 *Sub-division of the Okavango basin showing all available raingauges*

An examination of the observed flow records suggests that the runoff response of the western tributaries to rainfall is very different from that of the eastern tributaries. The western tributaries show a great deal more seasonal variation in flow, while the eastern tributaries have very high baseflows and relatively small seasonal variations. These observations are consistent with the geological differences between the two areas. The western parts of the upper basin are underlain by sandstones and mudstones, while the eastern parts are underlain by Kalahari Sands. These differences and the lack of sufficiently long and representative observed flow data for the eastern sub-catchments suggest that a regional calibration exercise would not be straightforward.

The generation of the catchment average rainfall, the annual potential evaporation totals and their seasonal distributions were part of a separate component of the study. This component reports on the initial calibration exercise and the results. The summary is divided up into three parts; the upper western catchments (Chinhama down to Mucundu), the eastern upper catchments (north-east down to Longa River) and the lower sub-catchments. The available rainfall data constrained the standard modelling period to January 1960 to December 1972, a total of 13 years. As the period is very short it has been difficult to follow standard modelling procedures of using part of the period for calibration and part for parameter value validation. The statistical correspondence between observed and simulated flows is presented as a set of statistics:

- R^2, or coefficient of determination, based on normal flows and natural log transformed flows.
- CE (coefficient of efficiency) based on normal flows and natural log transformed flows.
- % error in the mean monthly flows based on normal flows and natural log transformed flows; this is the % difference between the simulated and observed flows relative to the observed flows.

2.4.2 Calibration results

Details of the calibrated model parameters for all the sub-catchments are given in Hughes *et al.* (2003). Table 2.6 provides a summary of the statistical measures of correspondence between the observed and simulated flows for each.

Table 2.6 *Simulation results for the Okavango basin*

Sub-catchment	Months	Normal		Ln values		Mean monthly % error	
		R^2	CE	R^2	CE	Normal	Ln
Western upper sub-catchments							
Chinhama	109	0.734	0.733	0.819	0.808	2.0	2.8
Cutato	105	0.762	0.728	0.735	0.719	2.4	0.3
Artur de Paiva	111	0.745	0.740	0.764	0.738	7.3	3.7
Cuchi	105	0.583	0.579	0.672	0.653	-0.7	3.1
Cuelei	76	0.666	0.660	0.784	0.763	5.1	2.9
Serpa	130	0.672	0.632	0.731	0.718	-4.0	-0.9
Caiundo	120	0.776	0.769	0.762	0.731	7.4	3.2
Mucundi	121	0.777	0.763	0.788	0.749	9.6	2.8
Eastern upper sub-catchments							
Luasinga	32	0.117	-2.410	0.124	-2.953	-12.6	-7.8
Longa	36	0.182	-0.250	0.215	-0.224	12.1	5.5
Quiriri	69	0.261	0.145	0.240	0.087	-1.2	-0.2
Cuanavale	12	0.355	0.066	0.338	0.106	-9.9	-1.6
Cuito	67	0.708	0.626	0.727	0.713	-1.3	-0.2
Lower sub-catchments							
F Cuartir	72	0.815	0.758	0.797	0.763	9.0	1.7
Rundu	156	0.797	0.763	0.775	0.743	10.8	2.1
Mukwe	111	0.672	0.511	0.709	0.634	7.3	1.1
Mohembo	0	-	-	-	-	-	-

Western upper sub-catchments

Figure 2.15a shows the type of rainfall-runoff response of the western upper sub-catchments, which are all quite similar, suggesting that similar parameter value sets should be appropriate. The results (Table 2.6) indicate that overall the simulations have been successful and relatively consistent across all the sub-catchments. It is possible that channel losses are starting to play a role even in Mucundu, which might account for the somewhat higher positive percentage error in the mean flows based on normal values. In terms of parameter values the following observations can be made:

- ZMIN and ZMAX increase in value for the more easterly and southerly sub-catchments, probably reflecting both higher infiltration rates in the areas closer to the Kalahari sands region and the flatter slopes of the southern sub-catchments.
- ST also increases for the same sub-catchments, reflecting similar influences.
- POW is lowest for the upper central catchments, which is not simple to explain, while it is higher in the flatter southern sub-catchments, which is understandable.
- FT follows similar trends to the other parameters, although the low value for Cuelei appears to be anomalous and the physiographic differences within this area need to be further investigated.
- The groundwater parameter GW is always relatively high and needs to be viewed in the light of the differences between the two lag parameters TL and GL. The value of this parameter suggests that the runoff from these catchments is subject to relatively long delays.

In general, the calibrated parameter values demonstrate a high degree of consistency with those expected from a knowledge of the model conceptualisation and the variations in physiographic characteristics of the sub-catchments.

Eastern upper sub-catchments

Most sub-catchments have short records of very few months and only two have enough observed data for calibration purposes. The results are also extremely poor, except for Cuito (Figure 2.15b), which fortunately represents one of the larger contributions to downstream flow. The parameter values for Cuito are similar to those used for the Serpa Pinto sub-catchment, which appears to be transitional between the harder rock western areas and the Kalahari sands of the eastern region. ZMAX and ST values are high, POW values low, FT values moderate and GW values the same as FT (indicating that most of the flow is generated as slowly responding groundwater).

Lower sub-catchments

For all the lower sub-catchments, ‘dummy’ reservoirs were included at their outlets to represent channel losses. The volumes and surface areas of these reservoirs were quantified on the basis of the channel length and assumed channel plus riparian zone widths (for example Rundu and Mukwe have reservoirs with full supply volumes of 53 and 22 Mm^3, respectively). In general terms the calibrations have been successful (Figure 2.15c), although the percentage errors in the mean monthly flows are quite high and positive. It is therefore possible that upstream channel losses have been under simulated as the amounts of incremental runoff generated in these sub-catchments is quite low. The parameter values are consistent with relatively flat and arid catchments, the main contributions to flow only occurring during exceptionally high rainfall months.

2.4.3 Discussion and conclusions – Okavango basin

The results are as good as could be expected given the quality of the input data, the generally low degree to which the rainfall data are likely to represent actual spatial variations in rainfall, and the absence of detailed physiographic data. To determine whether improved simulations can be obtained, future attention needs to be given to the following issues:

- The real extent of the different geological zones in the upper catchment areas, as well as the surface soil characteristics of these areas.
- The character and location of the transitional area between the western and eastern sub-catchments.

- The vegetation cover characteristics of all sub-catchments (to refine the parameter values for the interception and evapotranspiration components of the model).
- The sizes of the channel and riparian areas and the way in which channel losses are allowed for in the model.
- Further refinement of the ZMIN and FT parameter values to ensure that the balance of runoff generated through different model components is represented optimally.

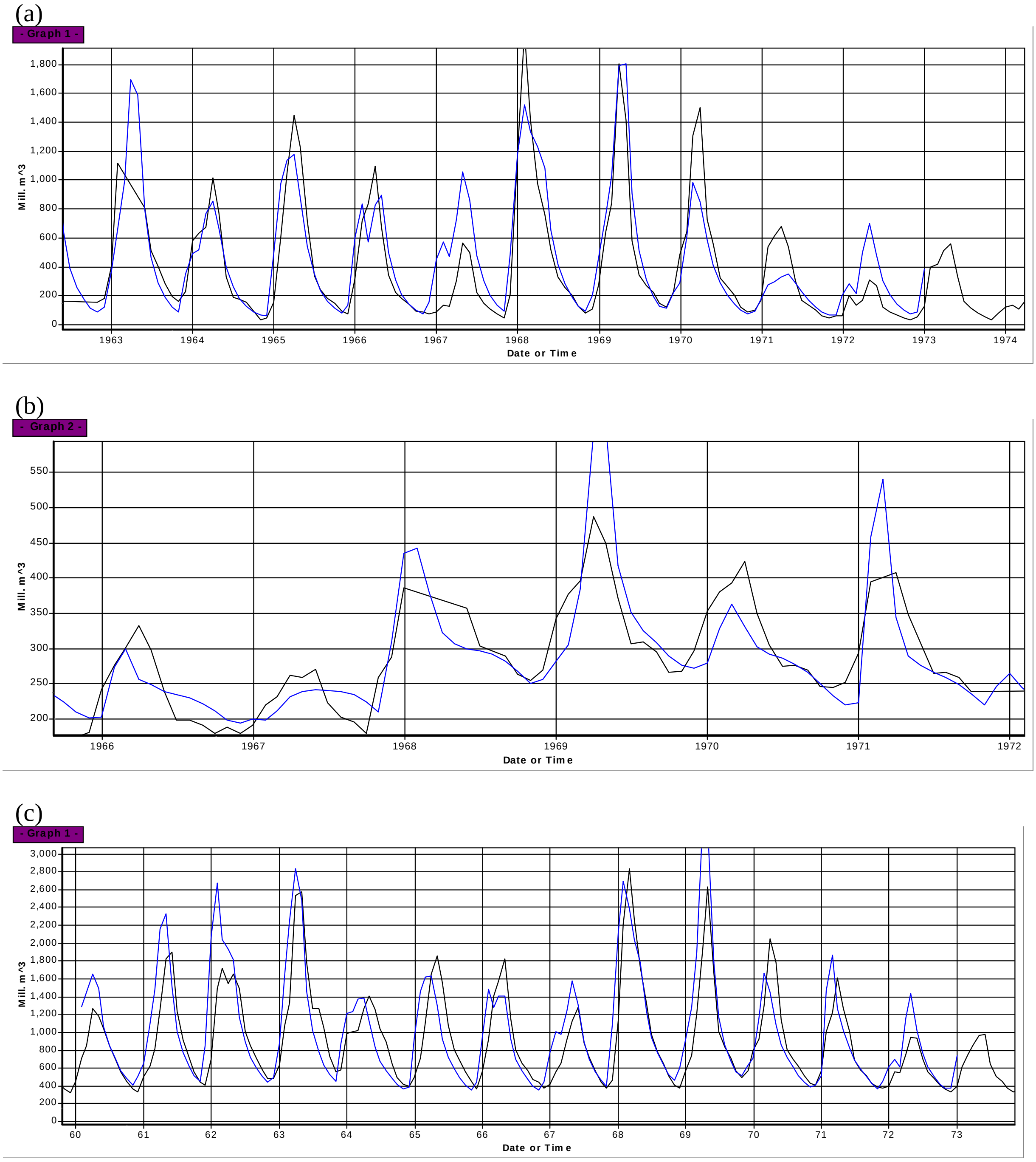


Figure 2.15 *Simulation results for: (a) Caiundo sub-catchment, (b) Cuito, and (c) Mukwe; observed monthly flows are shown in black, and simulated in blue.*

2.5 Overall conclusions

One of the objectives of this contribution to the FRIEND programme was to evaluate the SPATSIM package and its version of the Pitman model for use in this type of regional hydrological modelling study. The development of SPATSIM has continued throughout the project 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. It also seems to be relatively straightforward to learn how to use (based on the experience of some of the participants in the training programme). The latter is important 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 correct results and is also relatively straightforward to set-up and use. While the automatic optimizing function has not been used extensively in this project, it may prove to be useful elsewhere in the region and is a valuable addition to the available modelling facilities. One of its advantages is that it provides a check to ensure that the manually calibrated parameters for the headwater catchments are reasonably close to optimum values.

These somewhat more intensive modelling studies have 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 lower parts of the Okavango River) or man-made influences (the dams on the Kafue River) 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 to 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 in a larger study where several teams may be involved in modelling. If the teams do not closely follow similar procedures, there are likely to be anomalous patterns at major basin boundaries. Such a result is unlikely to engender common understanding and enable predictable outcomes. One possible approach to parameter regionalisation is to make use of the gridded spatial data set of basin characteristics used in the GWAVA study (Meigh *et al*., 1998; 1999)[1]. Part of the calibration process would then involve determining suitable relationships between these basin characteristics and calibrated parameter values. The best approach is likely to be the use of a selection of representative basins to establish the relationships, which will then guide the calibration process in the other basins.

Section 2.1 referred to the driving forces for the proposed long-term study of water resource availability in the SADC region. These relate to environmental sustainability and sound resource based planning in other economic and social sectors. Even at this stage of the project, the preliminary results for both the Kafue and Okavango rivers have the potential to provide hydrological information that can be used to assess environmental impacts of water resource developments. Examples are the effect of the operation of Itezhi-tezhi Dam on the inundation regime of the Kafue Flats, or the impacts of abstractions and return flows within the Copper Belt (sub-catchments C to F) on the dynamics of the Lukanga Swamps. In terms of resource based planning for agriculture, power generation and rural development, the Kafue again represents a good example. Current estimates of licensed consumptive abstractions for the whole basin amount to some 10% of natural mean annual runoff, which is already likely to have an impact on the generation of hydropower (an important element in the economy of Zambia) at the lower end of the basin, particularly during dry years. Any expansion of abstractions to satisfy development needs in the upper and middle parts of the basin will clearly have further impacts and will have to be planned and managed carefully to avoid negative economic impacts. Although there are still refinements that can be made to the calibrations of the model, given further information, its value for assessing various development scenarios should already be apparent. While it was not

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[1] See Chapter 5 for more information on the GWAVA approach.

part of this study to investigate the impacts of future changes to the rainfall and evaporation regime of the basin due to climate change, the model clearly has the potential to investigate such scenarios.

Neither this study, nor the proposed long-term SADC-wide project, directly address issues of social and economic improvement and poverty alleviation. However, they do address one of the fundamental bases for sustainable economic and social development in any region of the world – that of being able to reliably quantify the resource base upon which development depends. There can be little doubt that parts of Southern Africa lack the technical capacity and readily usable information to make their own informed decisions about water resource development options. In the past there has been a strong reliance on donor funded foreign expertise to generate the required information on an ad hoc basis. It is not the intention of this report to criticise the technical validity of these past efforts, but they have not resulted in any development of local capacity. This means that when situations change in the same basins in which the studies were undertaken it is often necessary to repeat the work, once again using foreign expertise. This is not a sustainable approach, nor is it an efficient use of donor funds in the long term. There are several water resource evaluation projects in the region that are currently in the tendering phase; these would have the potential to contribute to the objectives of the long-term study only if there exists a protocol to ensure that the methods used are compatible with similar studies in the region and that the results of such projects contribute to a developing regional database.

3 Drought assessment and monitoring software

M.J. Fry, S.S. Folwell, E.L. Tate and J.R. Meigh

3.1 Introduction

Drought affects large numbers of people in Southern Africa, particularly the poor who have less reliable access to fresh water supplies. Severe drought affects food security, but its impact on water resources has received less attention. The need to address water resource problems is made more urgent by the water-scarce situation that is developing in the region due to increasing population, urbanisation and, possibly, climate change. There has been some progress in mitigating the impacts of, and vulnerability to, drought, but responses (at both national and international levels) are still often inadequate.

The ARIDA project (Assessment of the Regional Impact of Drought in Africa) sought to investigate the water resources aspects of drought. The key aims were:

- To investigate better methods for identifying river flow droughts in Southern Africa, and
- To develop tools and software that water resources managers in the region could use to monitor droughts.

Within Southern Africa FRIEND phase II, the objective was to enhance the abilities of the countries to analyse historic water resources droughts and to monitor ongoing droughts, using the ARIDA approach, focussing on software development, training and dissemination. The ARIDA software was installed in two hydrological agencies in the region, with training in its use provided, leading to feedback and suggestions for improvements. The improved software was then disseminated more widely through the training workshops (Chapter 7). These aspects are described in Section 3.3, with a brief outline of the methods developed for drought analysis provided below. More detail on this work can be found in Tate *et al.* (2000), Tate and Freeman (2000) and Meigh *et al*. (2002).

3.2 Drought assessment methods

Quantitative indicators are needed to determine the timing, duration and severity of droughts. It is important that both indicators and methods take into account the hydrological characteristics of the area for which they are intended. Southern Africa is a vast region, with a wide range of hydrological regimes, so no single approach to drought assessment is likely to work region-wide. Various drought analysis methods were therefore developed in order to try to ensure that satisfactory results can be achieved across the whole area. Four methods were selected for further study.

Table 3.1 *Summary statistics for selected flow gauging stations*

Station	**Long. (°E)**	**Lat. (°S)**	**Drainage area (km^2)**	**MAP (mm)**	**MAR (mm)**	**Time with zero flow (%)**	**Q_{70} (mm)**	**BFI**
Okavango at Rundu	19.77	17.90	104,058	824	51	0	39.6	0.95
Ruhuhu at Masigira Confluence	35.19	9.94	2,007	1265	659	0	71.7	0.86
Lilongwe at Lilongwe Old Town	33.77	13.99	1,891	948	148	<1	11.0	0.51
Visrivier	20.36	31.81	1,502	248	9	95	0	0.01

MAP = Mean annual precipitation; MAR = Mean annual runoff; Q_{70} = Flow that is exceeded 70% of the time; BFI = Baseflow index, indicating the proportion of runoff derived from groundwater.

Comparisons were based on data from fifteen FRIEND flow gauging stations, chosen to represent a wide range of climatic conditions (average annual rainfall from 162 to 1370 mm), catchment sizes (52 to 104,000 km^2) and geomorphological situations, as well as having high quality, long and continuous records. The data covered the period 1941 to 1997, with record lengths from 17 to 51 years. Summary statistics for four stations, with a variety of flow regimes, are presented in Table 3.1.

The four methods compared were:

Low flow frequency analysis

Low flow frequency analysis (LFFA) is a standard procedure which has been widely used in temperate climates. Droughts are characterised in terms of the annual minimum discharge averaged over a range of durations. A probability distribution is then fitted to the annual minima, from which the estimated return period of a drought event can be extracted. A range of distributions was tested on the data from the 15 gauging stations, and it was found that, in general, the 3-parameter Log-Normal distribution using the L-moments method of parameter estimation performed best at almost all sites (e.g. Figure 3.1).

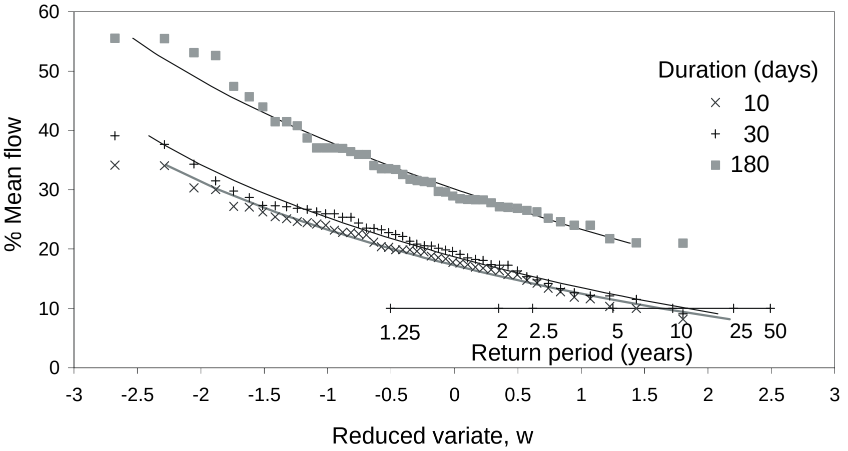


Figure 3.1 *Low flow frequency curves for the Okavango at Rundu using the Log-Normal (III) distribution fitted by L-moments*

Run-sum analysis

This method allows droughts to be characterised in more detail by simultaneously determining both the duration and the deficit volume of the event. It has been fairly widely studied in relation to temperate zone rivers, but its suitability for tropical and arid or semi-arid climates has been neglected, with the notable exception of Woo and Tarhule (1994).

Droughts are defined as flows below a pre-determined threshold. Continuous runs of flow less than the threshold are identified and statistical analysis of the drought characteristics is carried out. The characteristics that can be extracted are the duration of the drought (i.e., continuous length of time for which flow is below the threshold), the severity (i.e., cumulative volume of flow deficit over the duration of the drought), and the magnitude (i.e., average volume of flow deficit).

The run-sum method is applicable at a range of time scales. Daily data are most relevant for consideration of short droughts of less than a year. Longer droughts, especially those that extend over several years, are also of great interest as these tend to have the greatest socio-economic and environmental impacts. Annual data are the most appropriate for examining these. It was considered important to study both the shorter (within-year) and longer (multi-year) droughts.

- **Selection of suitable drought threshold levels.** The threshold level has a considerable effect on the analysis. For the analysis of short droughts, many workers have used thresholds based on percentage points of the flow duration curve (defined by Q_x, the flow that has an exceedance probability of *X*%). This was the approach selected since the value can be related to characteristics of the rivers and to abstraction levels for typical water uses, helping to provide a meaningful expression of drought. For much of the region thresholds of Q_{70} or Q_{90} were found to be suitable. However, for the many ephemeral rivers both Q_{70} and Q_{90} are zero. To extend the capability of the method, the mean flow was used as the threshold in the more arid and strongly seasonal regimes. For the analysis of long droughts based on annual data, the mean flow has been generally used as the threshold, and this approach was followed here.

- **Analysis of short (within-year) droughts.** During a prolonged dry period, it is often observed that flow exceeds the threshold for a short period of time, and thereby what is effectively a long drought is divided into a number of small, mutually dependent droughts. A consistent definition of drought events should include some kind of pooling in order to define an independent sequence. The problem of minor droughts also needs to be considered since the statistical analysis of drought characteristics tends to be complicated by a large number of very minor droughts that are usually present in the series (Tallaksen *et al*., 1997). A number of approaches to these problems were investigated, based on: an inter-event time and volume criteria; a moving average procedure; and the sequent peak algorithm. A series of sensitivity analyses was carried out to determine the most suitable parameters for each of the methods and to help in determining which of them is, in general, most appropriate for the region. It was found that, in terms of both its ability to eliminate dependent droughts and to minimise the number of minor droughts, the moving average (MA) method (with averaging interval t_d = 10 days) provided the most straightforward and robust option (Figure 3.2).

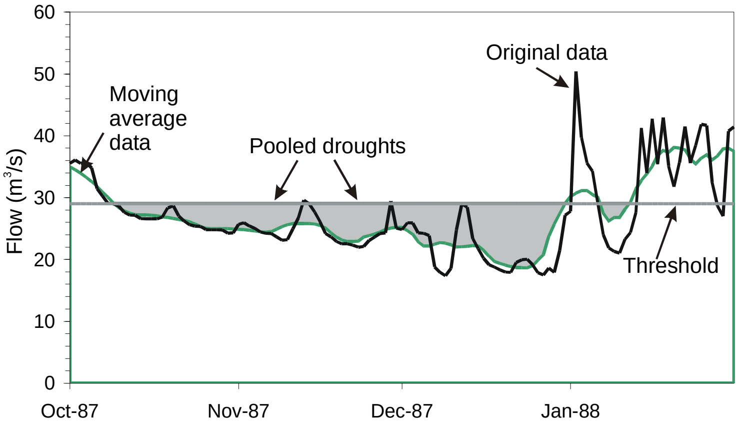


Figure 3.2 *Daily flow series for the Ruhuhu at Masigira Confluence with drought periods defined using the MA method*

- **Statistical analysis of short drought characteristics.** In order to analyse the statistics of the drought characteristics, frequency distributions were fitted to the data using the partial duration series (PDS) approach. Because it considers all the available drought events the PDS provides an intuitively sensible definition of the extreme value region. Only drought duration data were considered because it was found that the duration and deficit series are strongly correlated. Generally, the Generalised Pareto distribution provided the best results (e.g. Figure 3.3).

- **Analysis of long (multi-year) droughts.** Multi-year drought sequences were analysed using annual flow data, providing results complementary to those for short events using daily data. The use of annual data tends to have the result that data sets of drought durations are rather small. This has severe limitations for the frequency analysis of the drought series, which was therefore not attempted. However, ranking the results and extracting information on the durations and deficit volumes still yields useful information. Long drought sequences can be illustrated by plots of departures and cumulative departures from the mean (Figure 3.4). Since the threshold level is identical to the mean flow, all years with departures less than zero are treated as drought years.

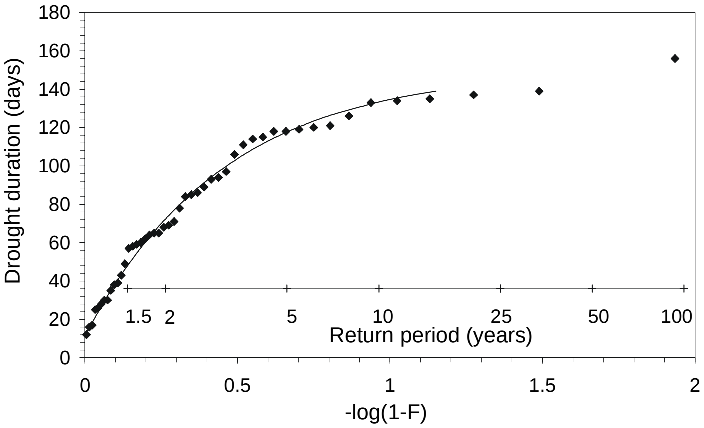


Figure 3.3 *Drought duration frequency curve for the Okavango at Rundu using the Generalised Pareto distribution fitted by L-moments*

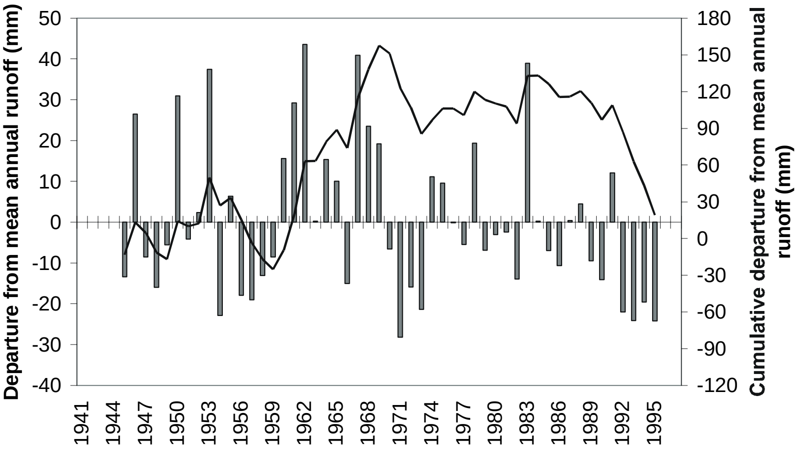


Figure 3.4 *Run-sum analysis output for long droughts for the Okavango at Rundu, showing the departure (bars) and the cumulative departure (line) from the mean annual runoff*

Runoff accumulation analysis

This is a relatively simple approach which was developed as a means of comparing the current flows to historic quantities. It is primarily an operational analysis, used as part of the assessment of ongoing droughts, but can also be used to illustrate past droughts. For each day from the start of the hydrological year (for all years of past data), the flow values are accumulated to find the total volume of runoff up to that point in time. Then the accumulated daily flow volumes are ranked, assigned probabilities of exceedance, and approximate curves of accumulated flow are created for a set of probabilities of exceedance (2, 5, … , 98%) by interpolation between the ranked data. The data for any year can be examined against these curves and an approximate assessment of the probability of the flow volume for the year (or part of the year up to the current date) can be made from the graph. shows examples of two very different flow regimes.

Ranking of flows and comparison with extremes

This is another relatively simple type of presentation of the data in which the current monthly flows are compared, both graphically and statistically, to historic minima, maxima and means. Flows for a period of five years are compared with extremes and monthly mean flows derived from the whole preceding period of historic data (Figure 3.6). The method also includes a tabulation of monthly flows and of flows summed over several months as percentages of long-term means, and ranking of the values in relation to historic data.

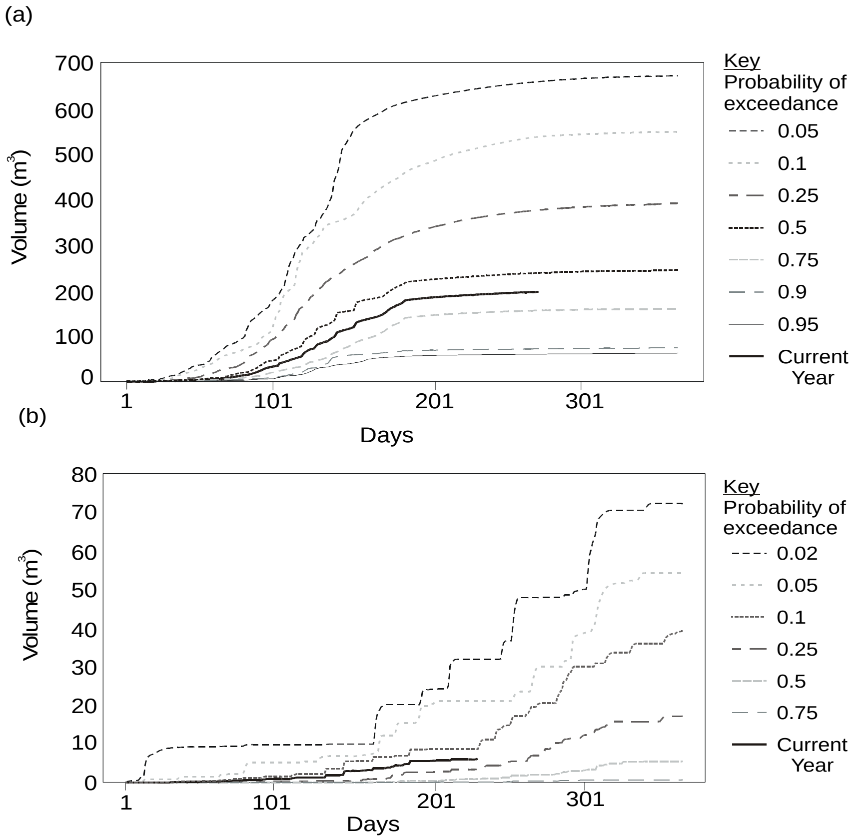


Figure 3.5 *Accumulated runoff analysis results for (a) Lilongwe at Lilongwe Old Town, (b) Visrivier*

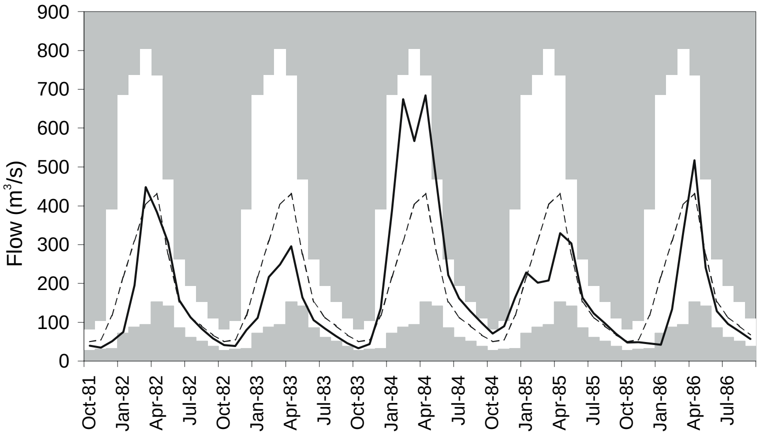


Figure 3.6 *Current monthly flows and comparison with extremes for the Okavango at Rundu (solid line is observed flow, dashed line mean flow, white bars show extremes from the historical record).*

Comparison of analysis methods
In order to compare the different analysis methods, the three most severe droughts determined by each method were extracted for each station Overall, there was a reasonable degree of agreement between the methods, with the limitations and advantages of each summarised as follows:

Low flow frequency analysis cannot identify droughts in arid and semi-arid areas where annual minima are quite often zero; this is a major limitation in Southern Africa. Other limitations are that the duration of the drought is not determined, only the properties of the low flows for given durations, and no information is available on the volume of flow deficit associated with the drought. An advantage is that it is straightforward to assign return periods to the results. Both runoff accumulation analysis and ranking of flows and comparison with extremes are limited by the fact that data are treated only in annual or monthly blocks, so that the true flow minima are not identified. The return periods or probabilities of the drought events can only be assigned in a crude manner. The methods are mainly useful in that they are very simple and they provide a good visual impression of flow events in the context of the behaviour of previous years.

The best method is to combine both the run-sum analysis approaches (using daily data for short droughts and annual data for multi-year droughts).. The ability to use a variety of thresholds means that it can be applied to all types of flow regime in the region. For short droughts the deficit volume is defined, and return periods can be assigned to the events. For long droughts, the analysis of annual flows gives adequate results, but it is limited in that return periods cannot be assigned unless exceptionally long runs of data are available, and the precise time points at which a drought started and ended are obscured. The two approaches are complementary; the daily analysis tends to extract droughts which are short but of great intensity, while the annual analysis picks out the more sustained periods of low flow. The impacts of the different types of events are likely to differ substantially.

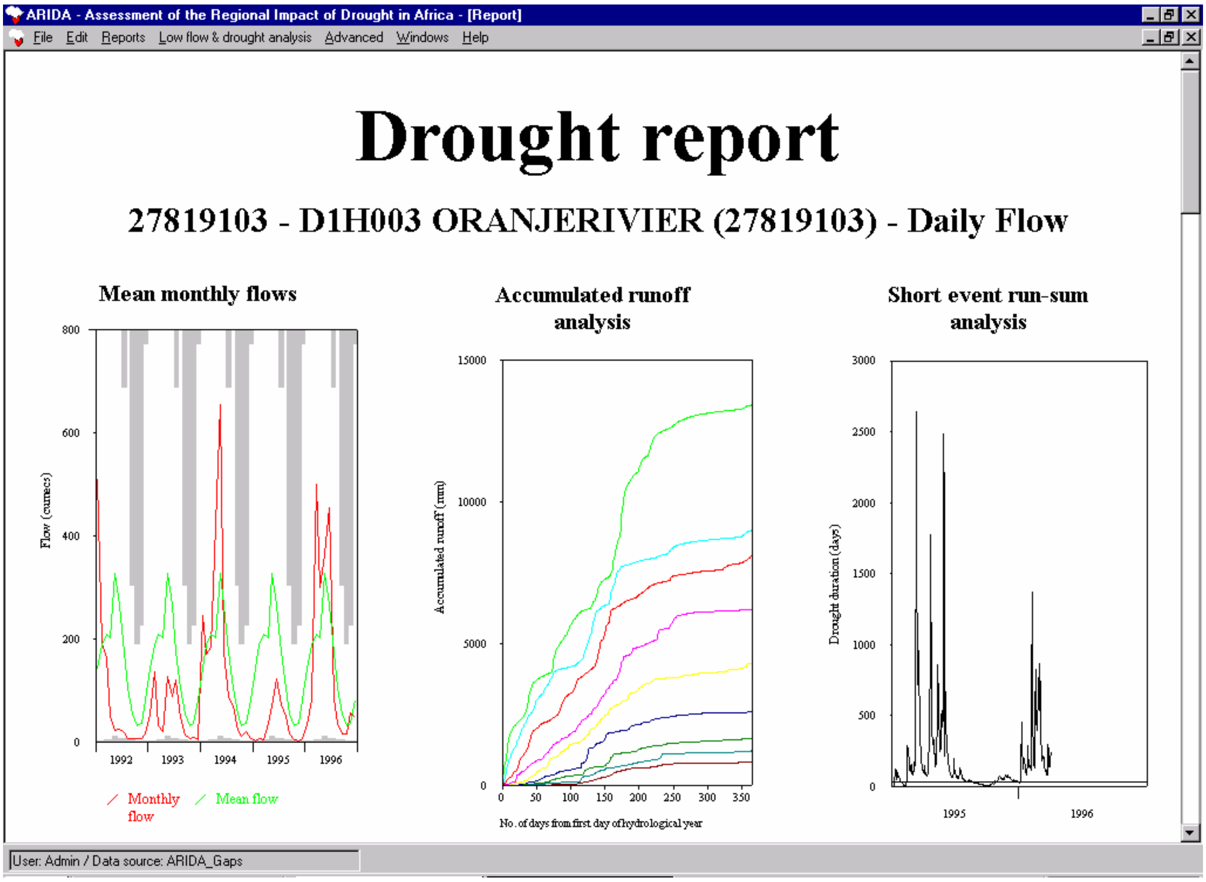
Conclusion
The analysis methods investigated in this study assist in the realistic determination of the characteristics of river flow droughts in southern Africa. Because of the wide variety of hydrological regimes across the region, a combination of different approaches is needed. In general, the run-sum analysis method was found to be the most robust and flexible approach and the one that is most widely applicable. By using the method to analyse both daily data for short droughts and annual data for multi-year droughts, in combination, it is especially advantageous. The use of a variety of different thresholds allows it to be applied over the whole range of flow regimes found in the region.

3.3 The ARIDA software

The methods were developed using historic data, but the approaches are also intended to be suitable with near real-time flow data so that they can be used to indicate how droughts are developing and to forewarn of possible future conditions. The techniques have been combined in a software package called ARIDA to provide a rapid assessment capability (Figure 3.7). The package includes graphical representation of flow or drought characteristics at a site and provides easily exported summaries of the state of a current drought relative to historical events.

The ARIDA software is a Windows-based system that links directly into the HYDATA (Hydrological Database and Analysis System; Institute of Hydrology, 1999; CEH, 2001) data processing format used for the hydrometric archive in many Southern African countries as well as for the Southern Africa FRIEND flows database. The ARIDA user can simultaneously produce multiple graph and statistic sets for different methods and for different flow series and these can be copied and pasted into other applications such as Word or Excel. The background settings for each method can be set and saved individually for each series for future use. Reports can be produced with any combination of graphs and tables for a specified selection of flow series. Statistics are produced for each drought period, providing a means of assessing the relative severity of droughts as measured by each method. When new data become available the methods can be re-applied, and statistics for the current drought updated, allowing its severity relative to historical droughts to be re-examined. The graphs, tables and statistics indicating the likely relative severity of the current situation provide useful information for water resources management and for drought mitigation.

Improvements in river flow monitoring are under way as part of the SADC-HYCOS project (Southern African Development Community – HYdrological Cycle Observing System), with river and meteorological measuring equipment being installed at sites across Southern Africa (Houghton-Carr *et al.,* 2000). Data are transmitted by satellite and made available, in near real-time, to linked databases in each country. The ARIDA software can be linked to the same databases, allowing it to benefit from the rapid availability of river flow data. This will help to reduce the time delay before river flow data are available for use in operational drought assessment, helping suitable management actions to be determined as early as possible while a drought is in progress.



Drought report

27819103 - D1H003 ORANJERIVIER (27819103) - Daily Flow

User: Admin / Data source: ARIDA_Gaps

Figure 3.7 *ARIDA software*

The software has been tested at some of the national water departments in Southern Africa, and a training workshop was held, at which the software was provided to all the departments in the region (Chapter 7). Feedback from the workshop was very positive, and many of the outputs were considered immediately usable within delegates' institutions. A workshop project was designed to place delegates in the position of hydrologists monitoring a developing drought and required them to produce regular reports on the progress of the droughts as seen by each of the different methods and to comment upon the effectiveness of each. The simpler of the methods, the monthly bulletin reports and accompanying statistics placing the months' flow within the context of the whole record, proved most readily understandable. Other methods, while more difficult to set up, provided more information on the length of the drought or the water deficits created. Overall it was considered a useful tool and many delegates attempted to put it to use within their own institutions. The software has been distributed to 30 representatives of other FRIEND projects, and it has been requested and used by hydrologists working in a variety of countries, including Ghana, Nigeria and Somalia.

4 Development and implementation of GIS water resources software

M.J. Fry, H.A. Houghton-Carr, S.S. Folwell and Z. Butao Uka

4.1 Introduction

It is now widely recognized that Integrated Water Resources Management (IWRM) is essential to sustainable development in Southern Africa. It is particularly relevant to efforts to promote equity and improve opportunities for the poor. This is illustrated by a recent review by the Global Water Partnership (GWP, 2003), which states “Since IWRM contains prospects for the equitable allocation of benefits from water and services dependent on it, it is important that these opportunities for healthier and more productive lives among the most at risk and disadvantaged population groups are not lost, but transformed into reality.”

As water use and water stress increase, the margin for error in assessing both water resources and the impacts of water use becomes smaller. At every level, from small catchments to international basins, water management needs to be carried out with the consideration of all stakeholders and with all possible awareness of what the future may bring. In practice, this means that water allocation decisions need to be made by water resource managers with as much information as possible on the available natural resources, the effects of existing water use on this resource, the water needs of stakeholders and the predicted change in these factors in the future.

The tools providing this information should form an interface between water availability and water use, allowing their impacts and interactions to be visualised. For instance, when assessing a planned irrigation abstraction from a river, the decision-maker should be able to ‘see’ the catchment above the point on the river from which the abstraction is to be made, and to understand the influences on the resource available at that point under natural conditions, as well as the variability of the resource. The decision-maker needs to be able to quantify the water use within the catchment, in order to estimate its impact and the effects of possible change in this water use. He or she also needs to be able to ‘see’ the water use downstream from this point in order to determine the effects of the new allocation on the resource for these users.

Within this phase of Southern Africa FRIEND, prototype tools for water resources management in Southern African countries have been developed. They are based on tools used in the UK, but they have been adapted to make them suitable for conditions in the region. The objective was to assess the viability of the tools and their appropriateness in the context of the water allocation processes in the region. Malawi was selected as the pilot region. There were two main parts of the study:

- Development of hydrological models to estimate flow statistics at ungauged sites within the country (Section 4.3).
- Development of a GIS water resources management software system which incorporates the hydrological models (Section 4.4). The software acts as a decision support system which can provide estimates of water availability anywhere on the river network (except the rivers Shire and Ruo). It allows water use information to be stored and visualised through the GIS interface. The water availability estimates and the water use information can be integrated to show the effects of both existing water use and future water use scenarios.

The work was carried out by CEH Wallingford and the Ministry of Water Resources Development (MWD) in Malawi. Delegates from eleven SADC countries were trained in the hydrological methods and the software system during one of the training workshops (Chapter 7). Feedback from delegates suggested that such a system would integrate well with the water resources management procedures practised in many of the SADC countries, and that it would provide a huge leap forward in GIS facilities, flow estimation and water resources management in most countries of the region.

4.2 Integrated Water Resources Management

Of the many definitions of Integrated Water Resources Management, three useful ones are:

- The co-ordinated planning and management of land, water and other environmental resources for their equitable, efficient and sustainable use (Calder, 1998);
- A framework for planning, organising and controlling water systems to balance all relevant views and goals of stakeholders (Grigg, 1999);
- A philosophy, a process and a management strategy to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits (DWAF, 1998).

In practical terms IWRM means the management of water using inputs and information from all factors affecting water availability and water use and from all stakeholders involved. Central to IWRM is the process of water allocation, usually an abstraction, a discharge, or an impoundment of water at a point on a stream or river. Allocations can also be non-consumptive uses such as for hydropower or environmental requirements. Information vital to this process can be classed into the following areas:

- Quantification of the available natural water resource, including its spatial and temporal variability;
- Factors that affect the natural resource, including rainfall, evaporation, land cover and other catchment characteristics;
- Changes that may alter these factors, for instance climate change, deforestation, soil degradation, etc;
- Current water use, both licensed and unlicensed, in different sectors, e.g. irrigation, public supply;
- Environmental water requirements;
- Changes in future water use, e.g. population change, need for increased agriculture, industrial development, community needs.

4.2.1 Water resources management in the UK

In the UK, the use of IWRM approaches has increased rapidly over recent years, as it has in many developed countries, with a move towards catchment-based water management strategies and environmental assessments of water bodies. The Environment Agency is the body responsible for water resources management in England and Wales. One component of their move towards IWRM has been the development of scientific methods for low flow estimation and software tools to provide managers with the ability to make water resources assessments and to manage water use data. The latest of these tools, Low Flows 2000, was developed by CEH-Wallingford and is now used in every EA region for making natural river flow assessments, monitoring the effects of existing licensed abstractions on river flows, and making water allocation decisions. For example, when an application for a new abstraction is made, the system provides an estimate of the natural low flow and the effects on key low flow statistics of the existing artificial influences and the new abstraction.

Despite obvious major physical, social and economic differences between the UK and Southern Africa, similarities in the processes involved in water resources management mean that there is still a great potential for technology and knowledge transfer in these areas.

4.2.2 Water resources management in Malawi

In Southern Africa water resources management is important because of the scarcity of water, the major role of water within the economies of many countries, and the levels of vulnerability of populations, especially the poor, to the water stress that can occur through drought, inadequate access and poor water management. In many areas where water use is high, decisions are having to be made to limit the effects of water shortage on irrigation, the population, or the environment, often to the detriment of other water users. These decisions should be made with the maximum possible understanding of all causes and effects. In other areas, where water stress is not yet at this critical level, there is a need for the development of water use within a well-planned process that views the future needs of all stakeholders.

Water resources data comes from the national networks of gauging stations, measuring river flows and reservoir storages. These networks by no means provide coverage of the entire region, and areas where little water development has taken place often have the poorest coverage. In addition, the extent and quality of the networks has declined rapidly in recent years, making the quantification of water resources even more problematic (Sene and Farquharson, 1998).

Although hydrological regimes within Southern Africa vary considerably, the water resource demands and problems faced in Malawi can be considered representative of those in many countries across the region. Exceptions are the very arid areas where water scarcity is extreme. Scales of water use in Malawi vary from large-scale commercial agriculture and major civic supply schemes to small-scale, domestic agriculture and village supplies. Generally, larger private bodies and public supplies within catchments of all sizes are licensed, whereas many of the numerous smaller domestic and agricultural abstractions are unrecorded. Water resource planning and management is carried out primarily by the MWD and regional water boards. The assessment of requirements and impacts are made by either government hydrologists or contracted consultants to varying levels of accuracy and detail. Other bodies with interests in water resource assessment include the Ministry of Agriculture and Irrigation, who consider sustainability of flow as a key factor in identifying new areas of agricultural potential. Tools are needed to standardise these assessment procedures and bring consistency to the process of licensing abstractions of all sizes. They are also required to integrate the meteorological, hydrological and water use data, and to allow estimates to be made at ungauged locations and in areas not adequately covered by the gauging station network.

4.3 Development of low flow estimation techniques for Malawi

Techniques for estimating low flows at ungauged sites were developed for Malawi using relationships between spatial catchment characteristics and flow regimes. The available data, particularly water use within the catchment, was of varying quality. These data are currently not held or recorded in Malawi,and the use of IWRM software tools to store this information could become an important factor in the future.

4.3.1 Brief description of the study area

Malawi is surrounded by Tanzania, Zambia and Mozambique. The country is located at the southern end of the East African rift valley, which dominates the topography (Figure 4.2). Lake Malawi, the third largest lake in Africa, occupies the northern two thirds of this section of the rift. The lake lies at an altitude of 470 m, and its only outlet, the River Shire, drains southwards to the lower rift valley at 90 m altitude, before joining the River Zambezi. All rivers in Malawi eventually drain into the Shire except for a small area in the east of the country, where there is the catchment of Lake Chilwa, which has no outlet, and a smaller area draining eastwards into Mozambique.

The topography of Malawi is varied, and the country may be divided into four broad hydrological zones: highlands, plateau, escarpment and rift valley. These zones can be distinguished in Figure 4.2.

The plateau is at an altitude of between 900 and 1200 m and features broad, undulating plains. The climate is temperate, and these are the most densely cultivated regions of the country, where little of the original woodland remains. An important feature of the plateau is the dambos, broad grass-covered swampy valleys which overlie impervious strata. They become saturated with water during the rainy season, and help to sustain river flows during the dry season. The particular hydrological behaviour of the dambos sets them apart from other types of catchment within the country.

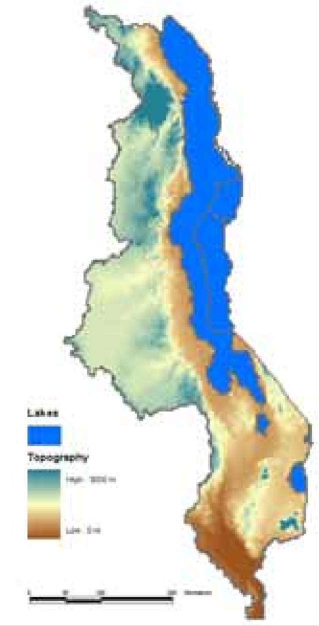


Figure 4.1 *Topography of Malawi, showing the four hydrological zones*

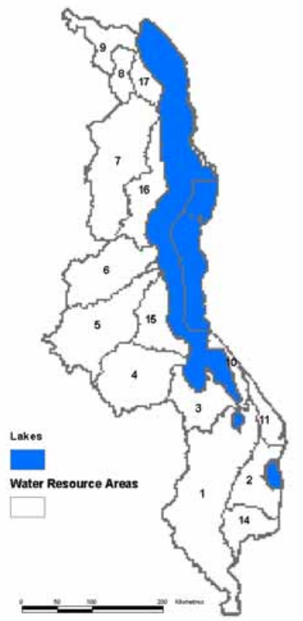


Figure 4.2 *Water Resource Areas (WRAs) of Malawi*

The highlands rise abruptly from the plateau reaching altitudes of between 2100 m and 3000 m. The climate is cool, and the vegetation is forest relicts and open grasslands. These areas are now either forest reserves or game reserves, partly covered with exotic trees.

The escarpment marks the boundary between the plateau and the rift valley. It drops down in a series of shelves and is an area of major faulting. Considerable portions of the escarpment are protected by forest or game reserves, but pressure to secure arable land results in some areas of steep land being cultivated outside these protected areas. The rift valley is mainly covered by alluvial deposits of the Quaternary age. The climate is tropical, and the original vegetation is mixed savannah woodland. The most favourable soils in this zone have been developed into irrigated rice and sugar schemes.

For the purposes of water resources management, Malawi is divided into 17 separate Water Resources Areas (Figure 4.1).

4.3.2 Flow estimation in Malawi

The main previous study of low flow hydrology and flow estimation in Malawi was that of Drayton *et al*. (1980) who developed methods for flow duration curve estimation using relationships between mean flow and rainfall, and mapped values of the low flow statistic Q_{95} for the country[2]. The method enabled the estimation of low flow statistics and flow duration curves at any point in the country, providing the facility to obtain flow estimates at points on the river network where gauged flow data

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[2] Q_{95} is a percentage point of the flow duration curve; it is defined by Q_X, the flow that has an exceedance probability of X%.

are unavailable. However, the time-consuming and technically challenging nature of this method, which had to be applied manually, has meant that it has not been regularly used. A further study by PEMconsult (1998) included a means of estimating flow duration curves, based on Bullock *et al.* (1990); this represents an earlier version of the regional curves developed in Phase I of SA FRIEND that are used here (see Section 4.3.4).

Recent international low flow studies have often concentrated on relationships between flow statistics and the hydrological response of soil types within catchments (Gustard *et al.*, 1992), assisted by the availability of high quality soil coverage data through the work of the United Nations' Food and Agriculture Organisation (FAO, 1996) and others. Another element of recent low flow estimation studies has been the creation of flow duration 'type curves', whereby a set of standardised flow duration curves are created using data from a number of stations representing the variety of flow regimes within a region, and the linking of these standard curves to a low flow statistic, typically Q_{70} or Q_{95} (Gustard *et al.*, 1992; UNESCO, 1997). Through estimation of this statistic from observed data, flow duration curves can be predicted. This study aimed to further the work of previous studies in Malawi, and Southern Africa generally, by investigating the application of these methods in Malawi in order to assess their feasibility for flow estimation as part of a water resources management tool.

The general approach can be outlined as:
(a) Selection of suitable gauged catchments;
(b) Detailed scrutiny to assess the reliability of the records;
(c) In cases where insufficient natural flow records are available, naturalisation of the observed flows (i.e., removal of the effects of artificial influences on the pattern of river flows);
(d) Extraction of low flow measures from data records for these catchments;
(e) Extraction of catchment characteristics from digital maps;
(f) Development of relationships between extracted flow measures and catchment characteristics, or country-wide mapping of flow measures.

4.3.3 Available data

Much of the work of Drayton *et al*. (1980) focussed on the validation of flow data from the network of gauging stations. At that time there were a total of 159 stations, with some having more than 20 years of data. Of the 159, 53 were considered suitable for inclusion in the low flow component of the study. One of the recommendations of this study was an increase in the number of gauging stations on small rivers and catchments, which would benefit scientific studies of this kind. Although further gauging stations have opened (including many on small catchments), the level of hydrometric monitoring, particularly discharge measurements for calibration, has recently dropped dramatically. Overall, there has been little improvement in the availability of accurate data since that earlier study.

Collection and validation of flow records is now performed by MWD within the management of their national database. Stations used in this study were selected using a variety of criteria. At a first pass, stations were excluded if their record lengths were very short or they had poor continuity of record. Stations on the Shire River were also excluded, as the flows are heavily dependant upon the level of Lake Malawi, the modelling of which was beyond the scope of this study. Further stations were excluded on a basis of large artificial influences within the catchment, such as releases from dams, where flows could be neither conceived to represent the natural regime nor naturalised through knowledge of the levels of influence. The remaining records were then subject to more detailed scrutiny, with stations being rejected on the suspicion of erroneous data or where rating equations were considered poor at low flows.

Artificial influence data and flow naturalisation
All licensed artificial influence data for the country were collected, resulting in a database of 1500 abstractions and 140 discharges (Figure 4.3). Abstractions varied from large storage dams to very small licenses for domestic usage of several cubic metres per day only. Some licenses had no data about licensed abstraction volumes. Irrigation licenses provided monthly abstraction volumes, and all

other volumes were provided on a daily basis. Discharges licensed were generally for small volumes of effluent with high pollutant concentrations, and were considered negligible in their effects on flow rates within streams.

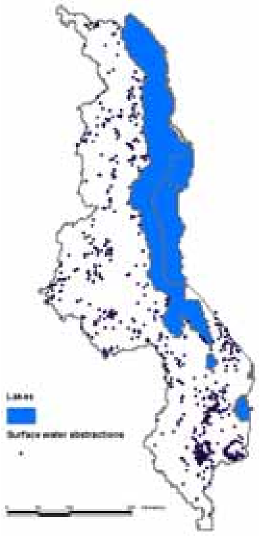
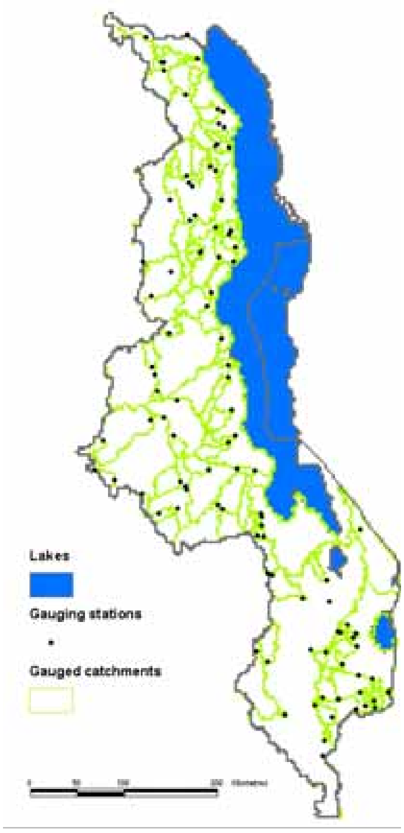
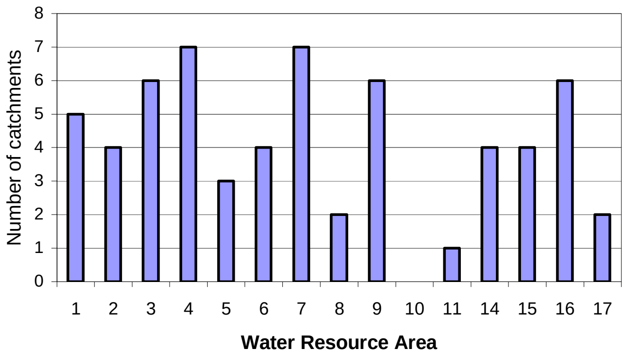


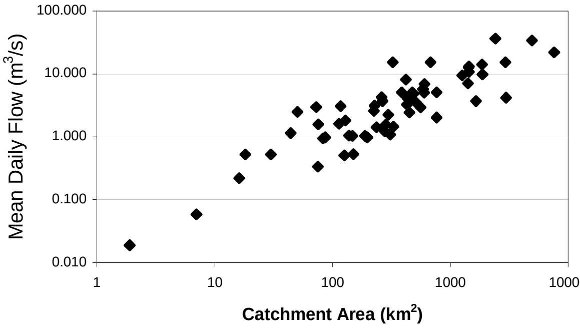
Figure 4.3 *Distribution of surface water abstractions*

An attempt made to use the abstraction data to 'naturalise' the flow records. The available information consists of the licensed abstraction volumes only, rather than the volumes that are actually abstracted. These could be considerably larger or smaller, and could have changed over time; but, because the licensed quantities are the only data available, they had to be used. The period of abstraction was assumed to be the period licensed; again, this is likely to be different in reality. These limitations mean that the naturalisation process can be considered as only an initial attempt. There are insufficient catchments with unaltered flow regimes to attempt a study using only the natural flow records, so it is a necessary exercise. In future studies, more detailed assessments of the real water use within catchments would be helpful to reduce the errors that arise from the naturalisation of artificially influenced flow data. These could be based on the estimation of water use from such factors as population size and distribution, and irrigation data. In South Africa, studies are starting to use satellite data to estimate water use from crop coverages. These types of studies will become more relevant in the future as unknown abstraction volumes start to play a significant role in more catchments.





a) Distribution of catchments by Water Resource Area



b) Mean daily flow against catchment area for the dataset

Figure 4.4 *Distribution of gauging stations used in study, and comparison of mean daily flow against catchment area*

After naturalisation, the remaining dataset consisted of 61 stations, with an average of 30 years of data. Figure 4.4 shows the distribution and variety of catchment sizes within the dataset, and Table 4.1 provides a summary of the hydrological characteristics of the catchments. There is a reasonable geographic spread of catchments over the country, representing a range of rainfall, topography, soils and catchment sizes, although there are fewer small catchments that might be wished.

Table 4.1 *Summary of hydrological characteristics of gauged catchments used in study*

Parameter	Unit	Mean	Standard deviation	Range
Catchment area	km^2	767	1260	1.9 – 7610
Mean flow	m^3/s	5.54	7.26	0.02 – 36.35
Mean annual rainfall	mm	1163	245	803 – 1904
Mean annual runoff	mm	366	314	44 – 1561
Baseflow Index*		0.54	0.17	0.23 – 0.88
Standardised annual Q_{70}		0.22	0.18	0.001 – 0.655

**Note:* For definition of the Baseflow Index, see Section 4.3.4.

Rainfall data

Rainfall data were obtained for 270 raingauges across the country, generally well distributed but with large numbers clustered in areas of more intensive water use, usually urban areas and large-scale irrigation schemes (Figure 4.5). Data had been processed to provide monthly mean rainfall measurements for the period of record at each station (Ministry of Agriculture and Irrigation, 2001). Because of this the quality of record is hard to judge, but with the omission of only a small number of misplaced or obviously erroneous stations, a reasonable coverage of monthly mean rainfall was obtained. The period of record varies between stations, and there is insufficient overlap to allow a common period of record. However, every station had at least 60% of data available over the period 1970 to 1999, which was deemed to provide a reasonable dataset. These data were used to create a rainfall grid for the country with a 5 km resolution (Figure 4.5).

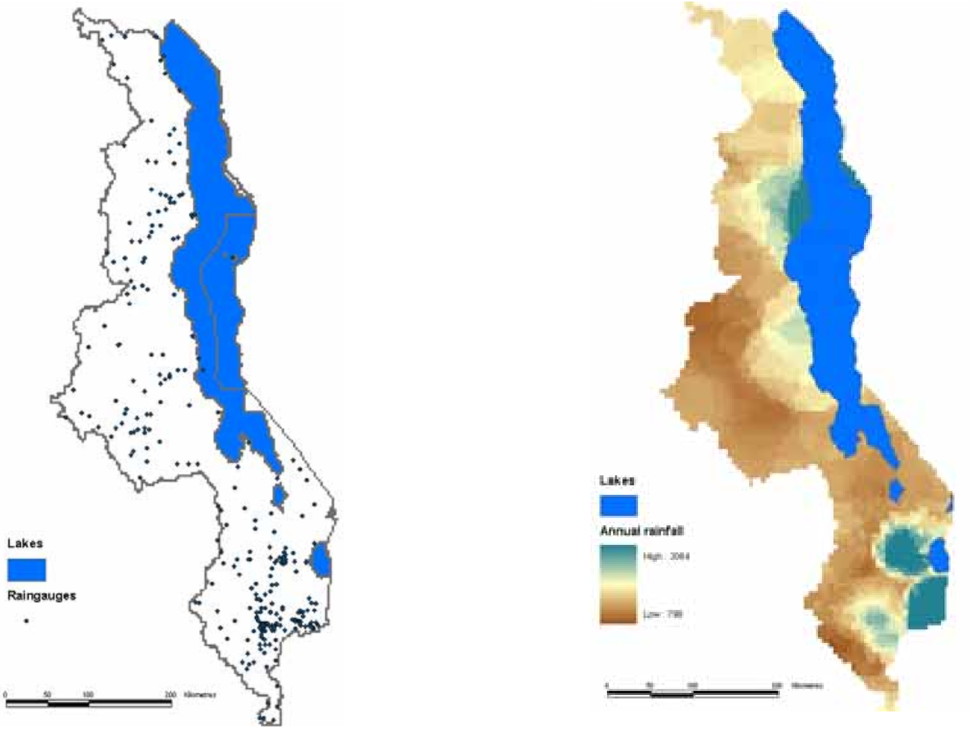


Figure 4.5 *Distribution of raingauges used (left) and the resulting rainfall grid (right)*

It can be seen that rainfall is mainly dictated by topography with variations highlighting the boundaries of the hydrologically similar zones. Areas of high rainfall can be seen at the massifs of Mulanje and Zomba, in the south of the country, Nyika, in the north, and along the northern lakeshore. The Shire valley, running south from Lake Malawi, and the plateau regions to the west display lower rainfall.

Soil data

Digital datasets of soils for the entire country were obtained from Land Resources Conservation Board (1992), using the classification of the Food and Agriculture Organisation of the United Nations (FAO, 1996). The digital coverages were used to calculate the percentage of each soil type within each gauged catchment.

4.3.4 Development of relationships between catchment characteristics and flow regimes

The analysis required a number of steps:

- Development of relationships between mean annual runoff and mean annual rainfall;
- Development of relationships between baseflow characteristics of the catchments and soil type;
- Development of a relationship between the flow duration curve and baseflow characteristics of the catchments;
- Selection of characteristic flow duration curves.

Each step was carried out independently, starting with the whole dataset and grouping catchments that exhibited similar behaviour. The aim was to determine a set of regions with reasonably consistent hydrological behaviour. The criteria also included consideration of topography and the four hydrological zones of the country described above (Figure 4.2). A practical limitation was that it was more convenient to treat each of the Water Resources Areas (WRAs) as a unit. For some analysis steps it was easy to identify distinct groups, but less so for others. The most prominent group was the highland and plateau areas around Nyika and Mulanje. The final division separated the country into three regions (Figure 4.6). WRA 1 did not obviously fit with any other grouping, but it does not contain enough catchments to form its own group. For the purposes of analysis it was assigned to the geographically closest grouping, where it had an insignificant effect on the analyses.

The three regions are:

Region I	Escarpment, rift valley and lakeshore catchments in the south (WRAs 1, 2, 3, 4, 5).
Region II	Plateau, escarpment and lakeshore catchments in the north (WRAs 6, 9, 11, 15, 16, 17).
Region III	Highland areas including Nyika Plateau in the north and Mulanje Massif in the south (WRAs 7, 8, 14).

Once the division into regions had been settled, the analysis was repeated using the same three regions in each step. Thus, it was an iterative process: the analysis was first done to identify the regions, and then repeated using those regions. The pragmatic justification of the selection is that each of the regions appears to have broadly similar hydrological (and specifically, low flow) behaviour, and that, of those examined, this combination seemed to give the best results in terms of goodness of fit of the relationships.

Relationship between mean annual runoff and rainfall

A simple linear model was found to be best for this relationship. In the study of Drayton *et al.* (1980), a number of approaches were tried, but in the present study these were not found to provide any improvement over the linear model. It was found that regions I and III could be satisfactorily grouped together, while region II was treated separately. The resulting equations were:

Regions I and III: $Q = 1.225P - 995 \quad (R^2 = 0.735)$
Region II: $Q = 0.443P - 241 \quad (R^2 = 0.389)$

where Q is the mean annual runoff in millimetres, P is mean annual precipitation (mm), and R^2 is the coefficient of determination, providing a measure of the quality of fit. While the relationship for regions I and III is reasonably strong (Figure 4.7), that for region II is weaker. There is a lack of data in this region, and it might be better to split it further, but currently there is insufficient evidence to do so.

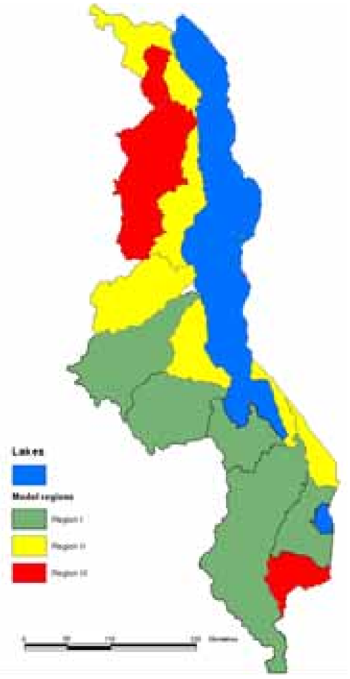


Figure 4.6 *Regions used within flow estimation model*

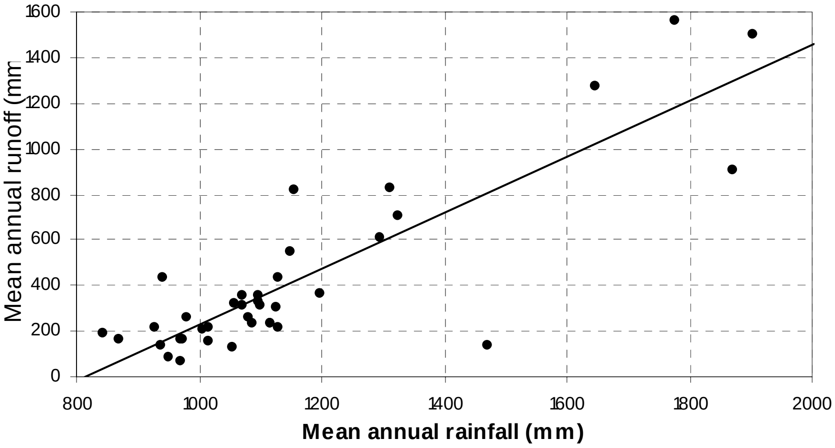


Figure 4.7 *Mean annual runoff against rainfall for regions I and III*

Monthly flow estimates were also needed, and these were achieved by establishing, for each month, a regression relationship between the mean monthly runoff (expressed as a proportion of the annual) and mean annual runoff. At first a relationship between mean monthly rainfall and mean monthly runoff was investigated, but, although there were obvious relationships in some months and for some catchments, for others it was unclear. Furthermore, in the dry season, mean monthly runoff exceeded mean monthly rainfall for all but six catchments, suggesting that dry season flow is dominated by baseflow and that a more complex rainfall-runoff model would be required. Therefore, treating the whole country as one region, mean monthly runoff was expressed simply as a proportion of mean annual runoff, and regression equations were derived for each month.

Relationships between the baseflow characteristics of the catchments and soil type

The Base Flow Index (BFI) was used as a measure of the baseflow characteristics of the catchments. The BFI provides a systematic way of assessing the proportion of baseflow in the total runoff of a catchment. It is a measure of the influence of soil and geology on river flows, and is important for low flow studies, as it is the baseflow component that is sustained in the dry season when there is no rapid runoff in response to storm rainfall. A higher BFI indicates a slowly responding catchment, whilst a lower BFI suggests that rainfall tends to create runoff quickly. For information on its development and the method of calculation see Gustard *et al*. (1992).

Table 4.2 *Summary of relationship between soil classes and model regions*

Soil class	Soil description	Region I	Region II	Region III
1	Luvisols and vertisols	0.44	0.54	0.49
2	Lixisols	0.62	0.48	0.81
3	Cambisols, gleysols and fluvisols	0.52	0.58	0.48
4	Leptosols	0.19	0.19	0.19
5	Ferrasols	0.93	0.77	0.93
6	Alisols	0.51	0.51	0.51
7	Acrisols	0.81	0.82	0.86
8	Arenosols	0.51	0.51	0.51
9	Regosols	0.76	0.76	0.76

While such factors as the slope of the catchment and the presence of lakes and wetlands can influence baseflow, it has often been found that soil type alone can provide a reasonable indicator of BFI. The individual soil fractions for each catchment were identified out of a total of more than 20 classes.. This was too many for meaningful analysis using only 61 catchments, so soils of a particular type were grouped together (e.g. all the arenosols) and some soils which frequently occur together were also merged. After a number of regroupings and iterations, the result was nine soil classes. Multiple regression was then carried out for each region to provide relationships between BFI and soil type for each (Table 4.2). In this table the values are the coefficients in relationships of the form *BFI* = a.*{fraction of soil class 1)* + b.*{fraction of soil class 2}* + … etc. The quality of fit is reasonably good, especially in region III, with R^2 values of 0.583, 0.650 and 0.979 being obtained for regions I, II and III respectively.

Relationship between the flow duration curve and baseflow characteristics of the catchments

To relate the BFI to a usable flow statistic, a relationship was derived between BFI and Q_{70}, the point on the flow duration curve at which flows are exceeded 70% of the time. Q_{70} was chosen because it is the critical point that has been most often used in most previous work, in particular in the first phase of the Southern Africa FRIEND project to define typical flow duration curves for the region (UNESCO, 1997). Treating the whole country as one region, the resulting relationship was (Figure 4.8):

$$Q_{70} = 0.899BFI - 0.265 \qquad (R^2 = 0.755)$$

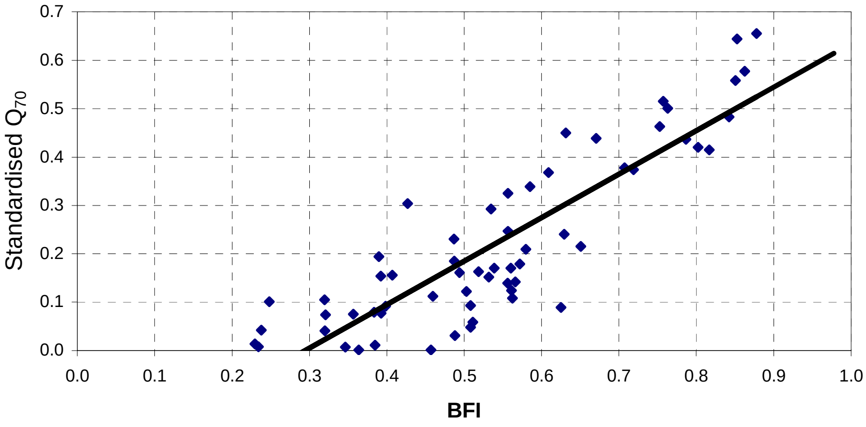


Figure 4.8 *Relationship between standardised Q_{70} flow statistic and Base Flow Index*

Selection of characteristic flow duration curves

In the first phase of Southern Africa FRIEND it was found that the slope of the flow duration curve is strongly associated with a key percentile, and a set of pooled curves were created for classes of Q_{70} (UNESCO, 1997), as shown in Figure 4.9. These curves were used to provide the characteristic curves for Malawi in this study. Although they are based on pooled data for the whole Southern Africa region, they appear to provide a reasonable representation of the situation in Malawi. A more detailed investigation of type curves specific to Malawi was carried out, but, within the scope of the present study, it was not possible to produce definitive answers. It is likely that more intensive studies would yield more conclusive results. The curves in Figure 4.9 provide an estimate of the standardised flow duration curve for any location, given the value of Q_{70}. The standardised curve then needs to be re-scaled by the mean flow for the site in order to create a usable flow duration curve estimate.

4.3.5 Summary of method, limitations and improvements

The method of estimating low flow characteristics in Malawi starts from the national coverages of mean annual rainfall and soil types. Relationships were derived first between soil type and baseflow index, and then between baseflow index and Q_{70}, thus enabling Q_{70} to be estimated for any point on the Malawi river network. A further relationship between rainfall and runoff was derived so that mean annual and mean monthly flows can be estimated for any location, based on the mean annual rainfall. The Q_{70} statistic was used to select a standardised flow duration curve, which can then be re-scaled using the mean flow value to provide an estimate of the actual flow duration curve for the catchment. Figure 4.10 shows the process of estimating a flow duration curve at an ungauged site using these relationships.

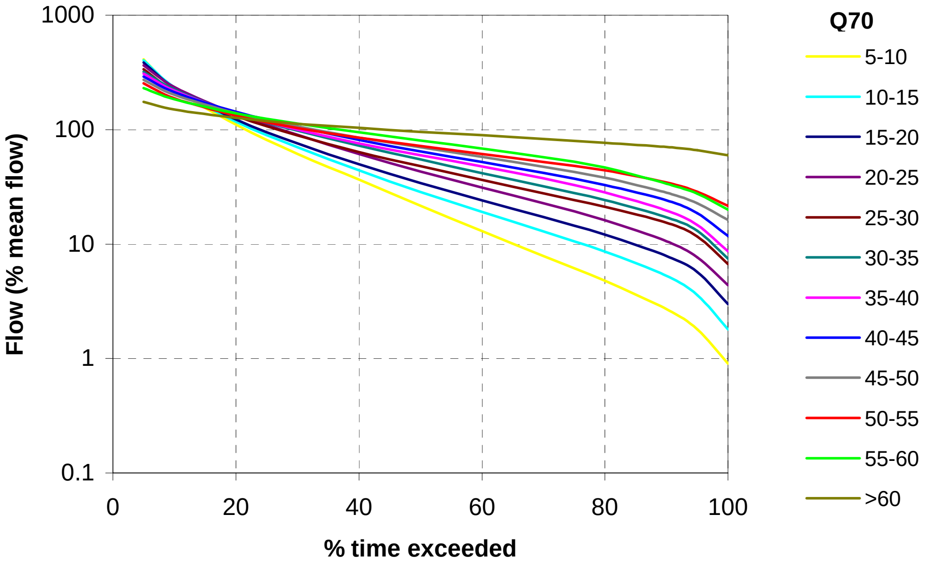


Figure 4.9 *Standardised flow duration type curves for perennial rivers in Southern Africa (from UNESCO, 1997)*

Where there are artificial influences in the catchment, their combined effect is calculated. This information is then used to estimate the influenced flows and flow duration curves, as shown in Figure 4.10. The flow duration curve for a particular month is simply shifted by the amount of the monthly volume of water abstracted from the catchment.

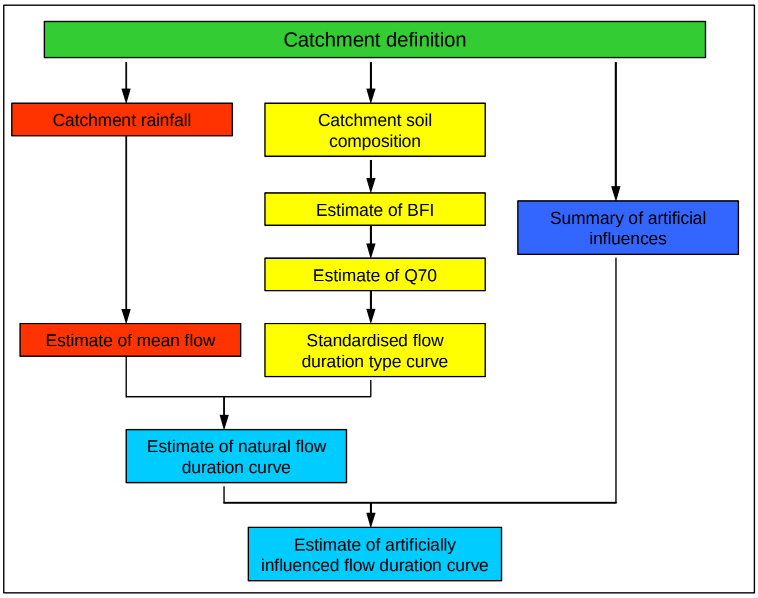


Figure 4.10 *Schematic diagram of stages in flow estimation procedure*

The flow duration curve provides estimates indicative of the average, long-term flow regime, and this is significantly simpler to model than the flows from specific rainfall events. Flow duration curves contain information appropriate to a decision support context, providing estimates of variability within the year, which can be combined with estimates of mean monthly and annual flows, indicating the long-term availability of the resource. The results are useful for assessing the potential of locations for supply to a variety of uses, but of course do not provide the full spectrum of information needed to assess possible drought impacts or for the detailed day-to-day planning of abstractions.

The quality of the methodology developed here is limited by a number of factors. First, the amount and quality of the available hydrological data is not high, and considerable effort had to be expended on data validation before the analysis could be attempted. As noted above, the information on artificial influences is very inadequate. This means that the naturalisation process is inevitably inaccurate, but there were insufficient gauged catchments with natural flow regimes to develop the method. There are also likely to be errors in the rating equations for the flow gauging stations, especially as very few calibration measurements are carried out. This, combined with the inaccurate naturalisation of flow records, is perhaps the most serious shortcoming. There is a need to systematically evaluate the artificial influences throughout the country, which would provide an invaluable addition to water resources management data in Malawi.

It should be noted that this was a preliminary study to create a prototype tool; it has not produced a definitive method for Malawi, which can be used without further analysis. The model has limitations which could be corrected, or at least reduced, by a more intensive and detailed data collection and validation exercise, followed by a re-evaluation of the methodology. Factors which are likely to be relevant include: the effects of hydrogeology, catchment slope and other factors on BFI; the influence of land or vegetation cover, slope and other factors on the estimation of runoff from rainfall. Land cover data is available (Land Resources Evaluation Project, 1992) and could provide a useful source of information for investigating this.

4.4 GIS water resources software

The method for estimating flows at ungauged sites is practically applicable within licensing and water resources management operations. The flow estimation method requires information on the extent of different soil types and on mean annual rainfall for each catchment. These data are digitised and available within GIS systems, but can be time-consuming to derive for a particular location.

A bespoke software tool can carry out this and other functions of the estimation process, and also allow additional information to be displayed to maximum effect. Software, incorporating these tools, was desired to exhibit a number of features:

- Visualisation of rivers, artificial influences, gauging stations and other spatial features
- Storage of artificial influence information
- Storage of catchment characteristics – rainfall and soil types
- Derivation of catchments at any point on the river network
- Retrieval of characteristics (rainfall and soil type extents) for given catchment
- Production and visualisation of natural flow duration curve
- Visualisation of the impacts of existing artificial influences upon natural flow regimes
- Creation of ‘scenario’ flow statistics under predicted future influences

Other important aspects considered within the software design included:

- Ease of use for potential users of all levels
- Consistency of flow estimates
- Usability of outputs within existing procedures
- Maximising the usefulness of data management tools
- Consistency of interface with common GIS applications and software within MWD

The software was based upon the Low Flows 2000 software developed by CEH for the Environment Agency of England and Wales. This has proved to be a large step forward for water resources management information systems in the UK. Much of the functionality has been carried across from this original version, but it has been adapted to the needs of Malawi, and many new features have been developed. The software is designed to be flexible in terms of both data stored against features within the database (section 4.4.2) and allowing different hydrological models to be ‘snapped on’. Because of this, the extension of the system to other areas of Southern Africa, which may have different hydrological models for flow estimation, would be fairly simple. The system is a fairly radical departure from the water resources and data management procedures currently used in Malawi. To develop a similar system in its entirety would require years of work and substantial financial input. The UK Environment Agency is keen to see its work used for such a benefit. The software was named LF2000-SA; for full details of the software see Fry *et al*. (2003).

4.4.1 GIS user interface

The system and its functionality are based around a GIS user interface. This displays geographical features in a map style allowing the user to zoom in and out to view different areas of the map at different scales. Data are stored and displayed as different ‘layers’ within the map, where a layer constitutes a map of a single type of data. For example, Figure 4.11 shows a map of Malawi consisting of separate layers of rivers, abstraction points, lakes and the boundary of the country. These different types of data are called feature types. Within the software the layers can be turned off and on in order to create an appropriate map of the data of interest.

Different layers can be stored in different ways, appropriate to the geographical representation of the type of data. For example, the boundary of Malawi is stored as a series of lines, the lakes of Malawi are stored as a series of polygons representing the lakes, the abstractions are stored as points, and the rainfall and soils data is stored as grids, with each grid square containing a different data value. More about GIS data types can be found in Chapter 6.

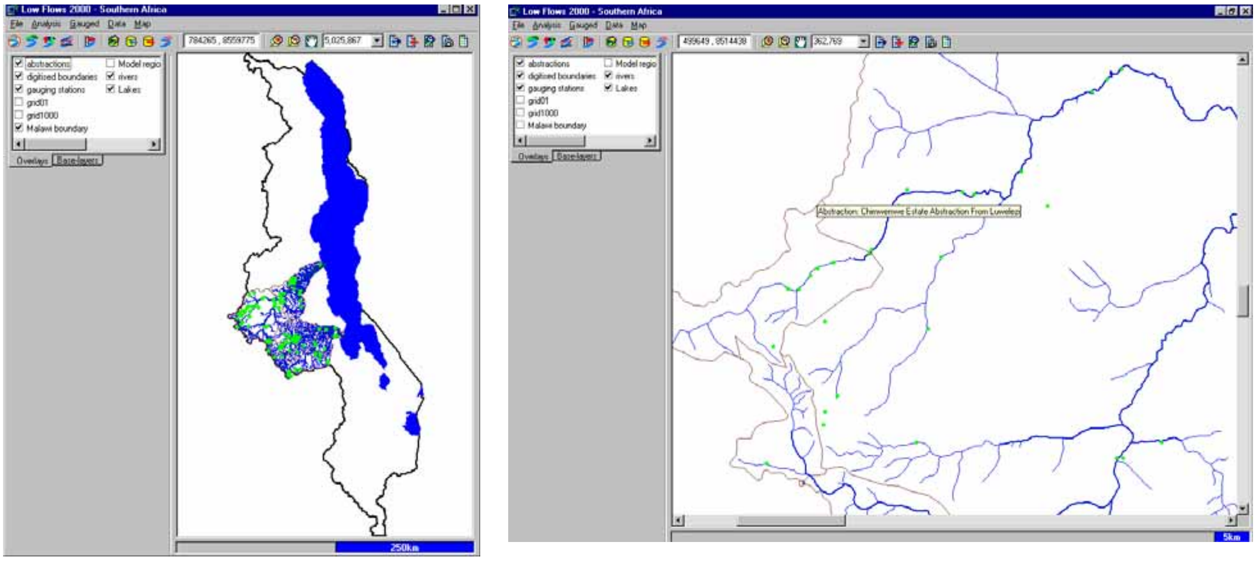


Figure 4.11 *Main GIS user interface window of the software, showing the whole of Malawi and detail of WRA 5*

The software uses the ESRI MapObjects component to draw and manipulate the maps. The data within the software is in ESRI's standard 'Shapefile' format (ESRI, 1998) meaning that the software is compatible with many other widely-used GIS products, including ESRI's ArcView, ArcInfo and ArcGIS systems. Additional data in this format can be added to the software to provide contextual information, for example, roads, villages, industrial areas and so on. These can assist the user in the siting of water use points and other features. The addition of familiar features can also help less confident users become more active in using the software.

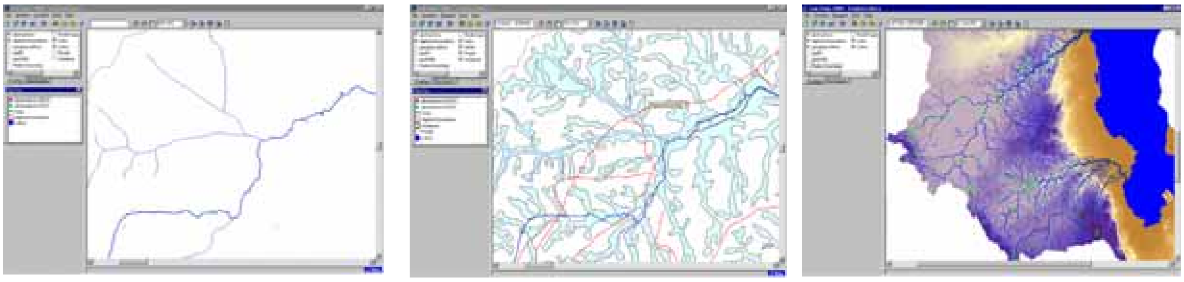


Figure 4.12 *GIS interface showing river stretches and abstractions before and after the addition of contextual layer (wetlands and roads), and a picture of the underlying topography*

Access to the software functionality is through a series of menu options at the top of the software window, or through helpful 'tooltip' hints and dropdown menus provided when the user clicks on a point of interest on the map. All functionality is provided within the Windows standards for software development so that users familiar with common Windows applications, such as Word or Excel, can find themselves at ease with the software within a short period of time. In addition GIS functionality is provided in such a way as to reflect commercially available GIS products such as ESRI's ArcView and ArcExplorer, on which some users within MWD have previously been given training both within the FRIEND programme (Chapter 7) and elsewhere.

All maps, as well as data from many other forms, can be copied to the Windows clipboard and pasted into other files such as Word documents or Excel spreadsheets.

4.4.2 Storage and display of feature information

The hydrologically important features within the software can be divided into three groups:

- Artificial influences – abstractions, discharges, impoundments
- Gauging stations
- Spot gaugings or instantaneous flow measurements

All of these *features* are stored within the database, each having different data stored against them in a varying number of fields, or *attributes*.

Artificial influences
The artificial influences interact with the model, providing estimates of water use. The software is designed to store these as licensed influences, but users can also enter influences that reflect estimated water use within the catchment. The structure of a licence can be quite complex, and consists of a number of sites on the river network. Each of these sites can have one or more purposes, the reason for the water use, such as irrigation, domestic use, etc. Typical attributes include *Licence start date*, *Name of holder*, *Monthly profile of abstraction*, *Name of purpose*.

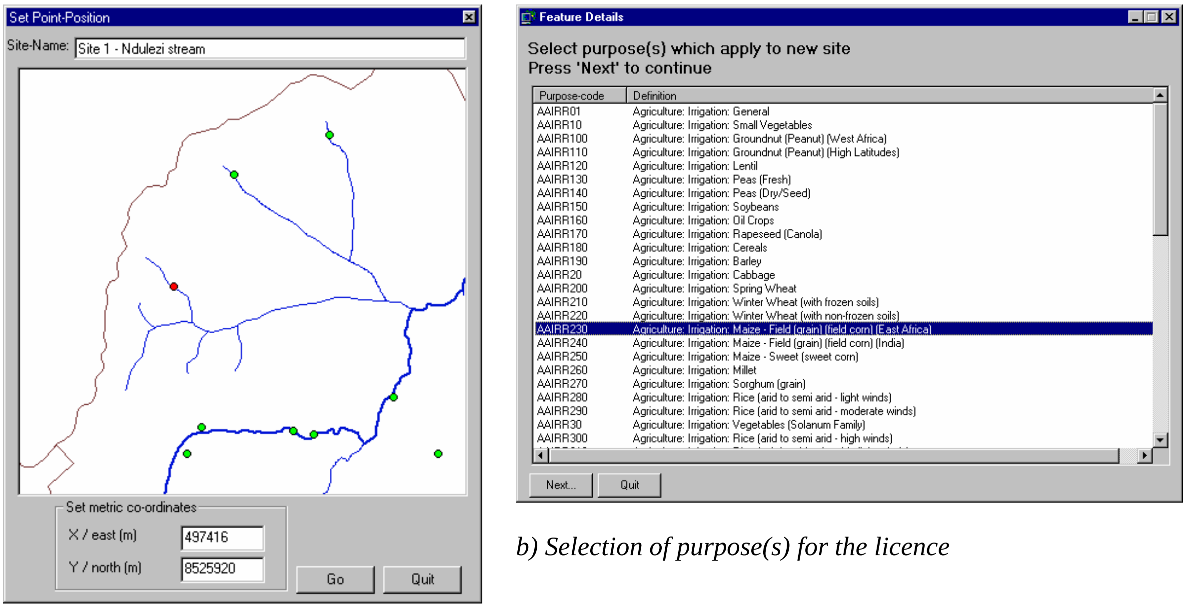
Gauging stations
Gauging stations store flow data measured at a particular point on the river network. These data can provide additional information about the flow regime, and real flow data can be used to underpin flow estimates. Attributes include *Year opened*, *Name of operator*, etc., as well as a time series of daily flow values.

Spot gaugings
Spot gaugings are occasional measurements of flow at a point in the river where there may not necessarily be a gauging station. These measurements can also provide information as to the validity of flow estimates. Attributes of a spot gauging include *Date of measurement*, *Time of measurement*, *Flow*, *Name of observer*.

Database structure
There are many attributes to each feature type and so the storage of such data can be complicated. A database could have thousands of abstraction and discharge licenses, each with dozens of attributes. In addition, the definition of a licence could change over time, adding new attributes to a feature that could be required to be stored. To manage both the data complexity and the need for flexibility, the system uses CEH’s WIS database structure (Roberts and Moore, 1999). WIS is a structure that stores feature and attribute definitions within data tables, rather than the table structures being dictated by the definitions. Data for all attributes of a given data type are then stored within a single table, i.e., all character data are stored within a character data table, and all real, or floating point number data are stored within a real data table, for all features and all attributes.

The feature types, attributes and the specification of the attributes stored by each feature type can be defined at the beginning of the project. If, in future, additional features or attributes are defined, these can very simply be added to the database, without affecting existing records, making the software extremely flexible. Within the software this flexibility is reflected in the user interface. When adding or editing a feature, the data is displayed in a grid, the parameters (rows, columns and validation rules) are determined by the definition of the attribute within the database. For example, the software form can find from the database that the ‘*Licence start date*’ attribute is of the data type ‘date’ and can display the data accordingly, offering a calendar to the user wishing to edit the field. Similarly, the ‘*Monthly profile of abstraction*’ field is provided as a dropdown list of twelve values. Any new attributes added would automatically be correctly displayed within the form without requiring reprogramming. With a view to use within several countries, this approach provides the ability to handle the different structures of licence that would inevitable arise.

Figure 4.13 illustrates the process of adding a new abstraction licence. The crop-water calculator form allows the user to estimate the water requirements for a given area of the selected crop, providing season information, irrigation efficiency and climatic information, following standard FAO methods (Doorenbos and Pruitt, 1977). When editing an existing abstraction, the feature edit window (similar to that in Figure 4.13), appears allowing the user to edit any of the fields available, move the feature, or delete the feature from the database.



Site-Name: Site 1 - Ndulezi stream

Set metric co-ordinates

X / east (m) 497416

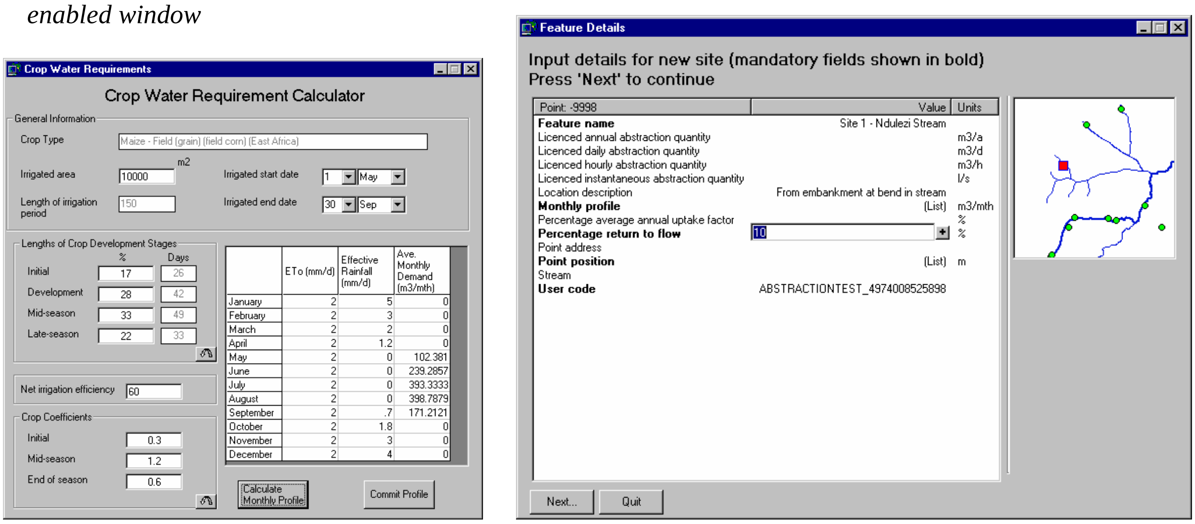
Y / north (m) 8525920

Select purpose(s) which apply to new site
Press 'Next' to continue

Purpose-code	Definition
AAIRR01	Agriculture: Irrigation: General
AAIRR10	Agriculture: Irrigation: Small Vegetables
AAIRR100	Agriculture: Irrigation: Groundnut (Peanut) (West Africa)
AAIRR110	Agriculture: Irrigation: Groundnut (Peanut) (High Latitudes)
AAIRR120	Agriculture: Irrigation: Lentil
AAIRR130	Agriculture: Irrigation: Peas (Fresh)
AAIRR140	Agriculture: Irrigation: Peas (Dry/Seed)
AAIRR150	Agriculture: Irrigation: Soybeans
AAIRR160	Agriculture: Irrigation: Oil Crops
AAIRR170	Agriculture: Irrigation: Rapeseed (Canola)
AAIRR180	Agriculture: Irrigation: Cereals
AAIRR190	Agriculture: Irrigation: Barley
AAIRR20	Agriculture: Irrigation: Cabbage
AAIRR200	Agriculture: Irrigation: Spring Wheat
AAIRR210	Agriculture: Irrigation: Winter Wheat (with frozen soils)
AAIRR220	Agriculture: Irrigation: Winter Wheat (with non-frozen soils)
AAIRR230	Agriculture: Irrigation: Maize - Field (grain) (field corn) (East Africa)
AAIRR240	Agriculture: Irrigation: Maize - Field (grain) (field corn) (India)
AAIRR250	Agriculture: Irrigation: Maize - Sweet (sweet corn)
AAIRR260	Agriculture: Irrigation: Millet
AAIRR270	Agriculture: Irrigation: Sorghum (grain)
AAIRR280	Agriculture: Irrigation: Rice (arid to semi arid - light winds)
AAIRR290	Agriculture: Irrigation: Rice (arid to semi arid - moderate winds)
AAIRR30	Agriculture: Irrigation: Vegetables (Solanum Family)
AAIRR300	Agriculture: Irrigation: Rice (arid to semi arid - high winds)

a) Selection of site through interactive GIS-enabled window

b) Selection of purpose(s) for the licence



Crop Water Requirement Calculator

General Information

Crop Type: Maize - Field (grain) (field corn) (East Africa)

Irrigated area: 10000 m2

Irrigated start date: 1 May

Length of irrigation period: 150

Irrigated end date: 30 Sep

Lengths of Crop Development Stages

	%	Days
Initial	17	26
Development	28	42
Mid-season	33	49
Late-season	22	33

Net irrigation efficiency: 60

Crop Coefficients

Initial: 0.3

Mid-season: 1.2

End of season: 0.6

	ETo (mm/d)	Effective Rainfall (mm/d)	Ave. Monthly Demand (m3/mth)
January	2	5	0
February	2	3	0
March	2	2	0
April	2	1.2	0
May	2	0	102.381
June	2	0	239.2857
July	2	0	393.3333
August	2	0	398.7879
September	2	.7	171.2121
October	2	1.8	0
November	2	3	0
December	2	4	0

Input details for new site (mandatory fields shown in bold)
Press 'Next' to continue

Point: -9998	Value	Units
Feature name	Site 1 - Ndulezi Stream	
Licenced annual abstraction quantity		m3/a
Licenced daily abstraction quantity		m3/d
Licenced hourly abstraction quantity		m3/h
Licenced instantaneous abstraction quantity		l/s
Location description	From embankment at bend in stream	
Monthly profile	(List)	m3/mth
Percentage average annual uptake factor		%
Percentage return to flow	10	%
Point address		
Point position	(List)	m
Stream		
User code	ABSTRACTIONTEST_4974008525898	

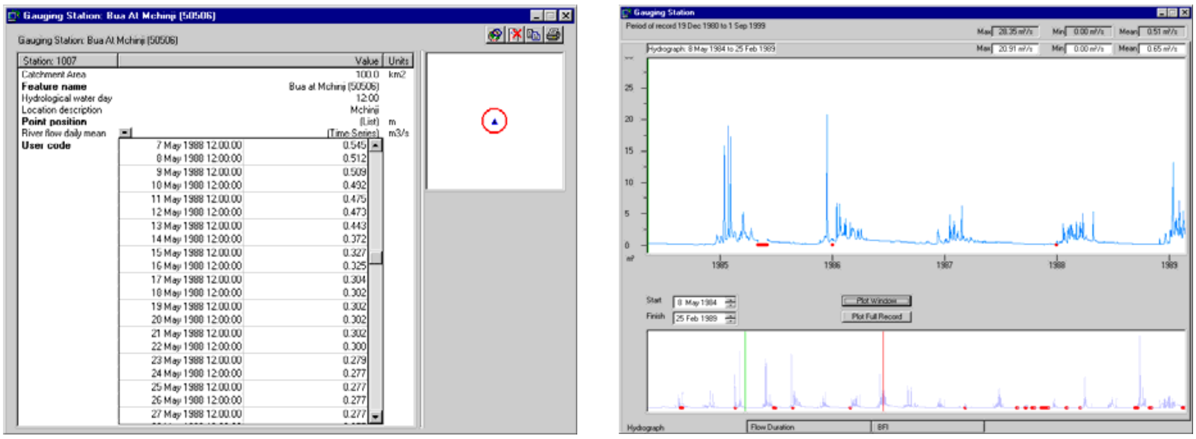
c) Alternative crop-water calculator method for calculating abstraction volumes (irrigation only)

d) Input of site level information, with interactive GIS representation of site location

Figure 4.13 *Steps in the process of adding a new artificial influence*

Gauging station analysis

In addition to the influences which interact with the hydrological model, the system also displays gauging station data as daily flow values and some descriptive station level information. A module is included allowing analysis of these data, displaying flow hydrographs, flow duration curves and Base Flow Index (Figure 4.14). This is included as a useful tool and is not designed to replace the functionality of the existing flow database system.



Gauging Station: Bua At Mchinji (50506)

Gauging Station: Bua At Mchinji (50506)

Station: 1007	Value	Units
Catchment Area	100.0	km2
Feature name	Bua at Mchinji (50506)	
Hydrological water day	12:00	
Location description	Mchinji	
Point position	(List)	m
River flow daily mean	(Time Series)	m3/s
User code		

7 May 1988 12:00:00	0.545
8 May 1988 12:00:00	0.512
9 May 1988 12:00:00	0.509
10 May 1988 12:00:00	0.492
11 May 1988 12:00:00	0.475
12 May 1988 12:00:00	0.473
13 May 1988 12:00:00	0.443
14 May 1988 12:00:00	0.372
15 May 1988 12:00:00	0.327
16 May 1988 12:00:00	0.325
17 May 1988 12:00:00	0.304
18 May 1988 12:00:00	0.302
19 May 1988 12:00:00	0.302
20 May 1988 12:00:00	0.302
21 May 1988 12:00:00	0.302
22 May 1988 12:00:00	0.300
23 May 1988 12:00:00	0.279
24 May 1988 12:00:00	0.277
25 May 1988 12:00:00	0.277
26 May 1988 12:00:00	0.277
27 May 1988 12:00:00	0.277

Gauging Station

Period of record 19 Dec 1980 to 1 Sep 1999

Max 28.35 m³/s Min 0.00 m³/s Mean 0.51 m³/s

Hydrograph: 8 May 1984 to 25 Feb 1989

Max 20.91 m³/s Min 0.00 m³/s Mean 0.65 m³/s

Start 8 May 1984

Finish 25 Feb 1989

Figure 4.14 *Gauging station analysis forms*

4.4.3 Catchment definitions

One of the features of the software is that it allows users to produce catchment definitions for any point on the river network. This exercise had previously to be completed by hand using paper maps. Catchment definitions are useful for a number of purposes, and in addition, the software retrieves data from the underlying catchment characteristic datasets to provide statistics for that catchment. The user simply either enters an X-Y coordinate of the catchment outlet or clicks on the river network to select the point from which to define the catchment. The catchment boundary is then calculated and relevant statistics (e.g. catchment area, mean annual rainfall, monthly rainfalls, soil types) are displayed (Figure 4.15). Defined catchments can be saved for later use, which is useful when a catchment is under regular scrutiny.

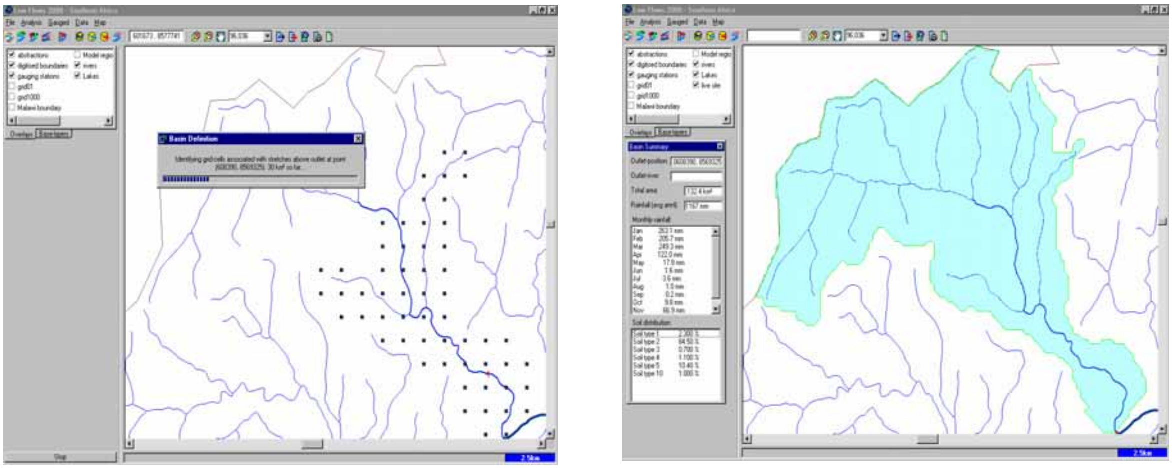
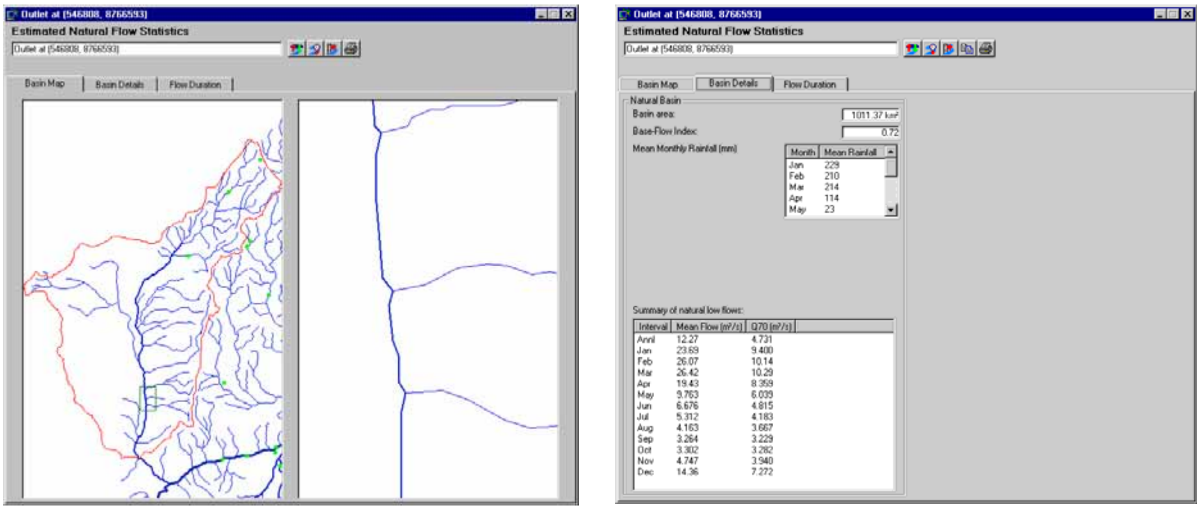


Figure 4.15 *Software windows displaying catchment definition process (left); defined catchment and details (right)*

4.4.4 Flow estimation

Natural flow estimates

Catchment characteristics retrieved from the underlying datasets are used within the model to estimate flow statistics using the method outlined in Section 4.3. The user runs the catchment definition as before, selecting the starting position required but this time choosing to run the model. The outputs are the flow duration curves and monthly flow statistics. The natural flow estimates window consists of four panels, as shown in Figure 4.16. This information gives water resources managers an idea of the hydrological characteristics of the natural, or uninfluenced, catchment: estimates of area, monthly rainfall, baseflow index and monthly mean- and low-flow statistics. The information is essential for estimating the impact of water use at the catchment outlet. The flow duration curve allows further statistics to be derived graphically; they are displayed by clicking on the name of each flow duration curve, a new form then appears, providing the flows at a various percentile intervals.



Natural Basin

Basin area: 1011.37 km²

Base-Flow Index: 0.72

Mean Monthly Rainfall (mm)

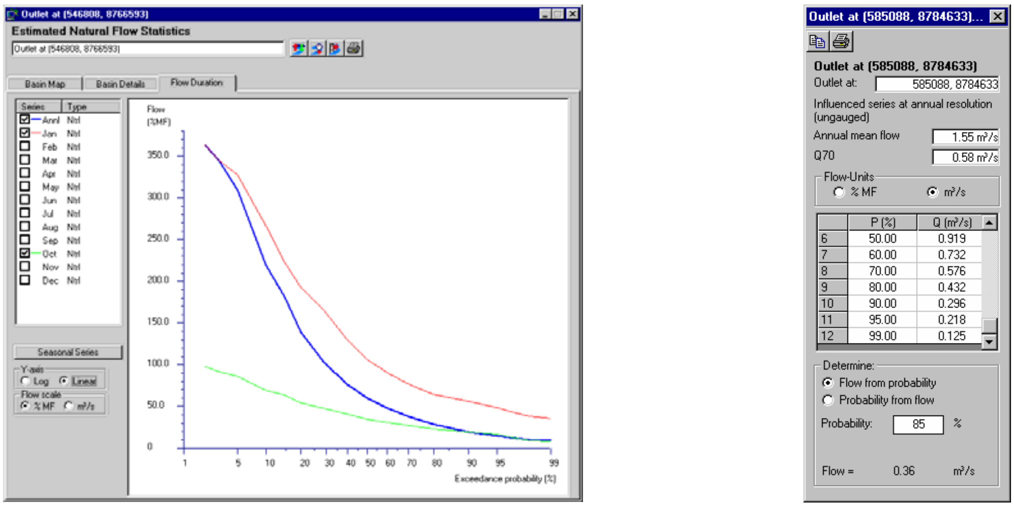
Month	Mean Rainfall
Jan	229
Feb	210
Mar	214
Apr	114
May	23

Summary of natural low flows:

Interval	Mean Flow (m³/s)	Q70 (m³/s)
Annl	12.27	4.731
Jan	23.69	9.400
Feb	26.07	10.14
Mar	26.42	10.29
Apr	19.43	8.359
May	9.763	6.039
Jun	6.676	4.815
Jul	5.312	4.183
Aug	4.163	3.667
Sep	3.264	3.229
Oct	3.302	3.282
Nov	4.747	3.940
Dec	14.36	7.272

a) Basin map and selected detail

b) Basin details – catchment characteristics and calculated flow statistics



Outlet at (585088, 8784633)...

Outlet at (585088, 8784633)

Outlet at: 585088, 8784633

Influenced series at annual resolution (ungauged)

Annual mean flow 1.55 m³/s

Q70 0.58 m³/s

Flow-Units ○ % MF ● m³/s

	P (%)	Q (m³/s)
6	50.00	0.919
7	60.00	0.732
8	70.00	0.576
9	80.00	0.432
10	90.00	0.296
11	95.00	0.218
12	99.00	0.125

Determine:
● Flow from probability
○ Probability from flow

Probability: 85 %

Flow = 0.36 m³/s

c) Flow duration curves

d) Flow duration statistics

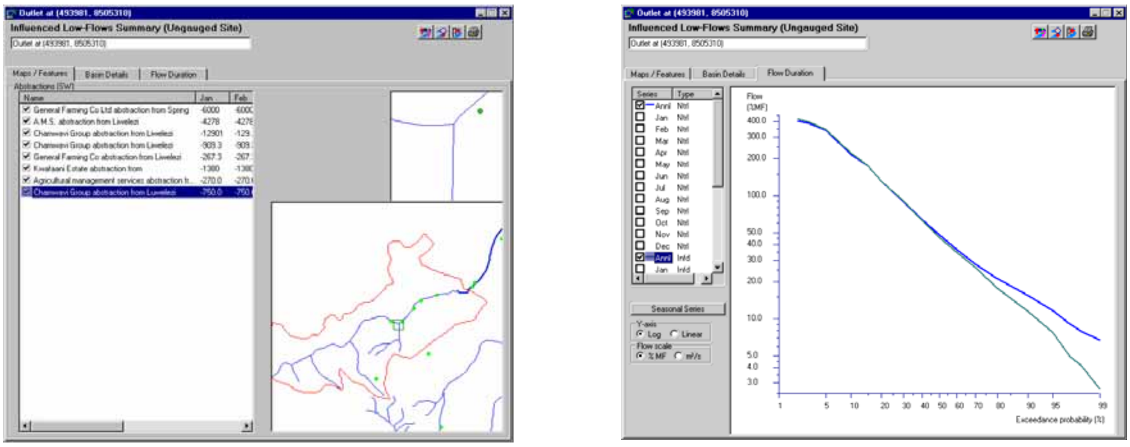
Figure 4.16 *Panels of the natural flow estimation window*

Influenced flow estimates

Once the natural flow estimates have been made, these can be modified to show the impact of artificial influences within the catchment. The software retrieves the influences within the catchment and updates the panels described above with the influenced flow statistics (Figure 4.17). The influences are listed, showing the name of the influence and the monthly volumes abstracted or discharged; the form allows users to find individual influences through the map on the right-hand side. The basin-details are updated to show the flow statistics before and after the impact of influences, and the flow duration curve form then allows users to plot monthly and annual curves for both natural and influenced regimes.

Comparing estimates with gauged data

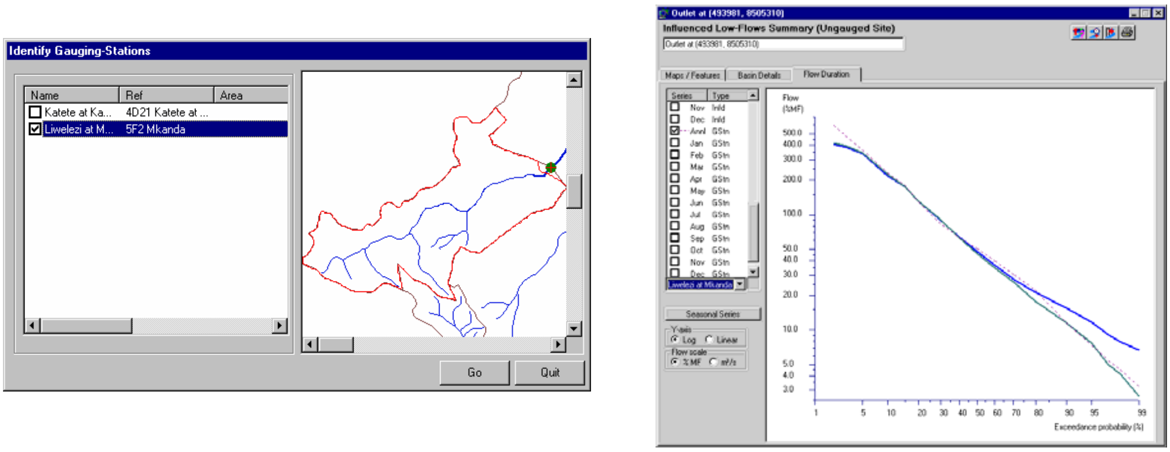
The flow duration curves displayed are estimates made using the model described in Section 4.3. In order to make the system more appropriate to Southern Africa, where flow estimates may not always be reliable due to inaccuracies in the underlying datasets, a feature was added to allow observed flow duration curves to be viewed alongside the estimates. A form is shown listing all gauging stations on the database, with a map enabling users to see where the stations are situated relative to the catchment in question. A nearby gauging station or one with a similar catchment is selected and its data is displayed on the original graph (Figure 4.18). Results can be viewed as a percentage of the mean flow in order to compare data from catchments of different sizes.



Name	Jan	Feb
☑ General Farming Co Ltd abstraction from Spring	-6000	-600C
☑ A.M.S. abstraction from Liwelezi	-4278	-4278
☑ Chamwavi Group abstraction from Liwelezi	-12901	-129.
☑ Chamwavi Group abstraction from Liwelezi	-909.3	-909.
☑ General Farming Co abstraction from Liwelezi	-267.3	-267.
☑ Kwataani Estate abstraction from	-1300	-130C
☑ Agricultural management services abstraction fr...	-270.0	-270.
☑ Chamwavi Group abstraction from Liwelezi	-750.0	-750.

a) Summary of artificial influences *b)Natural and influenced flow duration curves*

Figure 4.17 *Flow estimation windows with the addition of artificially influenced flow data*



Name	Ref	Area
☐ Katete at Ka...	4D21 Katete at ...	
☑ Liwelezi at M...	5F2 Mkanda	

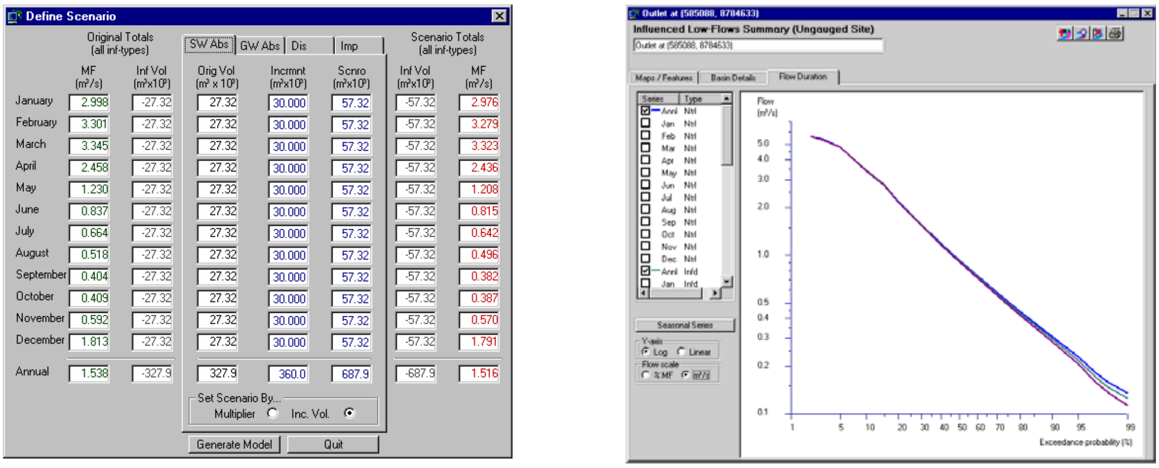
a) Selection of gauging station

b) Natural and influenced estimates compared with observed flow duration curve

Figure 4.18 *Selection and display of observed flow duration curve from a gauging station alongside natural and influenced flow estimates*

Creating influence scenarios

The user can observe the effect of a planned, estimated or hypothetical influence through use of the ‘Define scenario’ form. This allows existing monthly abstraction, discharge or impoundment volumes to be increased, either as a percentage of the existing volume, or by a fixed amount. The resulting total influence is re-applied to the flow statistics and three sets of annual and monthly flow duration curves are then visible – natural, influenced and scenario (Figure 4.19).



Define Scenario

	Original Totals (all inf-types) MF (m³/s)	Original Totals (all inf-types) Inf Vol (m³x10⁶)	SW Abs Orig Vol (m³ x 10⁶)	SW Abs Incrmnt (m³x10⁶)	SW Abs Scnro (m³x10⁶)	Scenario Totals (all inf-types) Inf Vol (m³x10⁶)	Scenario Totals (all inf-types) MF (m³/s)
January	2.998	-27.32	27.32	30.000	57.32	-57.32	2.976
February	3.301	-27.32	27.32	30.000	57.32	-57.32	3.279
March	3.345	-27.32	27.32	30.000	57.32	-57.32	3.323
April	2.458	-27.32	27.32	30.000	57.32	-57.32	2.436
May	1.230	-27.32	27.32	30.000	57.32	-57.32	1.208
June	0.837	-27.32	27.32	30.000	57.32	-57.32	0.815
July	0.664	-27.32	27.32	30.000	57.32	-57.32	0.642
August	0.518	-27.32	27.32	30.000	57.32	-57.32	0.496
September	0.404	-27.32	27.32	30.000	57.32	-57.32	0.382
October	0.409	-27.32	27.32	30.000	57.32	-57.32	0.387
November	0.592	-27.32	27.32	30.000	57.32	-57.32	0.570
December	1.813	-27.32	27.32	30.000	57.32	-57.32	1.791
Annual	1.538	-327.9	327.9	360.0	687.9	-687.9	1.516

Set Scenario By... Multiplier ○ Inc. Vol. ●

a) 'Define scenario' form showing original influences, increases, and the new total influences

b) Flow duration curves, under natural conditions, original influences and scenario of influences, showing the effect of a 100% increase in abstractions

Figure 4.19 *Definition and application of scenario of artificial influences to flow estimates*

Residual flow diagrams

A more advanced feature of the software is the residual flow diagram. This allows the model for flow estimation to be applied repeatedly at every river stretch within a catchment defined by the user. In this way an estimate of the variability of flows through a catchment can be visualised, and the relative impacts of artificial influences within individual stretches can be monitored. Figure 4.20 shows the two panels of the residual flow diagram window, one displaying changes in a chosen flow statistic through the catchment, and the other displaying a map of influences by river stretch. This form of output can be particularly useful for assessing the state of flows within an entire catchment and for environmental assessments of rivers.

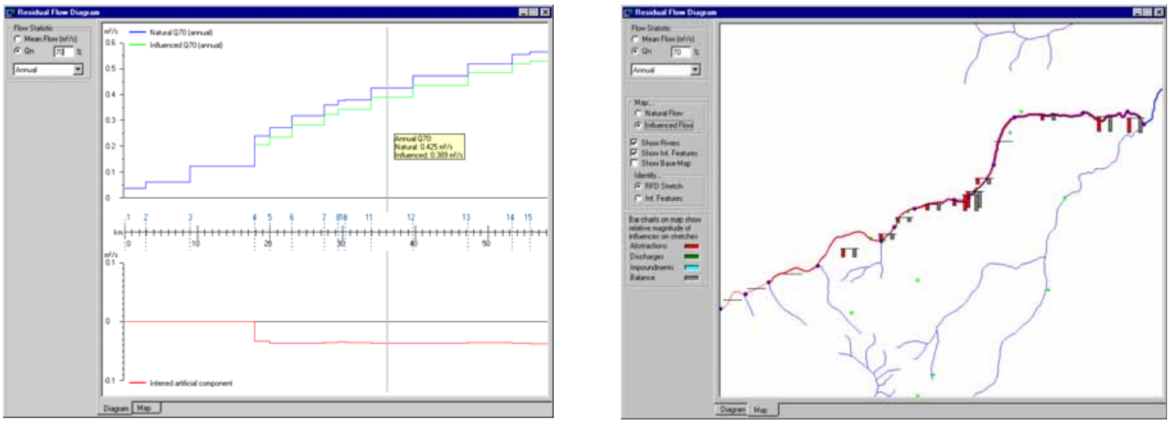


Figure 4.20 *Residual flow diagrams showing the change in natural and influenced flow statistics at stretches through the catchment and the extent of influence*

An important advantage of the system is the consistency it provides. Any user selecting a point on the river network will get the same results. This allows the system to be used by operational staff, providing results which the more experienced staff will interpret. When the flows are recalculated at a later date, the result will be the same. Furthermore the process of retrieving results is simple and quick, so the time taken for the production of flow estimates is negligible within the length of the assessment procedure. In addition, all of the data, graphs and maps produced within the software can be copied to the Windows clipboard for use within other applications such as Word documents or Excel spreadsheets, significantly enhancing the usability of the results within the standard water resources management process.

4.4.5 Implementation

The version of the software implemented within the Ministry of Water Development was set up for three areas of Malawi – the Bua, Lilongwe and South Rukuru catchments – covering about one fifth of the country. This was considered sufficient for an assessment of the feasibility and applicability of the system and its outputs within the Malawian procedures for water resources management.

All of the surface water abstractions for these regions and many of the gauging stations were loaded into the databases. The software was installed in MWD, staff were trained in its use, and feedback on its appropriateness to the licensing procedures and systems within Malawi was obtained. Three users were given full training on the use of the software; and other staff within the Hydrology department and other departments of the Ministry were given a demonstration of the software, an explanation of the methods underpinning the flow estimates, and outline training in its use.

It was found that the software could provide a leap forward in the capacity of the Ministry to process licence applications, particularly in its ability to obtain and to summarise the important hydrological data pertinent to the allocation decision. As well as the gauging station flow data previously available, users could obtain visual information concerning the current abstraction and discharge licenses within the catchment and could obtain a flow duration curve, providing information on mean flow, intra-annual variation of flows and dependability of flows at any point on the river network. Prior to the introduction of this assessment system, existing abstraction information could not be obtained at and around a specific site, and flow estimation was a long and difficult task that was rarely performed.

The software was also demonstrated extensively at one of the training workshops, attended by 18 delegates from 11 Southern Africa countries, and some preliminary training was provided (Chapter 7). Discussion sessions were held concerning the appropriateness of the software system to the water resources management procedures within the different countries. The current state of development varies considerably between the countries of the regions, from a limited level of computerised licence database system, to no method of storage of licensed water use information. Despite this, many countries are currently moving to catchment-based water management approaches and are currently hoping to manage water use data in this way in the near future. Few countries have an integrated approach to managing GIS, water availability data and water use data. Many of the countries use a process similar to Malawi for the licensing of water use, and the delegates considered that this new system would be highly appropriate in their countries.

4.5 Summary and conclusions

A GIS-based water resources management software system was developed for Malawi, as a prototype for such systems within Southern Africa in general. Methods were developed for estimating flows at ungauged sites at any point on the river network by linking flow regimes to catchment characteristics and these were incorporated into the software system. The system provides water managers with tools, currently unavailable, for assessment of water resource availability and the quantification of the impacts of current and future influences, such as abstractions and discharges, on river flows. A FRIEND workshop demonstrated the software to delegates from 11 Southern African countries. Feedback suggested that such a system could be successfully integrated into many water resources management processes within the region, and would provide a marked improvement in water resources management capability.

In order for the prototype tool to be implemented as a functional system for water resources management in Malawi, a number of steps must be taken. First, the hydrometric and abstraction databases need to be thoroughly rationalised, and the methodology checked and validated once this has been done. Because of the present inadequacy of the database, the prototype system should not be treated as a functional system for water resource management in Malawi. Secondly, the river network for the remaining area of the country requires digitising, and thirdly, a more formal introduction period is required, with the assistance of MWD. Thorough training is required for staff members from the surface water department, the water board and other government departments, such as the Department of Irrigation within the Ministry of Agriculture and Irrigation. MWD are keen for a fully-functioning system to be implemented.

Improved rainfall, flow and water use datasets could improve the accuracy of models, and further research into the inter-month variability of flow regimes could improve the accuracy of the system for estimating within-year variations in water resources. New models would be needed to extend its use to other countries. A similar approach could be appropriate in the more humid part of the region, for instance in Tanzania, Zambia, northern Zimbabwe and Mozambique, with a different approach required for more arid regions.

This phase of Southern Africa FRIEND has seen the development of a prototype that could become a very useful tool for day-to-day water resources management within Southern Africa. The following two main recommendations should be followed in order to realize the benefits from implementing the system more widely within the region, and to a greater depth within water-stressed catchments where improved management is most urgently required:

- **Generalisation of underlying datasets.** Standard digital elevation model (DEM) data should be used for the derivation of catchments. A one-kilometre grid of all of Africa is currently available, and its use within the system would allow the automated and more accurate definition of catchments in all countries of the region. In addition, a more general approach to flow estimation in the region could be useful, initially providing simple estimates of rainfall and runoff for catchments at any point on the river network. Linkage with national hydrometric data and the WR90 regional water resources assessment (Chapter 2) could also prove useful.

- **IWRM tool for water-stressed catchments.** The system could be modified to allow more general information to be stored in addition to the licensed water use data currently held. Sources of data could include environmental requirements for river stretches, estimated water use from irrigation, forestry, population statistics, etc. The study should analyse the different aspects of this information that is important to water resources, for instance temporal variability, flow reliability and long-term change, both historic and future. Other useful aspects could be the optimisation of water use through various scenarios, allowing managers to plan long-term water use in a more inclusive fashion. As such, this prototype could be the basis of an appropriate tool for water resources for many countries within southern Africa providing a huge advance in the technology for IWRM in the region.

5 Water resources and climate change in Swaziland

E.L. Tate, S. Dhlamini and J.R. Meigh

5.1 Introduction

Declining water availability is an increasing concern worldwide and especially in developing countries. Increases in population combined with urbanisation and industrial and agricultural development will create extra demands for water. At the same time, it is likely that climate change due to global warming will affect both the availability of supply and the demands for water, leading to further uncertainty about the future balance of water supply and demand. At the global scale the reports of the Intergovernmental Panel on Climate Change (IPCC, 2001) provide much insight, but at the more local scale at which the real work of planning and adaptation for the future is needed, knowledge of the problem and its possible consequences is inadequate. In the context of Southern Africa, there is a clear need to improve the abilities of the countries themselves to make water resources assessments in relation to the potential impacts of climate change. The objective of this component of the FRIEND programme was to make a step in that direction. The work was carried out as a case study for Swaziland, for which assessments were made using the grid-based GWAVA (Global Water AVailability Assessment) model. This approach provides a rapid overview of the situation, following a standardised methodology; a range of scenarios of change can be examined in order to estimate the potential scale of future water resources problems. It should be thought of as complementary to more intensive studies of individual basins, which would be able to give more detailed results for specific areas.

The work was carried out as a collaboration between CEH-Wallingford and the Water Resources Branch of the Ministry of Natural Resources and Energy in Swaziland. The model was installed in Swaziland and training was provided. The Swazi team carried out a large part of the data collection and were involved in setting up, calibrating and running the model. The results were presented to the other countries in the region as part of one of the training workshops (see Chapter 7).

5.1.1 The case study area

Swaziland is a land-locked country, bordering South Africa and Mozambique, with a surface area of 17,400 km^2. All of Swaziland's major rivers are international, thus the study area also covers parts of the neighbouring countries. See Figure 5.1, which also shows the main reservoirs (World Bank/UNDP, 1990).

The climate ranges from sub-humid and temperate in the higher western parts of the country to semi-arid in the eastern lowlands. Average annual rainfall varies from about 500 mm to 1500 mm, with more than three-quarters of the rain falling during October to March. Swaziland is well-endowed with surface water resources, but the runoff has a high degree of seasonal and inter-annual variability, meaning that dams are necessary for storage and effective utilisation of the resource. In the South African headwaters of the major rivers, large inter-basin transfers exist to supply other regions of South Africa. Swaziland also has several major dams, and the number is set to increase. Groundwater resources are limited, but they are currently the most important source for rural water supply; there is little potential for further development of this resource.

The fact that all of Swaziland's surface water resources are shared with other countries highlights the importance of international water agreements. Swaziland is already involved in bilateral and tripartite agreements with its neighbours to ensure that each of the countries gets equitable shares, with six agreements or treaties having been signed between 1976 and 2002. In addition there are overall agreements on water resources covering the whole region of the Southern African Development Community (SADC, 1995; 2000).

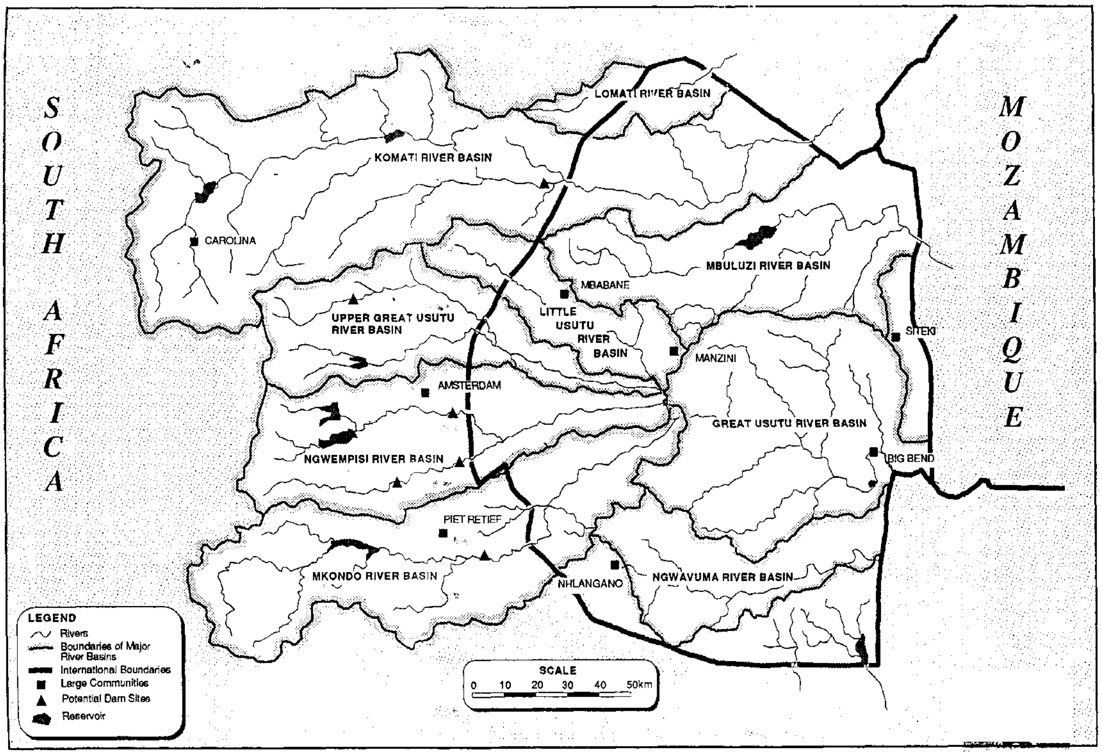


Figure 5.1 *Map of the modelling region*

Swaziland’s economy is heavily reliant on agriculture, which accounts for approximately 95% of all water abstractions. Hence the largest surface water developments (mainly run-of-river) are primarily for irrigation to commercial estates and afforestation for producing wood pulp, along with municipal water supply, industrial and hydropower supply. Intensification of agriculture is a primary objective for Swaziland, with a potential irrigated area of 90,000 ha, equivalent to approximately 52% of the country’s total land area.

5.2 General methodology and its application in Swaziland

The GWAVA model was originally designed to address the problem of making improved estimates of current and future water resources on a global scale (Meigh *et al.*, 1998; 1999). The study attempted to improve on previous global-scale hydrological and water resources modelling approaches, for instance, Shiklomanov (1997), Arnell and King (1998), Alcamo *et al.* (1997; 2000). It relies on the use of a 0.5° by 0.5° latitude-longitude grid (approximately 50 km by 50 km) to represent the spatial variability in both the availability of water and the demands for water. In contrast, many previous studies have examined country-wide aggregates of resources and demand, which can mask significant variations between different parts of the same country. The GWAVA approach includes the following elements in an attempt to make the assessments realistic:

- A consistent methodology which can be applied across all countries and regions;
- Within each grid cell surface water resources are assessed using a rainfall-runoff model;
- The individual grid cells are linked to represent the flow patterns of the natural drainage basins;
- The effects of lakes, reservoirs and wetlands, of water consumed and return flows, and of inter-basin transfers, are all included;

- Seasonal and year-to-year variability in the surface water flows are taken into account to assess the amount of water which is actually available for use;
- Both surface and groundwater resources are included so that the total water availability at any location can be assessed;
- Water demands are assessed, including those for human and livestock consumption, industry and irrigation.

A key point is that water availability and water demands are both assessed and compared at the scale of the grid cell to derive an index of water abundance or scarcity for each cell.

For an approach which is capable of application at the global scale, a compromise is needed between the spatial scale required to represent spatial variability and the availability of suitable data. It is believed that the 0.5° grid allows spatial variability to be represented to a reasonable level – a coarser grid would begin to lose adequate representation of variability, while a finer resolution would require excessively large amounts of data and greatly increased computational effort. Another reason for choosing a 0.5° grid is that several global data sets are available at this resolution.

A brief overview of the main components of the GWAVA methodology is given below; for fuller details see Meigh *et al*. (1998; 1999). Information on data sources and assumptions in applying the model to Swaziland is also provided below, and this is described more fully in Tate *et al*. (2002).

5.2.1 Estimation of surface flows

Based on the 0.5° by 0.5° grid, surface runoff is generated for each cell using a rainfall-runoff model and the flows are then routed through the linked cells to estimate total runoff for each. The effects of lakes, reservoirs and wetlands, water abstractions, return flows, artificial water transfers, flow routing and transmission losses are also taken into account. The basic time step of the model is monthly, and a 30-year time series of flows is generated.

Definition of flow directions and cell linkages

The preliminary stage, before generation of flows, is to determine the main direction of flow for each cell. It is assumed that all the flow from one cell flows into one of the adjoining cells. Based on these directions, the order in which the cells must be processed is determined so that the flows from upstream cells have always been calculated before processing the cell into which they flow. The 0.5° by 0.5° grids and cell linkages are shown in Figure 5.2.

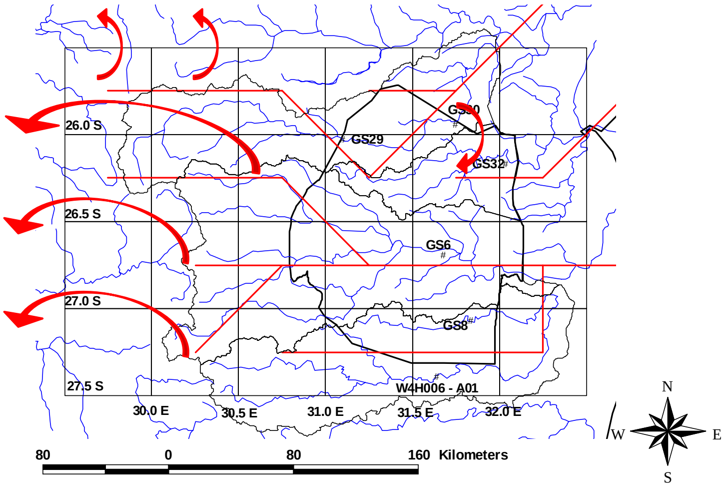


Figure 5.2 *Cell linkages used in the model and flow gauging stations (red lines indicate normal cell linkages and curved red arrows show artificial transfers)*

Generation of local runoff

Runoff is generated for each cell using a rainfall-runoff model; the model chosen was the probability-distributed model (PDM) developed by Moore (1985). This is a conceptual model, based on physical processes, which does not require a large number of parameters. The input data are monthly mean precipitation, potential evaporation and temperature values for each cell, and anomaly series of these for the baseline period (1961 to 1990). The same inputs, based on climate change scenarios, are needed for future periods. Initial values of the two key parameters of the PDM can be determined from physical characteristics of the cells, but calibration can also be carried out in order to improve model performance. The model has other parameters, but it is normally sufficient to hold them constant throughout the area.

Additional elements that have been added to the PDM include an interception model to take account of precipitation that is intercepted by forest canopy and a component to make the model response more realistic in arid areas where there is no flow in the dry season.

Baseline climate data

Monthly climate data at a 0.5° grid resolution for the baseline period were obtained from the Climate Impacts LINK Project, Climate Research Unit (CRU) at the University of East Anglia, UK. Gauged precipitation data were used to verify the accuracy of the CRU precipitation data; generally good agreement was found, but small adjustments to the CRU data were made for one cell. Monthly reference crop and open water potential evaporation estimates were made using the Penman method (Doorenbos and Pruitt, 1977), based on temperature, radiation, humidity and wind speed data. Mean annual rainfall and potential evaporation values on a grid-cell basis are shown in Figure 5.3.

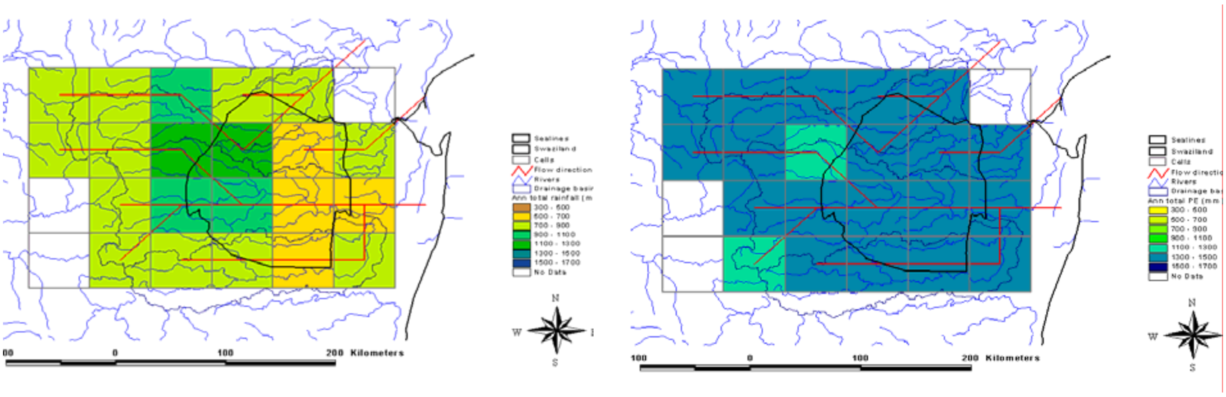


Figure 5.3 *Mean annual precipitation (left) and potential evaporation (right) for the baseline period*

Key rainfall-runoff model parameters

Initial values of the two key parameters of the PDM (field capacity f_c and saturation capacity c_{max}) were estimated from physical characteristics of the cells: soil properties and vegetation cover. Soil texture information for the dominant soil type in each cell was obtained from the FAO soil map of the world (FAO/UNESCO, 1974), and assigned to one of seven classes. Vegetation cover data classified according to the Olson ecosystem classification was obtained from NOAA-EPA (1992). The values were expressed as an assumed percentage of forest cover (as opposed to grass) for each cell. The two parameters were then derived following Vörösmarty *et al*. (1989), as shown in Table 5.1.

Data for model calibration

Observed river flow data were assembled for the main river basins from a variety of sources including the Southern Africa FRIEND project, the Water Resources Branch in Swaziland and the Department of Water Affairs and Forestry, South Africa. Generally, stations were only selected if they had at least ten complete years of data so that low flow statistics could be estimated with reasonable reliability. Some of the stations chosen were downstream of large dams to ensure that the effects of dams on downstream flows were being captured by the model. The station locations are shown on Figure 5.2.

Table 5.1 *Key PDM parameters derived from soil texture and forest cover*

Soil texture class	**Field capacity, f_c (mm)**		**Saturation capacity, c_{max} (mm)**	
	Forest	Grass	Forest	Grass
sand	328	131	888	355
sandy loam	400	200	826	413
silt loam	588	382	936	608
clay loam	530	331	806	504
clay	580	338	653	381
lithosol	27	27	50	50
organic	50	50	100	100

Summing runoff from upstream, routing between cells and transmission losses

Having generated the local flows using the PDM, flows are routed between cells and summed to provide the total runoff in each cell. At this stage, water which is consumed in the cells (abstractions less return flows) is taken into account, and a loss in flow between the cells can also be included. As the overall model time step is monthly, flow routing is generally not important except in very large basins where the difference in timing between flows from different parts of the basin could be significant. The method used is the simple Muskingum method which provides a time delay and a degree of dispersion of the flood wave. For situations where there is loss of water in transmission along the rivers through seepage into the banks or bed, a simple proportional loss can be applied.

Artificial water transfers between cells

In addition to the natural transfer of water between cells along the river channels, there are also artificial transfers along canals and pipelines, both within basins and between different basins. The amount to be transferred is defined either as a fixed amount, or as the amount of water needed to satisfy the demand in the cell into which the transfer is arriving. In both cases, the amounts are limited by the available flow in the cell supplying the transfer and by the capacity of the canal or pipeline. In this study there are substantial transfers from the headwaters to other regions of South Africa, as well as one within Swaziland. The details are listed in Table 5.2 (data on approximate annual volumes from World Bank/UNDP, 1990), and the locations of the transfers are shown in Figure 5.2.

Table 5.2 *Artificial transfers included in the model*

River basin	**Source**	**Destination**	**Annual abstraction (Mm^3/year)**
Komati	Nooitgedacht dam	Olifants basin	131
Usutu	Westoe dam	Olifants basin	40
Usutu	Jericho dam	Olifants basin	20
Usutu	Morgenstond dam	Olifants basin	70
Assegaal/Usutu	Heyshope dam	Vaal basin	100
Komati	Lower Komati river	Mbuluzi river, via irrigation schemes	130

Effects of lakes, reservoirs and wetlands

Where there are lakes, reservoirs or wetlands, these can cause considerable alteration to the flow pattern, and therefore they need to be included in the model. In most cases, where the lake, reservoir or wetland is not very large, or detailed data do not exist, it can be modelled by a simple water balance procedure. For large reservoirs, with detailed data on physical characteristics and operation, a more detailed sub-model is used. The two approaches are:

- The simple water balance procedure is a monthly calculation of the change in storage compared to the water flowing in and out, direct abstractions, and the precipitation on to and evaporation from the lake surface. If the storage becomes greater than the capacity of the lake or wetland, it spills, adding to the outflow. In cases where the relation between surface area and storage is not known, it is normally sufficient to assume that it is linear. The problem with this procedure is that the outflow is unknown, and a simplifying assumption has to be made. This is done by assigning lakes to one of two types. In the first, which applies to natural lakes and wetlands and to reservoirs where the main function is to regulate the outflow, it is assumed that the principal effect of the lake is to reduce the variability of flows, and this is done by defining outflow as a function of net inflow. Alternatively, for reservoirs where the main function is to store as much water as possible, outflow only occurs when storage exceeds the maximum capacity.

- Typically, large reservoirs are controlled by operating rules or curves which define the optimum storage for each month. To simulate them, the operation curve is aimed for in each month, but the outflow is checked to ensure that it satisfies the minimum requirement (where there is one). If it does not, the storage in that month is reduced so that the minimum flow requirement can indeed be satisfied. Next, the resulting storage is checked against the minimum possible storage in the reservoir. In the event that this minimum storage is reached, the direct abstractions from the reservoir are necessarily curtailed. Should the reservoir volume reach its maximum possible, any spare inflow is simply spilled.

Data on the smaller lakes and wetlands in the study area were taken from maps, supplemented by published information where available (TPTC, 2001; Carl Bro *et al.*, 1989; Knight Piésold, 1993). Data on larger reservoirs were provided by the reservoir operating authorities. For the baseline period there are eleven existing major dams with a combined gross capacity of 3873 Mm^3. For the scenarios, two recently constructed dams (Driekoppies in South Africa and Maguga in Swaziland, completed in 1999 and 2001 respectively, combined capacity 585 Mm^3) are included, as well as six more that are proposed, mainly in the Lomati and Komati basins (estimated combined capacity 1155 Mm^3), based on information from GKS/GRSA (1992).

Water consumption and return flows
The summation of flows between cells includes water consumed and return flows. Water consumed is the water diverted for use (irrigation, water supply, etc.), and this is calculated from the demands in the cell (see Section 5.2.3), with the proviso that, if demand exceeds the available supply, the water consumed is taken as the available supply only. It can be seen that the values specified for demands will affect the model results for surface water availability because the water consumed in an upstream cell reduces the amount of water which flows to the next cell downstream. Demands can be supplied from either surface or groundwater or from a combination of the two. In order to determine that part of the demand which is supplied from surface water, some default assumptions are made based on figures found in earlier studies to be those most likely to apply in the majority of situations. For each cell, the model has the capability for these default values to be over-ridden by different figures reflecting the true situation for that cell, but the ability to do this is often constrained by a lack of adequate data.

Surface water which is available for use
Generally, the gross annual quantity of water in a cell is not actually accessible for use. Rather, it is assumed that the driest month in each year which occurs with a certain degree of reliability provides a reasonable estimate of the amount that can actually be utilised by people. A reliability level of 90% was selected as a compromise between that typically specified for irrigation (80%) and the higher levels of 95 or 98% generally required for drinking water supply. The 90% reliable monthly flow is estimated for each cell by performing a frequency analysis on the 30-year sequence of monthly flows, following Gustard *et al.* (1992). Additional allowances are made where there is a large lake or reservoir in the cell. This measure of water availability is adequate for comparison with demands which are more or less constant throughout the year. However irrigation demands are usually scheduled to take account of the variation in flow; the planting and growing seasons are fitted to the times of year when high flows are expected. To take this into account the availability of water throughout the year is also considered for these cases.

5.2.2 Estimation of groundwater resources

When working at the global scale, groundwater resources were estimated from hydrogeological maps using the UNESCO (1970) classification scheme, combined with estimates of likely maximum borehole densities, and compared to figures for potential groundwater recharge from the surface water model. However, for this study, data on groundwater availability were available for the neighbouring areas of South Africa, and this information was used to make estimates for Swaziland, rather than relying on the general approach used at the global scale. Data were provided by DWAF in the form of sustainable groundwater abstractions, defined as the maximum annual volume of groundwater that may be abstracted without depleting the aquifers. The simplest way to make estimates for Swaziland was to interpolate with the assistance of South African maps produced by WRC (1994); these delineations are shown on Figure 5.4. It was considered that, in general, groundwater quality meets the WHO recommended drinking water guidelines, and therefore it was not necessary to reduce the groundwater availability estimates because of inadequate water quality.

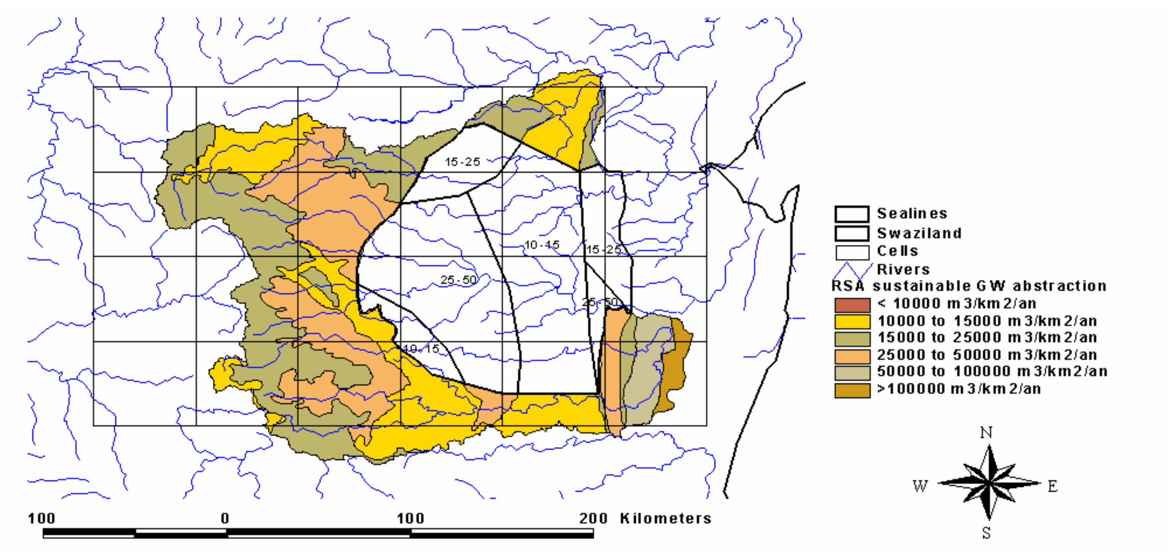


Figure 5.4 *Groundwater availability map of the model region (estimated sustainable groundwater yields in Swaziland shown in units of 1000 m^3/km^2/year)*

5.2.3 Estimation of water demands and demand scenarios

Water demands are considered in three broad categories: domestic (rural and urban water supply); industrial; and agricultural (irrigation, livestock and forestry). A number of sources of data on water demands are available (Water Resources Branch archives; Burke and Mogensen, 1997; Knight Piésold, 1997; TPTC, 2002). However, these tend to be contradictory and the values used here are based on the most recent study available (Mwendera *et al*., 2002) which is thorough and authoritative. The values are summarised on a national basis in Table 5.3.

Table 5.3 *Estimated water use in Swaziland (1996)*

Sector		**Amount**	
		(Mm^3/yr)	**(%)**
Domestic	Rural	9.75	0.9
	Urban	14.43	1.4
Industrial		12.51	1.2
Livestock		12.02	1.2
Irrigation		992.65	95.3
Total		**1041.36**	**100.0**

Two future demand scenarios were envisaged for the 2050s period: a low development scenario and a high development scenario. The low development scenario was based on continuation of the status quo, with lower levels of population growth, a lower limit of unit water use and less infrastructure development. The high development scenario was based on stable economic growth, with slightly higher population growth, a higher level of unit water use, more infrastructure and irrigation development. A summary of demands and related information, for the baseline period and future scenarios, is presented in Table 5.4.

Domestic demands

Domestic water supplies are mostly for consumption by people for drinking, cooking and washing, but small industrial demands may sometimes be included here as well. They are estimated from the population in each cell and data for water requirements per capita. Urban and rural demands are separated because water use is generally higher in urban areas. Future domestic demands are derived from a combination of scenarios of population growth (which are assigned separately to rural and urban areas) and changes in per capita requirements. In this way, spatial changes in population water demand resulting from, for example, migration to urban areas, are included.

Table 5.4 *Summary of demands and demand scenarios*

	Baseline (1961-90)	Low development (2050s)	High development (2050s)
Population – total	926,860	1,937,320	2,638,981
Population – urban	245,318	1,049,692	1,689,808
(% of total)	(26%)	(54%)	(64%)
Head of cattle	416,089	457,698	457,698
Head of sheep & goats	382,779	1,182,788	1,182,788
Per capita daily demand (litres) – urban	60	140	190
Per capita daily demand (litres) – rural	25	50	75
Industrial demand (Mm^3/yr)	11.5	12.7	14.4
Irrigated area (ha)	54,400	76,444	86,319
Irrigation efficiency (%)	50	60	60
Reservoirs	Those existing in 1961-90	Only those existing in 1961-2002	Full planned installations

Data on population, population projections and levels of urbanisation were assembled from the Central Statistical Office (1998) and a variety of other sources (HABITAT, 1996; WRI, 1998; World Bank/UNDP, 1990; Meigh *et al*., 1998; Knight Piésold, 1997). The data were compared and the apparently most reliable values selected. Estimated levels of urbanisation vary from 15% (in 1986) to between 25% and 36% by 2000. Swaziland's population growth rate of around 3% is one of the highest in the world, but it is estimated that HIV/AIDS may affect around 8% of the population, so estimates of future populations may not be very reliable. Data on per capita water consumption for the baseline, and future (low and high development) scenarios were taken from Meigh *et al*. (1998), which was based on a wide investigation of consumption levels for eastern and southern Africa. Losses between the points of abstraction and consumption were assumed to be 20% for rural supplies and 40% for urban. Sewerage systems are generally little developed, and so return flows were assumed to be fairly small: 20% for urban areas and zero for rural supplies.

Industrial demands

Industrial demand refers to large-scale industrial water users which are not included in the rural or urban water supply. The economy of Swaziland is steadily expanding, being primarily based on agriculture and forestry production, with industry being a very minor water user in comparison (just 1.2% of the country's total water demand in 1996). It is necessary to make some allowance for industrial demands in the future, but no information was found on predicted levels of future industrial growth; assumptions were made that for the low development scenario growth in water use would be 10%, and for the high development scenario 25%.

Agricultural demands

Agriculture is by far the largest water user in Swaziland, with about 95% of total water usage in 1996. At the national level, land uses are: 12% small-scale subsistence agriculture, 6% large-scale commercial agriculture (mostly sugarcane), 50% extensive communal grazing, 19% ranching, 8% plantation forest, and 5% other (hunting, parks, settlements, water) (Remmelzwaal and Dlamini, 1994). Data on the irrigation systems (including irrigated areas, main crops and cropping patterns) were obtained from the Ministry of Agriculture. Estimates of the demands, varying through the year, were made following FAO guidelines for crop water requirements (Doorenbos and Pruitt, 1977), and taking account of effective precipitation (Dastane, 1974). Irrigation efficiencies vary widely, with the higher efficiencies tending to come from the larger commercial irrigators, although most use sprinkler irrigation. Irrigation efficiencies for the baseline situation were set at 50%, increasing to 60% for the scenarios. Livestock farming is an important activity within the study area; livestock population data were obtained from the Ministry of Agriculture, and water consumption figures were taken from Meigh *et al*. (1998).

Forestry

Forestry products are of considerable importance to Swaziland's economy, and much afforestation has taken place to satisfy the wood pulp industry; forested areas now total about 130,000 ha. It is thought that afforestation is causing significant runoff reduction, but, unfortunately, there is little concrete information on water use by forests that is specific to Swaziland. Considerable research into water use by trees has been carried out in South Africa, and Van der Zel has derived curves which could be used to estimate the impacts in Swaziland until local information becomes available (Knight Piésold, 1997). In this study, forestry is not identified as a specific water demand which is then compared to water availability in the same way as the other demands. This is because forest water consumption occurs before runoff becomes available for other uses, and the demand cannot be controlled or rationed in the normal way. Instead, the model uses the percentage of forest cover in each grid cell as one of the main factors which determines the key model parameters. Thus water use by forests is implicit in the model scheme, and, in future work, it would be possible to examine the impacts of various scenarios of forest cover.

Changes in agricultural demand

Data on forward projections for livestock populations were taken from Meigh *et al*. (1998). The question of increases in irrigation is more complex. Irrigated areas are set to increase by 15,000 ha to 20,000 ha in the coming five to ten years, and the total irrigation potential is 90,000 ha (Mwendera *et al*., 2002). There are several specific large irrigation schemes being planned, and these were included in the future scenarios. Since the construction of the Maguga Dam (completed in 2001) it is anticipated that the irrigation area on the Komati River in Swaziland may increase by about 7,400 ha (TPTC, 2001). There are also plans for a large smallholder irrigation project in the Lower Usutu River Basin, involving the construction of a system of dams and diversions to irrigate 11,500 ha of crops (GFA-AGRAR, 1998). The projected increased irrigation areas used in the scenarios (Table 5.4) were based on a reasonable interpretation of these various plans and proposals.

5.2.4 Integration of measures of availability and demand

The estimates of the water which is available for use in each cell need to be integrated with the estimates of water demands for that cell to produce an index of water resources availability or scarcity. A number of different indices have been developed for use with GWAVA, but the most useful one is:

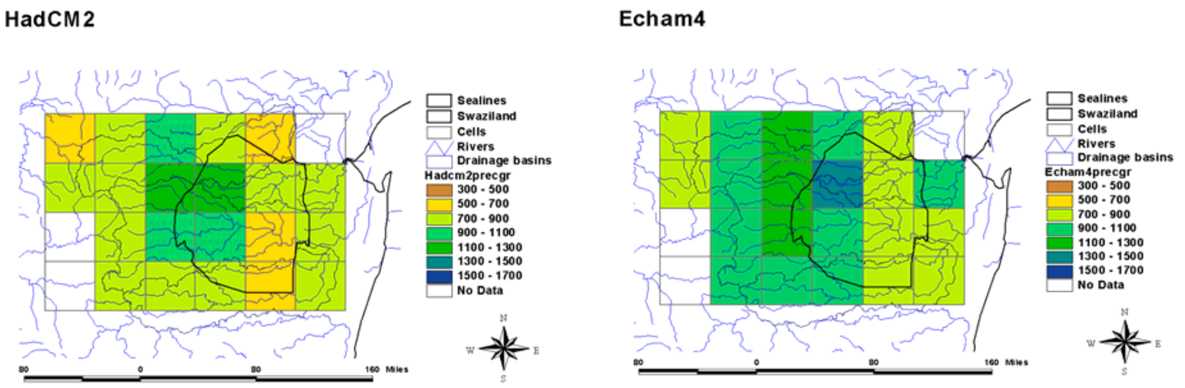
$$I = \frac{Minimum\ of: (90\%\ reliable\ runoff + Groundwater\ yield - Demand)}{90\%\ reliable\ runoff + Groundwater\ yield - Demand}$$

where I is the water availability index. It is calculated by determining the 90% reliable flow for each month of the year separately, and then finding the minimum (over all months in the year) of this value minus the demand in the same month. This reflects the critical point in the year whether or not there are variable irrigation demands. The result is then standardised so that it can be expressed as a ratio. This ranges from -1 (negligible water available to meet demand), through zero (available water equals demand), to 1 (available water much greater than demand). By mapping the values of the index, the balance of availability versus demands in each cell can easily be distinguished.

5.3 Climate change scenarios

It is expected that global climate change resulting from the emission of carbon dioxide and other greenhouse gases will lead to changes in both rainfall and evaporation which could have profound effects on the water resources of the study region. Climate change scenarios for the period of the 2050s were obtained by applying the outputs from global climate models (GCMs) as inputs to the GWAVA model. A range of GCMs was used in order to assess the possible range of impacts on water resources that might occur. The three chosen were: HadCM2 from the UK Hadley Centre for Climate Prediction and Research, Echam4 from the German Climatic Research Centre, and CGCM1 from the Canadian Centre for Climate Modelling and Analysis. Each of the three models uses a number of atmospheric and oceanic layers coupled together to simulate the climate, resulting in each model having a 'climate sensitivity', or a predicted increase in the global temperature due to a doubling of the effective CO_2. HadCM2 has a climate sensitivity of about 2.5°C, Echam4 2.6°C, and CGCM1 3.5°C. The greenhouse gas emissions scenario used is the IS92a scenario (Leggett *et al*., 1992) defined by the Inter-governmental Panel on Climate Change (IPCC) in 1992 and amended by them in 1995. For more information on the GCMs see the IPCC-DDC website at http://ipcc-ddc.cru.uea.ac.uk.

The size of the GCM cells varies between 2.5° and 3.75° of latitude and longitude, a much coarser resolution than the 0.5° grid cells used by the GWAVA model. In order to avoid the problem of sudden jumps in model results occurring at the edge of the GCM cells, the GCM results were 'down-scaled' to the required resolution using the geo-statistical technique of kriging to interpolate them. This provides a reasonable gradient between the GCM 'points', but it does not add any meaningful meteorological detail.



HadCM2

Echam4

CGCM1

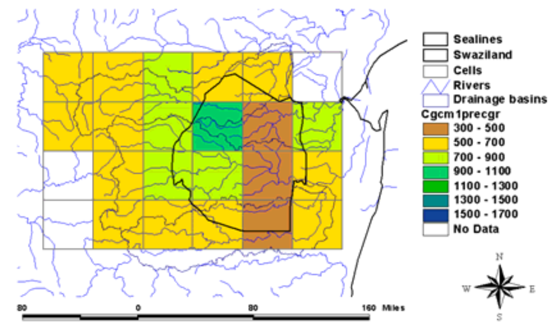


Figure 5.5 *Precipitation scenarios for the 2050s period*

The GCM scenarios of precipitation cannot be used directly because the baseline values from the GCM are different to the CRU baseline precipitation data used in this study. Hydrological processes are very sensitive to precipitation inputs, and therefore it is important that realistic spatial and temporal rainfall inputs are used. The GCM baseline data could not be expected to reflect this satisfactorily because of the coarse grid size. Thus, it was necessary to retain the original baseline precipitation data set. In order to apply the scenarios, the percentage changes in each month were calculated for the GCM scenario compared to its own baseline, and these percentage changes were then applied to the 0.5° by 0.5° CRU baseline precipitation datasets. A similar procedure was followed for the evaporation scenarios. The precipitation scenarios for the three GCMs are plotted in Figure 5.5, and all the scenarios are summarised on an annual basis in Table 5.5.

Table 5.5 *Summary of changes in annual hydrological values for the 2050s*

		Baseline value	GCM 2050s value (change from baseline)					
			HadCM2		Echam4		CGCM1	
Precipitation (mm)	Min.	591	636	(+8%)	753	(+27%)	389	(-34%)
	Ave.	817	838	(+3%)	971	(+19%)	638	(-22%)
	Max.	1160	1204	(+4%)	1321	(+14%)	950	(-18%)
Temperature (°C)	Min.	15	18	(+3°C)	18	(+3°C)	18	(+3°C)
	Ave.	18	21	(+3°C)	21	(+3°C)	22	(+4°C)
	Max.	23	25	(+2°C)	26	(+3°C)	26	(+3°C)
Potential evaporation (mm)	Min.	1293	1387	(+7%)	1353	(+5%)	1268	(-2%)
	Ave.	1389	1509	(+9%)	1499	(+8%)	1401	(+1%)
	Max.	1503	1686	(+12%)	1647	(+10%)	1573	(+5%)

5.4 Results

Model validation

After calibration, mean annual runoff was on average modelled well (Table 5.6). Monthly patterns of flow were also modelled well at most sites, although dry season flows tended to be underpredicted in the north of the country. The model has inherent limitations since it derives key model parameters from physical characteristics, and the 0.5° grid scale is such that many variations in catchment characteristics are masked. Also, the length and quality of the validation series is in some cases rather inadequate, and they do not always represent the same time period and conditions as those being modelled. Taking this into consideration, the model is seen to perform well on this comparatively small water resources system.

Table 5.6 *Observed and modelled mean annual runoff*

Gauging station	Observed MAR (Mm^3)	Modelled MAR (Mm^3)	(%) of observed
GS6	1642	1560	(95%)
GS29	482	421	(87%)
GS30	399	463	(116%)
GS32	201	173	(86%)
GS8 + W4H006	821	692	(84%)

Changes in river flows

The projected changes in population, water demands and climate were used to examine a range of scenarios of future conditions compared to the baseline case. Flow series were generated for the 30-year period (2040-69) which is taken to represent future conditions in the decade of the 2050s. Table 5.7 shows the changes in mean annual flows for the main rivers at the flow gauging sites described above for each combination of climate and development scenarios. Figure 5.6 shows a typical example of the monthly patterns of flows under the different change scenarios.

The different scenarios produce a wide range of results which are mainly driven by the differences in the GCM precipitation predictions (shown in Figure 5.5). The resulting flows are more variable between GCMs than are the rainfalls. This is as expected because runoff is typically sensitive to small changes in rainfall inputs. The lowest change in rainfall (+3% with HadCM2) leads to a decrease of 26% in flow even with the low development scenario (flows decrease even though rainfall increases because of increasing evaporation and abstractions). Generally, the results show that the impact of the different development scenarios is relatively small compared to the potential impact of climate change. Because the different GCMs produce very different results there is a high degree of uncertainty in the impacts; this is discussed further below.

Table 5.7 *Scenarios of future mean annual river flows*

Climate model/ Gauge site	**Low development scenario** MAR (Mm^3)	(% change)	**High development scenario** MAR (Mm^3)	(% change)
HadCM2				
GS6	1366		1244	
GS29	229		193	
GS30	291		184	
GS32	125		99	
GS8 + W4H006	600		599	
Total	**2611**	(-26%)	**2319**	(-35%)
Echam4				
GS6	2558		2417	
GS29	790		771	
GS30	822		669	
GS32	344		303	
GS8 + W4H006	1251		1250	
Total	**5765**	(+63%)	**5410**	(+53%)
CGCM1				
GS6	819		735	
GS29	185		135	
GS30	226		125	
GS32	83		69	
GS8 + W4H006	329		328	
	1642	(-54%)	**1392**	(-61%)
TOTAL				

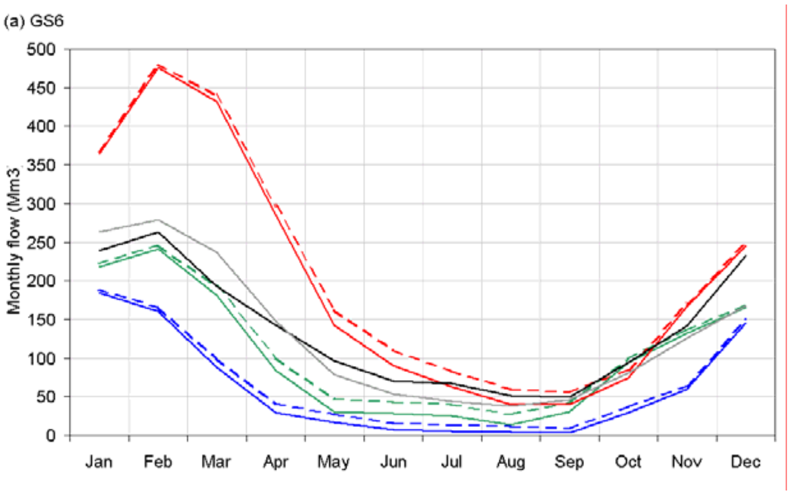


Figure 5.6 *Monthly flows under 2050s scenarios for GS6 (black line is observed flow, grey is modelled for the baseline period; scenarios are HadCM2 green, Echam4 red, CGCM1, blue; dashed lines, low development; solid, high development)*

Current water availability

The results shown so far have illustrated the potential impacts in terms of changes of river flows at certain key sites. However, one of the most significant features of the model is its ability to examine the balance between water availability and demand at the level of the grid cell, using the water availability index (Section 5.2.4). For the baseline case, using present climatic conditions and present water demands, the index is plotted for each grid cell over the study area in Figure 5.7. It can be seen that over much of Swaziland the situation is already tending towards water stress (index values between –1 and 0, shown brown in the figure). This pattern reflects the large areas of irrigation and forest with their heavy demands for water, and also the more populated areas, where water demands are also high. It also reflects the current climate, with lower levels of precipitation in the eastern lowlands of Swaziland, coupled with the large irrigated areas in that region. In the South African headwaters however, there is generally a situation of water abundance.

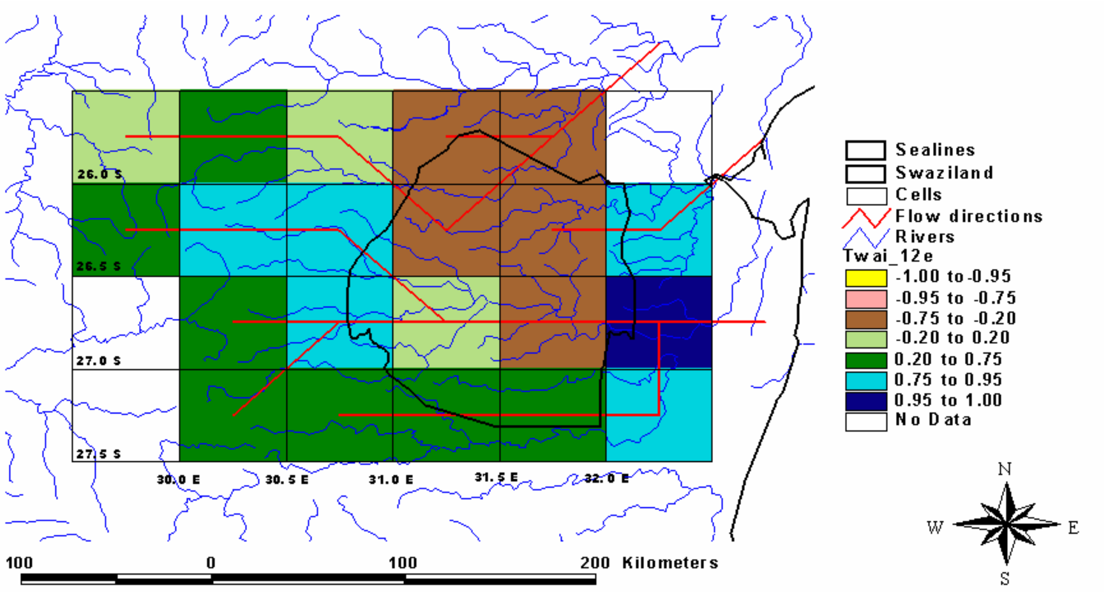


Figure 5.7 *Water availability index for baseline conditions*

Future water availability

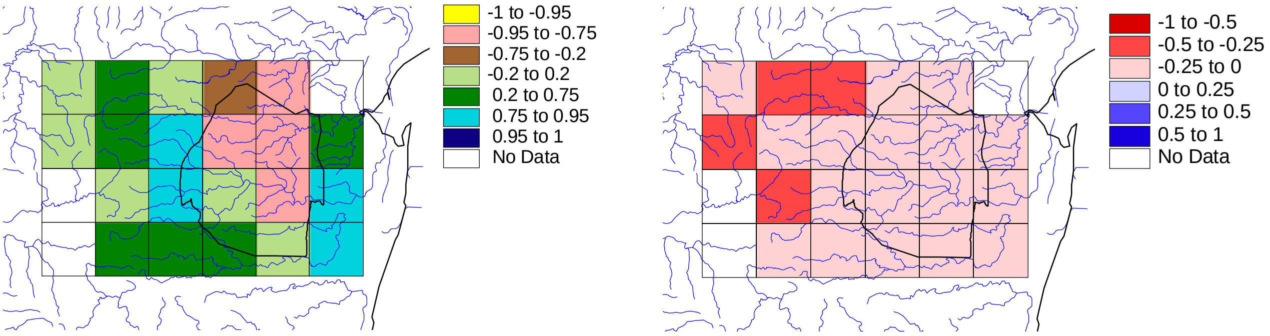
Scenarios of future water availability versus demand for the 2050s are shown in Figure 5.8 (low development assumption) and Figure 5.9 (high development assumption). In general, the results indicate an increase in water stress across much of Swaziland. However, there are very substantial differences between the results produced by the different GCMs. Relative to these differences, the probable impacts due to changes in water resources development are rather small. The three climate scenarios can be characterised as follows: CGCM1 is “dry” with a decrease in precipitation everywhere, Echam4 is “wet”, and HadCM2 is intermediate (see Table 5.5). Using CGCM1, the combination of decreasing rainfall with increasing demands leads to a substantial increase in water stress across the whole country. In contrast, Echam4 predicts a general decrease in water stress as the increasing flows are sufficient to offset the increase in demands. The intermediate climate scenario, HadCM2, predicts a small increase in rainfall, but, as evaporation also increases, there is still a considerable decrease in river flows. With increasing demands due to the growth in population as well as in per capita demands and in irrigation and industrial use, there is still an overall increase in water stress across the whole country. Part (a) of Figure 5.8 shows that with HadCM2 the index value is expected to decline everywhere, and that there would be substantial water shortages over much of the country (eastern and northern parts), while for smaller areas in the south and west the index is expected to remain greater than zero.

Looking at the results in Figure 5.9 compared to Figure 5.8, it can be seen that the impacts of the different development scenarios are relatively small compared to the impacts of climate change.

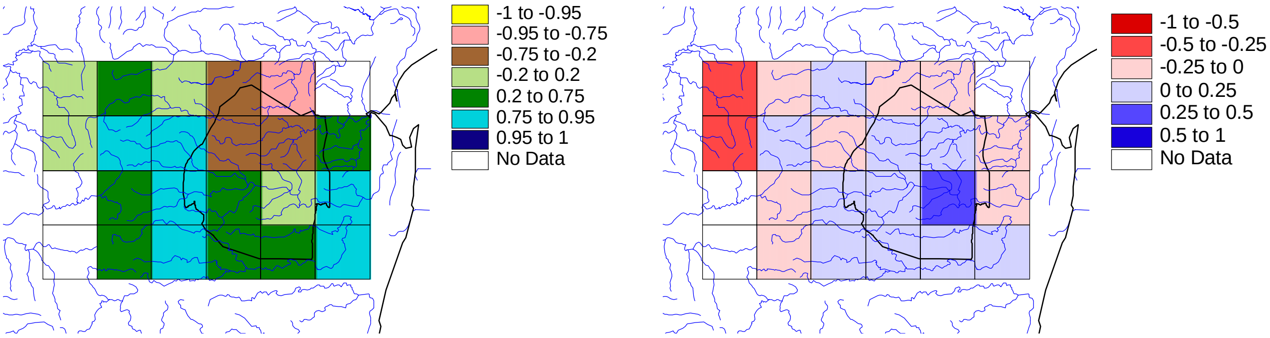
Generally, with the high development scenario, a somewhat greater increase in water stress is predicted, which might be expected due to the higher water demands associated with this assumption. However, there is one contrasting area in the north of the country where the high development scenario shows an increase in water availability. This is because only this scenario includes substantial dam development, and the new dams are concentrated in the north (Komati basin). Although the dams would increase evaporation losses and may have other undesirable impacts, their effects in terms of water availability would be to substantially reduce the seasonal variability of flows, thereby increasing the availability of water in the dry season and allowing demands to be met throughout the year.

Index: 2050s **Change: 2050s versus baseline**

(a) HadCM2



(b) Echam4



(c) CGCM1

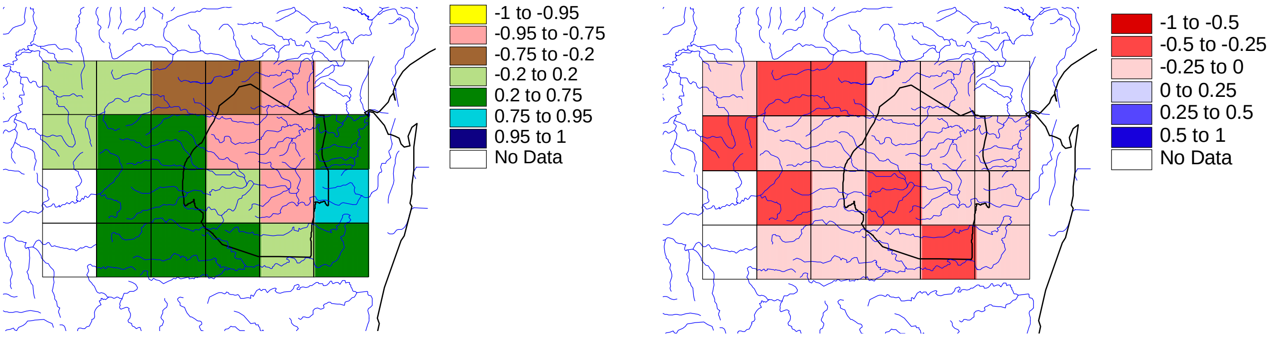
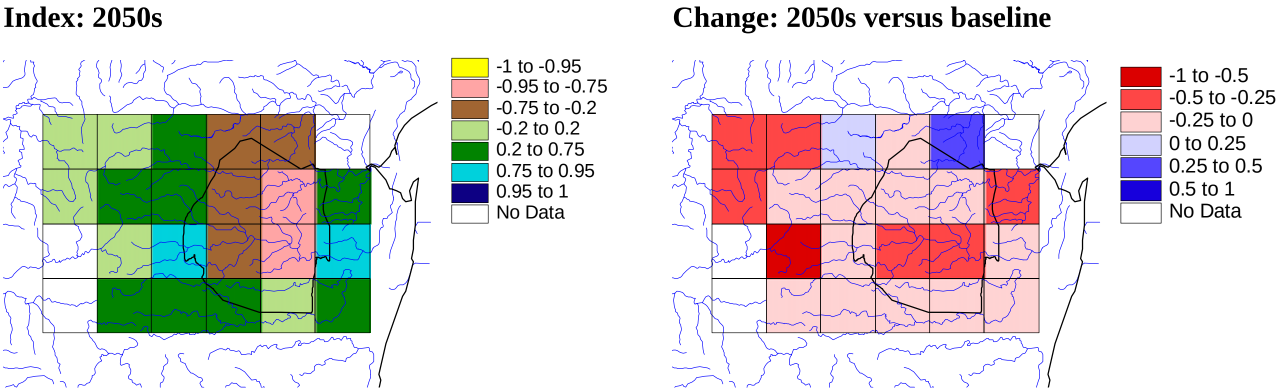


Figure 5.8 *Scenarios of water availability index for 2050s with low development assumption – index (left), change relative to baseline (right)*

As HadCM2 produces intermediate results compared with the other two climate scenarios, it seems reasonable to treat this GCM as providing the most likely estimate of future water conditions in Swaziland. On this basis we can tentatively predict a general situation of increasing water stress – that is, a shortage of available water compared to demand – across the whole country, with substantial shortfalls in availability compared to demand in most areas. However, the differences in the results provided by the GCMs illustrate how tentative this result is, and show that the uncertainty in estimates of future water resources remains high.


Index: 2050s

Change: 2050s versus baseline

Figure 5.9 *Scenario (HadCM2) of water availability index for 2050s with high development assumption – index (left), change relative to baseline (right)*

5.5 Discussion and conclusions

The water resources situation in Swaziland is quite complex, with an increasing number of developments such as large reservoirs, inter-basin transfers and abstractions. The 0.5° by 0.5° grid size used in the GWAVA model tends to mask many of the variations in characteristics of the river basins, but nevertheless it reproduces the observed baseline flows with a reasonable degree of accuracy, so that some confidence can be held in the predictions of future flows.

The results show that over much of Swaziland the situation is already tending towards water stress, reflecting the current climate pattern and the large areas of irrigation and forest with their heavy demands for water, as well as the more populated areas, where demands are also high. For the future, the HadCM2 climate model gives predictions which are in the middle range of the three studied, and it seems reasonable to assume that this provides the most likely indication of future conditions. A general decline in river flows is expected: combined with increasing demands resulting from growth in population, per capita consumption, irrigation and industrial use, this would lead to an increase in water stress across the whole country. The northern and eastern parts are expected to have the greatest deficit in water availability compared to demand. However, for the high development scenario, which includes a substantial increase in large dams, one grid cell in the north shows the reverse trend, with a decline in water stress; this is produced by increased storage availability. Thus, based on the HadCM2 results we can tentatively predict a general situation of increasing water stress – that is, a shortage of available water compared to demand – across the whole country, with substantial shortfalls in most areas. However, the differences in the results provided by the three GCMs illustrate how tentative this result is, and show that the uncertainty in the estimates of future water resources remains high.

The methodology applied here is one which was chosen in order to provide rapid results following a standardised approach. Clearly, more detailed studies might provide improved estimates. Among the possible aspects which could be considered for future work are the following:

- Global climate models are being continually revised and improved. Newer GCMs may show more consistency between the different models, thus helping to reduce the uncertainty in the predictions of future conditions. In addition, Regional Climate Models, which usually provide results on the same 0.5° by 0.5° scale as used here, are starting to become available and may help to provide more accurate predictions.

- The 0.5° by 0.5° grid is rather coarse compared to the variability of the natural and man-made aspects of the study area. Application of a finer grid-scale or of traditional catchment-based modelling approaches could be used to reflect this more realistically, though at the cost of a far greater investment of effort.

- The current version of GWAVA does not have the facility to include environmental water needs. This is recognised as a shortcoming, but in order to make it possible, more work would be needed to define the flows needed in relation to the ecological status of the rivers. Inclusion of the instream flow requirements would help to guarantee that water resources development is carried out within the sustainable limits of the riverine environments.

- The water use of forestry is an important issue in Swaziland and in neighbouring countries. While this aspect is implicit in the current version of the model, more explicit treatment of the water use by forestry plantations would be an advantage so that the implications of different options could be examined.

- As all Swaziland’s rivers are shared with neighbouring countries, international obligations and agreements are a constraint on water availability. They are not specifically included in the model, and this is an addition which would also be beneficial in future studies.

6 The Southern Africa spatial database

M.J. Fry and S.S. Folwell

6.1 Introduction

In the first phase of the Southern Africa FRIEND project an extensive spatial database of hydrological, climatological and physiographic information covering the whole region was assembled. The datasets provide valuable information for water resources planning, and could provide useful information for the development of decision support tools for water resources management. The spatial data cover the following types:

- National boundaries
- Hydrometric boundaries
- Major river basins of Africa
- FRIEND flow gauging stations
- Geology
- Soils
- River network
- Raingauge locations
- Vegetation
- Precipitation
- Potential evaporation
- Temperature
- Mean annual runoff
- Wetlands

The data were distributed on CD-ROM to the national hydrological agencies and other organisations in the participating countries. This fits within the overall aim of the global FRIEND programme to support the “Application of methods of analysis using regional data sets”, and particularly within the Southern African context of providing improved knowledge on flow regimes, following a demand driven approach, and establishing them in hydrological agencies in the region. The CD-ROM has also been distributed to 30 representatives of other FRIEND projects.

Besides the spatial datasets themselves, a specially developed piece of software, the “Southern Africa FRIEND Spatial Data browser”, was distributed to provide easy access to the data and documentation on its origin and interpretation. A brief description of the datasets and browser software follows. More detail on these topics can be found in Fry *et al*. (2001).

6.2 Description of the data

A brief description is given below for each type of data. The data can be viewed and manipulated using the browser software in combination with the freely-available GIS software ArcExplorer, developed by Environmental Systems Research Institute (ESRI, 1998). The descriptions also give guidance as to which options within ArcExplorer should be selected in order to view the data in a satisfactory way (**Table 6.1**).

National boundaries These are polygon coverages showing the national boundaries for the selected country, derived from topographic maps at a scale of 1:250,000 (except 1:500,000 for Angola) with Lambert Azimuth projections (Figure 6.1).

Hydrometric boundaries A polygon coverage shows both catchment and hydrometric zone boundaries for all of Southern Africa. It has approximately 500 national hydrometric zones, more than 1000 gauged catchment boundaries (including all the FRIEND stations), and national boundaries for the eleven SADC countries involved in the project at that time. It was created from 1:250,000 scale topographic maps (except 1:500,000 for Angola). An additional coverage is available which contains information on regional topology, linking polygons which lie in the same catchment to maintain the nested structure. For any individual river basin or gauged catchment polygon, this coverage automatically identifies all other polygons that lie upstream.

Table 6.1 *Attributes of the coverages and options required to view them*

Attribute	*Explanation*	*Classification option*
Hydrometric boundaries		
N_H_ZONE	National river basin number	Standard Labels
F_H_ZONE	Unified FRIEND river basin number	Standard Labels
N_C_CODE	National gauging station number	Standard Labels
F_C_CODE	Unified FRIEND gauging station number	Standard Labels
AREA_KM	Area of polygon in square kilometres	Standard Labels
NATION	FRIEND country code, based on IDD telephone code	Standard Labels
PRIM	FRIEND primary zone code	Standard Labels
HYDRO	FRIEND hydrometric code, without country code (the first two digits)	Standard Labels
Major river basins of Africa		
BASIN_MAJO	Major river basins in Africa	Unique Values
NAME	River basins in Africa	Standard Labels
FRIEND flow gauging stations		
FRIEND_STN	Symbol for each gauging station location	Single Symbol
GAUGES_ID	Unified FRIEND gauging station number	Standard Labels
Geology (except South Africa)		
NAT_LITH	National geological classification for each country, adopted directly from the separate geological map legends	Unique Values
REG_LITH	Unified geological classification for the whole region (see Table 6.2)	Unique Values
AQU_TYPE	Predominant aquifer type, based on the UNESCO hydrogeology legend: I intergranular, F fissured, L local	Unique Values
AQU_PROD	National aquifer productivity category: H high, M medium, L low	Unique Values
YIELD_LOW; YIELD_MID; YIELD_HIGH	National aquifer yield categorisation (in l/s), with each polygon assigned values for lower, mid and upper yields	Unique Values
Vegetation		
OLSON14D	Percentage forest cover from Olson World Ecosystems classification	Unique Values
NDVI_87	Percentage forest cover from the NDVI approach	Unique Values
Precipitation		
ANNUAL_RAIN	Mean annual precipitation (mm)	Class Breaks
JAN_RAIN … DEC_RAIN	Mean monthly precipitation (mm) for each month	Class Breaks
Potential Evaporation		
ANNUAL_PE	Mean annual Penman potential evaporation (mm)	Class Breaks
JAN_PE … DEC_PE	Mean monthly Penman potential evaporation (mm) for each month	Class Breaks
Temperature		
ANNUAL_TEMP	Mean annual temperature (^{o}C)	Class Breaks
JAN_TEMP … DEC_TEMP	Mean monthly temperature (^{o}C) for each month	Class Breaks
Wetlands		
WET1 … WET21	Wetland types: 1 lake, 2 dry lake, 3 lagoon, 4 dam, 5 mangrove/ papyrus swamp, 6 marsh, 7 area liable to flood, 8 mbuga, 9 dambos, 10 seasonally hydromorphic soil, 11 perched dambos, 12 fringing wetland, 13 sodic soil, 14 vertisols of lithomorphic origin, 15 vertisols of topographic depressions, 16 claypan soils, 17 pan, 18 perennial pan, 19 non-perennial pan, 20 dry pan, 21 minor pan	Unique Values
TOTAL	Total wetland density	Unique Values

Major river basins of Africa This is a polygon coverage showing the major river basins for the whole of the African continent, derived from 1:1,000,000 scale maps, and obtained from the Global Ecosystems Database (NOAA-EPA, 1992). For South Africa, DWAF also provided a river network derived at 1:250,000 scale.

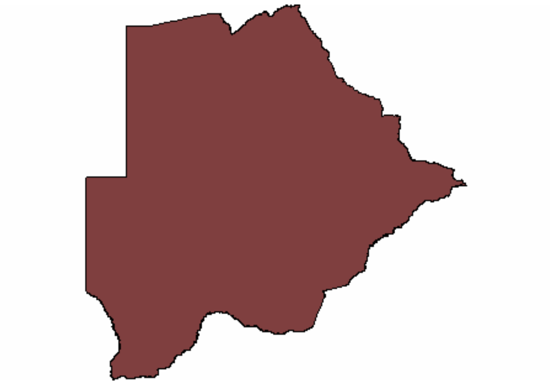


Figure 6.1 *Example of national boundaries for Botswana*

FRIEND flow gauging stations. This point coverage shows the locations of the Southern Africa FRIEND flow gauging stations as identified by the National Hydrological Agencies (Figure 6.2).

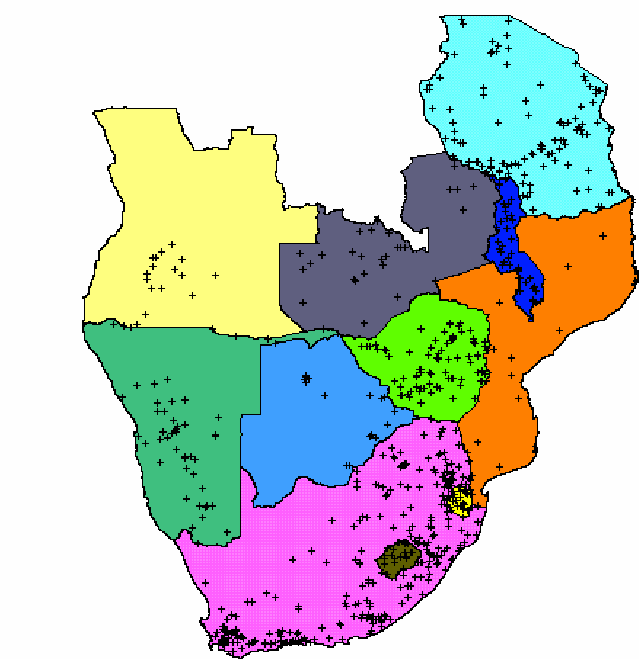


Figure 6.2 *FRIEND flow gauging stations for all of Southern Africa (with national boundaries added)*

Geology. Polygon coverages of the geology and hydrogeology are provided for each country and for the whole region. National maps were digitised and integrated, with a degree of standardisation, to create a new regional geology/hydrogeology coverage. Each contains five attributes, showing the national lithology (as defined on national maps), a new regional lithological classification which integrates the different national lithological schemes (Table 6.2), aquifer type, aquifer productivity and aquifer yield[3]. For more information on the data sources see UNESCO (1997), and Vetger (1995) for South Africa. An example for Mozambique is shown in .

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[3] The coverage of Angola is incomplete, and the South African coverage does not contain the same attributes as the other countries.

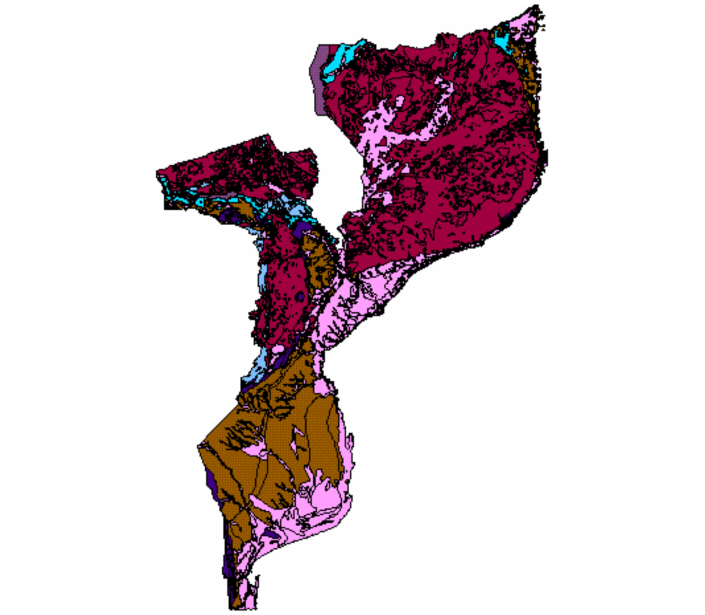


Figure 6.3 *Example of geology (REG_LITH) for Mozambique*

Table 6.2 *Unified regional geological classification (description of the REG_LITH attribute)*

Age	*Formation*	*REG_LITH value*	*Lithology*
Tertiary to Quaternary	Alluvium	1	Sands, silts, clays including lake beds
Tertiary to Quaternary	Kalahari Sands	2	Sands
Late Jurassic – Late Cretaceous – Tertiary		3	Marine sandstones, siltstones, shales
Upper Carboniferous to Lower Jurassic	Karroo Basalts	4	Lavas and associated igneous rocks
Upper Carboniferous to Lower Jurassic	Karroo Sediments	5	Sandstones, mudstones, siltstones
Upper Ordovician to Lower Carboniferous	Cape System	6	Marine sandstones, shales
Late PreCambrian to Lower Palaeozoic	Transvaal and Waterberg groups	7	Dolomites, quartzites, shales, sandstones
Middle to Late PreCambrian		8	Metasediments, igneous complexes, volcanic
Old PreCambrian Archaean		9	Basement granites and gneisses of shield areas

Soils This is a polygon coverage of information on soils for the whole of Southern Africa. The data were obtained from the Global Ecosystems Database (NOAA-EPA, 1992), which were themselves derived from the FAO Soil Map of the World (FAO-UNESCO, 1974; FAO, 1996). Each mapped unit is defined by a code which determines the soil unit or association of soil units. The codes provide information on: the dominant soil (using 106 soil units, grouped in 26 major soil groupings – Table 6.3); component soils for cases when the mapping units are not homogeneous; and texture and slope classes of the dominant soil.

Table 6.3 *Main soil unit symbols*

A	Acrisols	H	Phaeozems	O	Histosols	V	Vertisols
B	Cambisols	I	Lithosols	P	Podzols	W	Planosols
C	Chernozems	J	Fluvisols	Q	Arenosols	X	Xerosols
D	Podzoluvisols	K	Kastanozems	R	Regosols	Y	Yermosols
E	Rendzinas	L	Luvisols	S	Solonetz	Z	Solonchaks
F	Ferralsols	M	Greyzems	T	Andosols		
G	Gleysols	N	Nitosols	U	Rankers		

River network. This is a line coverage for the African continent, derived from 1:1,000,000 scale maps, obtained from the Global Ecosystems Database (NOAA-EPA, 1992). For South Africa, DWAF also provided a river network derived at 1:250,000 scale.

Raingauge locations. This is a point coverage of the raingauges in each country and for the whole region, except Angola, Lesotho, South Africa and Swaziland for which information was not available. The data were provided by National Hydrological Agencies. The regional coverage contains locations for those raingauges which are on the Climatic Research Unit (CRU) database at the University of East Anglia rather than the gauges included in national coverages.

Vegetation. Two half-degree grid coverages are provided: the Olson World Ecosystems vegetation data, derived from a combination of published vegetation maps, remotely-sensed data and observations; and a NDVI classification created using the temporal variability of remotely-sensed monthly Normalised Difference Vegetation Index data for 1987 (chosen to be a representative year). Both datasets were obtained from the Global Ecosystems Database (NOAA-EPA, 1992), and for both, the values were simplified from the original classifications and presented as estimates of the percentage of forest cover (as opposed to grassland).

Precipitation. These are half-degree grid coverages for the whole region, giving mean annual and mean monthly precipitation data for the standard period 1961-1990 (Figure 6.4). The data were provided by the Climatic Research Unit (CRU) at the University of East Anglia.

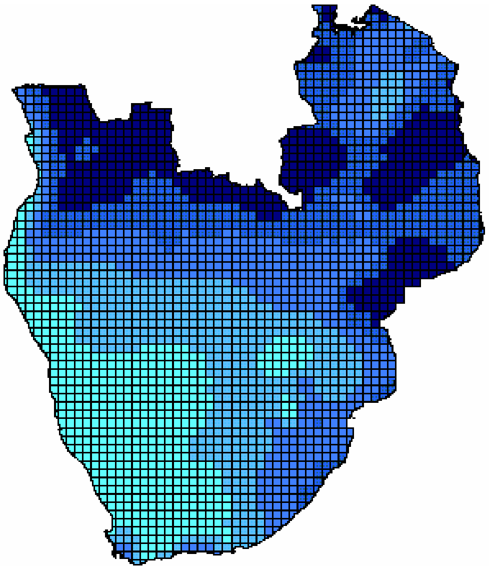


Figure 6.4 *Mean annual precipitation for all Southern Africa*

Potential evaporation. These are half-degree grid coverages for the whole region, giving mean annual and mean monthly potential evaporation data, estimated by the Penman method, provided by CRU for the standard period 1961-1990.

Temperature. These are half-degree grid coverages of mean annual and mean monthly temperature for the whole region, provided by CRU for the standard period 1961-1990.

Mean annual runoff. These are half-degree grid coverages of mean annual runoff expressed as millimetres depth for the whole region, averaged over the standard period 1961-1990. The values were derived using a grid-based rainfall-runoff modelling technique in which each grid cell is treated as an independent catchment. The model was based on the Probability Distributed Model (PDM), comprising a soil moisture store with a capacity that varies across each grid cell, and a groundwater store (Moore, 1985). The parameters were derived from physical and climatic characteristics, rather than by optimisation, and the input data were the rainfall and potential evaporation values described above and time series of monthly rainfall from the same source.

Wetlands. This is a half-degree grid coverage which was created by sampling mapped wetlands. It provides information on several different definitions of wetland, floodplains and other water bodies as defined on national topographic map series.

6.3 The data browser software

The "Southern Africa FRIEND Spatial Data browser" provides a means of easy access to the spatial data and to documentation on its origin and interpretation. It works in conjunction with the freely-available GIS software ArcExplorer. Illustrations of a few of the facilities of the browser software are given here; for the detailed operation manual see Fry *et al*. (2001).

The coverage (or theme) that is displayed in ArcExplorer can be interrogated – it contains more information than meets the eye. Geographical features are represented in GIS coverages in various forms, for example, polygons, lines, points and grids. The characteristics of these geographical features are called 'attributes' (e.g. each polygon of a geological coverage may contain attributes such as lithology, or aquifer type). They can be examined or displayed separately, and the appearance of a coverage can be determined by selecting the attribute to be displayed and the method of displaying. The most commonly used methods are:

- Polygon or line coverages – polygons displayed in map view, colours determined by an attribute with similar colours representing similar attribute values;
- Point coverage – points displayed have symbol size and colour representing attributes values;
- Gridded coverage – squares where selected attribute data is similar are coloured similarly.

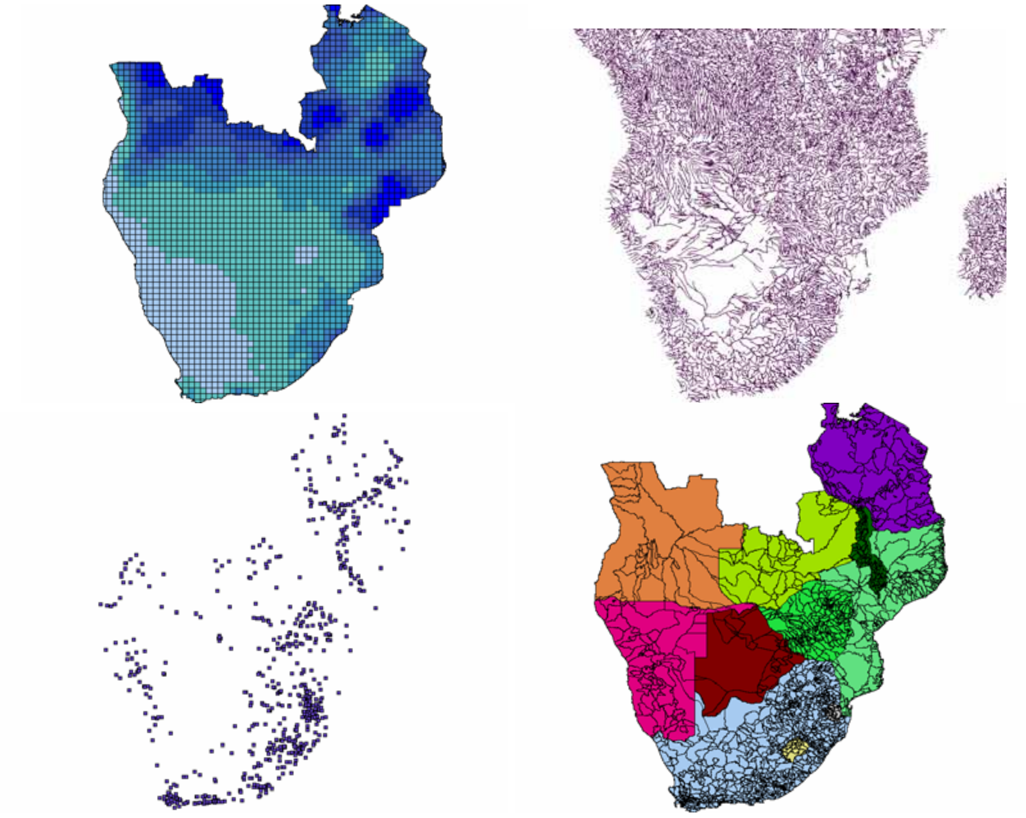
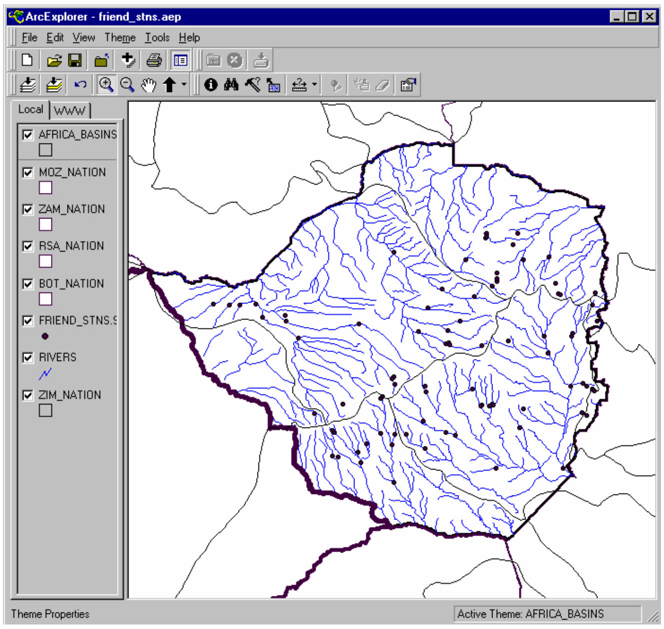


Figure 6.5 *Examples of gridded (rainfall), line (rivers), point (gauging station) and polygon (catchment) data*

New ArcExplorer projects can be created by superimposing several datasets to show, for example, a region's rivers, gauging stations and national boundaries together. The viewer can zoom in or out to focus on any area of the data. When the desired picture has been created, it can be exported and incorporated into reports and documents. The format of the data files is such that they can be used by national hydrological agencies for further analysis work using the more sophisticated GIS packages, ArcView and ArcInfo.



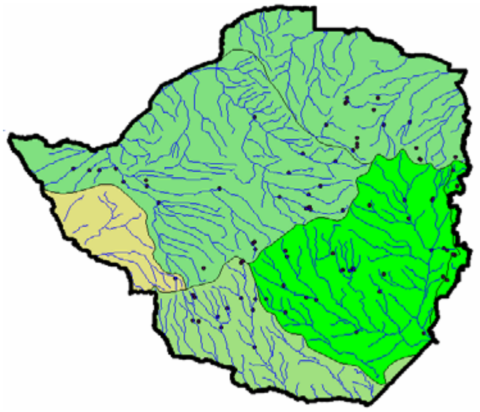


Figure 6.6 *National boundary, FRIEND gauging stations, rivers and basins for Zimbabwe can all be displayed, the settings adjusted appropriately, and the image exported*

7 Capacity building

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Southern Africa FRIEND aims to strengthen the technical and institutional capacity of national and regional water institutions. Capacity building is important for the future effectiveness of many of these institutions which are at risk due to budget constraints that limit the training of staff in new technologies and ideas, and hinder the development and maintenance of important datasets. In the second phase of Southern Africa FRIEND a complementary approach to capacity building was taken, involving a programme of three regional workshops based on the hydrological themes covered in this report, and a studentship within the region, training a key member of staff to a high level of attainment within a particular research area. There were also a variety of in-situ training activities; these were integral components of the development work discussed elsewhere in this report.

7.1 Background

Many hydrological institutions within Southern African countries have major problems of capacity, including staffing and availability of technology and training. The technical and scientific training required for hydrologists is not widely available and, increasingly, staff with such training have tended to move to private water companies or other industries. In addition, low life expectancy and the impacts of HIV/AIDS, causes serious manpower problems for many large employers in the region. This has led to an erosion of the skills base within the national hydrological agencies of Southern African countries, a fact that is recognised by governments and workers alike. Compounding the issue have been recent leaps in technology; within a very short space of time the hydrological agencies have had to update the way they work, with the concomitant costs of new hardware, maintenance, software and training. The combination of these factors, together with internal funding pressures, has restricted the development of some institutions with regard to the adoption of newer methods for water resources management, an outcome which will undoubtedly have a negative impact upon their effectiveness in the future.

Phase I of Southern Africa FRIEND collated sets of hydrological and meteorological time series and spatial data for use within research programmes in the region. A number of staff were trained in GIS and time series database techniques. In Phase II, recognising the success of these aspects of the earlier work, capacity building was continued along the same lines. The steering committee made the decision to concentrate capacity building into three areas: low flows, droughts, and water resources. Within the second phase of the FRIEND programme, the aim was to strengthen capacity in these areas through training and technology transfer. The training on new hydrological techniques and technologies aimed to increase the overall level of knowledge of staff within institutions, providing ongoing hydrological training that is otherwise not generally available. The aim of the technology transfer component was to make use of knowledge from both outside and within the region for the application of improved hydrological techniques and technologies in Southern Africa. Within these areas training focussed on:

- Learning and consolidating hydrological skills,
- Training in the use of standard GIS software, and
- Training in the use of specialist hydrological software for drought analysis and water resources management.

Three training workshops were held, each linking to one of the hydrological themes and one of the products of the technology transfer aspects of the programme. In this way staff attending a workshop gained an introduction to the skills in one of the key areas, training in technology appropriate to that area (e.g. GIS) and training on technology developed within that area. Technology transfer involved the development and dissemination of products such as the spatial data CD-ROM (Chapter 6), the ARIDA software (Section 3.3) and the GIS water resources software (Section 4.4). The two areas were strongly linked, with the products used intensively within the workshops for training in the application of the hydrological skills learnt.

Hydrological skills training
Training on hydrological skills central to the three areas covered in the second phase of the FRIEND project was provided through three workshops, on such topics as flow duration curve and low flow frequency curves, drought analysis techniques and modelling methods for flow estimation. All are essential to water resources management.

Computer skills training
The rate at which Southern African institutions keep step with changes in technology varies dramatically. The FRIEND workshops covered the basics of some important new technologies, providing training in hydrological databases, GIS, drought analysis and IWRM, alongside training in hydrological skills. The approach taken was to demonstrate the ideas behind each of these technologies and the benefits of using them, so providing skills which could be applied to any system, rather than familiarity with any single technology or piece of software.

7.2 Technology transfer

Technology transfer is an efficient means of providing appropriate technologies, such as specialised software for water resources management based upon knowledge and work previously developed elsewhere, to institutions within the Southern Africa region. Three major products within FRIEND were provided in this way: the Spatial Data CD-ROM, the ARIDA drought analysis and monitoring software, and the LF2000-SA water resources software. Significant effort was spent ensuring the products were appropriate to the hydrological conditions and the needs of the potential users, and making sure the systems could be used effectively within the institutions in the region. Technology transfer has allowed very complex systems to be developed at a fraction of the cost of bespoke systems created for each country, helping Southern African institutions to keep pace with developed nations in the field of water resources management. More emphasis on following up the work done – integrating the systems within the work programmes of the institutions in Southern Africa – is required to encourage the maximum use of, and benefits from, these systems. In addition there is a need for maintenance of the systems for long-term use which should be addressed in future.

7.3 Studentship

Under a studentship at the Institute for Water Research at Rhodes University in South Africa, a different approach was taken to the same general objectives for capacity building. This was in the form of a post-graduate studentship, with research being undertaken within the region on regional water resources and river flow modelling. This provided much more intensive training to a much higher level than was possible under other components of the programme. The output of this research is reported in Chapter 2. Besides the training of a researcher to a high level, the results represent a significant step forward in capabilities for water resources assessment in Southern Africa.

7.4 Training workshops

The three training workshops each tackled a different research area, providing training on completed FRIEND work. Delegates were invited from the national hydrological agencies (NHAs) of every Southern African country. Some NHAs sent additional delegates, and some non-governmental organisations within the region sent additional delegates at their own expense. Delegates ranged from those who had good knowledge of various hydrological techniques to those who had little previous experience. Some of the delegates had attended earlier FRIEND and SADC-HYCOS workshops where they had used CEH's HYDATA hydrological database software (Institute of Hydrology, 1999; CEH, 2001); this includes some analysis routines and is used as the national hydrological database in the majority of Southern African countries.

Workshops provide a useful training situation, allowing the full attention of delegates away from their usual place of work for sufficient time to cover complex subjects in detail, both in theory and application. In addition delegates gain experience through discussion of issues with staff from other regional institutions, thereby developing international co-operation. Work was planned so that delegates of all levels could gain as much as possible from each workshop.

The main aim of the workshops was to give the delegates as much practical experience of the various techniques and hands-on experience of the different software systems as possible. The workshops were all based around sets of prepared exercises covering the main aspects of the training. These included individual exercises (both written and computer-based), syndicate group exercises and group projects. Sessions typically comprised a short presentation on the topic under consideration, interspersed with group discussions, and manual and computer exercises. The delegates had ample opportunity to ask supplementary questions and discuss particular problems. In addition, a proportion of each workshop was given over to presentations from the delegates on topics relevant to the workshop theme, and their countries' current approach. A field trip was held for one day of each workshop, allowing users to gain an understanding of the water issues within the host country, and the local approaches to water resources management. At each workshop delegates were provided with a complete set of course notes and copies of the prepared exercises.

As part of a review of FRIEND activities, the delegates were asked to complete a questionnaire after each workshop. There were many opinions and little consensus on most topics, as a result of the range of backgrounds of the delegates. However, most commented that they found the computer exercises and group projects worthwhile. Most delegates also welcomed the insight provided by the opportunity to share low flow, drought, and water resources management experiences with counterparts from different countries.

Low flows workshop, Lilongwe, Malawi

The workshop was held in Lilongwe in January 2001. It was attended by 17 delegates from 11 countries. Mauritius participated in FRIEND for the first time at this workshop. Two representatives from the Lesotho Highlands Development Authority also attended.

The major part of the workshop was concerned with methods for calculating low flow statistics at gauged sites and a framework for estimating low flow statistics at ungauged sites. The principal methods covered for gauged sites included flow duration curves, low flow frequency curves and baseflow index. For ungauged sites, correlation and spot current metering techniques were introduced, but a regional method could only be covered at a preliminary level. For many of the topics, the delegates had an opportunity to repeat the manual exercises using the analysis options within HYDATA and data from the Southern Africa FRIEND time series database, developed under Phase I.

During the workshop, the Spatial Data CD-ROM and the accompanying report (Fry *et al*., 2001) were released to disseminate the spatial data to the national hydrological agencies and other organisations in the participating countries (Chapter 6). Training in installing the software and manipulating the data was provided to develop GIS skills at an introductory level. Delegates who already had advanced skills were able to examine the data sets in more depth.

Drought analysis workshop, Gaborone, Botswana

The drought analysis workshop was held at the Training Centre of the Department of Water Affairs in Gaborone in November 2001. It was attended by 17 delegates from 11 countries. A representative from the Lesotho Highlands Development Authority and two representatives of the Zimbabwe National Water Authority also attended.

The workshop focussed on the application of the four methods of drought assessment provided in the ARIDA software (Chapter 3). The computer exercises provided an opportunity for delegates to get hands-on experience of using the software. In addition to the ARIDA tutorial database provided for the exercises, the Southern Africa FRIEND time series database was available, giving the delegates the chance to apply the software using all the FRIEND data available for their particular country. The workshop project simulated temporal changes in data availability to simulate the situation of a drought unfolding. Feedback and suggestions for improvements were collected for use in software upgrades.

Group discussions focussed on various aspects of drought impact and management. These discussions were animated and highlighted that participants' understanding and perception of droughts varied considerably, primarily as a consequence of different hydro-meteorological conditions in different countries and because of different priorities when considering impacts. The insight that the discussions provided enabled the workshop training to be placed within the context of real-world issues pertaining to drought impacts and management in the SADC region (Houghton-Carr *et al.*, 2002). The presentations and discussions highlighted that:

- The SADC region is prone to drought; in some countries (e.g. Namibia) drought is the norm, not the exception.
- Reducing the region's long-term vulnerability to drought requires drought risk to be properly accounted for in water resources planning.
- Demand management measures are difficult to introduce once a drought has started. Consequently, they must be practised by all sectors all the time. Water pricing may be a way of limiting consumption.
- The resilience of water resources systems to drought can be improved, and the impacts of drought can be mitigated, through effective, timely and efficient management.
- Improved drought management requires: improved monitoring of the status of water resource systems (i.e., rainfall, river flows, reservoir levels, groundwater levels, water delivery systems, urban supplies, etc.); effective databases to store and access information (e.g. HYDATA); and analysis tools that can inform decision-making (e.g. ARIDA).
- Institutional strengthening and improved legislative measures are needed in many of the countries of the region to improve drought planning and management.
- For international rivers, co-operative agreements on the sharing of water resources between the riparian countries are needed before effective drought planning can be initiated.
- Research is needed to improve long-term drought forecasting and early-warning systems, to improve analysis tools for droughts and to investigate alternative water supply options.
- There is a need to identify communities and sectors of society most at risk from drought and ensure that mitigation measures target their requirements.
- Environmental water requirements are often ignored in a drought. There is a need to incorporate them in drought management plans.

Water resources workshop, Pretoria, South Africa

The workshop was held at the Roodeplaat Dam Training Centre of the Department of Water Affairs and Forestry near Pretoria in February 2003. It was attended by 17 delegates from 11 countries. A representative from the Lesotho Highlands Development Authority also attended.

The main aim was to give the delegates a sound background in the following, all within the context of Integrated Water Resources Management:

- The need for accurate water resources assessment;
- The need for hydrological data within the assessment procedure;

- Knowledge of the techniques used to produce low flow statistics from gauging station data for this purpose;
- An introduction to the concepts and realities of modelling flows at ungauged sites;
- How to produce catchment characteristics from GIS systems for input into such models;
- Water resources issues within Southern Africa;
- Modelling water resources for the future using climate change scenarios using the GWAVA system (see Chapter 5).

The major part of the work was taken up by the GIS water resources software (LF2000-SA), discussed in detail in Chapter 4. Delegates were given an understanding of the underlying principles and of the practicalities of using the software. As much practical use as possible of the software tool using real hydrological data was included. Throughout the workshop, water resources concepts were introduced, stressing the practical applications within delegates' countries, and focussing on what the national hydrological agencies could input to water resources management procedures. A field trip to the DWAF offices to view the flow and flood monitoring systems in place demonstrated the type of advanced facility that is possible within the region.

7.5 Other training activities

A number of staff from hydrological institutions within Southern African countries were provided with in-situ training over the course of the programme. During the testing phase of the ARIDA software, four staff from the Department of Water Affairs in Gaborone and the University of Botswana were trained in the theory and use of the software, as were five staff from the Department of Water Resources in Tanzania and the University of Dar es Salaam. During the testing of the LF2000-SA software in Malawi, three staff were given thorough training in the use of the software and a further three were provided with demonstrations of the functionality available within the system. One member of staff from Malawi spent three weeks at CEH working on the development of the underlying methodology for the software, and gained a deeper understanding of all aspects of the development work. In Swaziland two staff were trained on the theoretical background and use of the GWAVA modelling system, as well as contributing to the data collection and being involved in setting up, running and calibrating the model.

The SPATSIM (Spatial and time series information modelling) software was another area in which capacity building was carried out. SPATSIM is a software package, designed as a database, data analysis and modelling system, specifically for hydrological and water resource applications (see Section 2.2). It was developed at the Institute for Water Research, Rhodes University (Hughes, 2002). Part of the development of the system was supported by the Water Research Commission of South Africa to address some of the database and modelling requirements of the ecological reserve component (determining environmental flow requirements of rivers) of the South African water law. Training of the staff of the Department of Water Affairs and Forestry (DWAF), as well as some of the key DWAF service providers began during 2002 and was continued into 2003. Additional training of interested people within the SADC region was included in the FRIEND programme, and included individuals from Zambia, Tanzania, Zimbabwe and Swaziland.

7.6 Summary

Under Phase II of the Southern Africa FRIEND project, 51 people have been trained in three regional workshops, one intensive two-year studentship has been provided, and 18 people have benefited from in-situ software and other training. Each of the three workshops covered one of the areas on which FRIEND has focussed: low flows, droughts and water resources. Staff from the regional hydrological institutions were provided not only with hydrological skills and training in these areas, but with training on relevant technologies, on the research carried out under the FRIEND programme, and in the resulting software and systems developed from the research. This has provided a continuity of learning within the institutions, an understanding of the work that FRIEND has accomplished and of how technologies could change water resources management in Southern Africa in the future.

Integration of the capacity building and technology transfer elements of the FRIEND programme has allowed for cutting-edge hydrological methods and software systems to be developed and for these systems to be disseminated directly to users within the hydrological institutions of the region with training on their use and on the hydrological ideas behind them. This integrated approach is seen to be very effective, involving staff from regional institutions with the work being done and increasing the usefulness, and usage, of the end products. It is recommended that future training programmes follow a similar approach. Efforts to encourage their effective uptake in regional institutions, with more detailed implementation, training and support programmes, would be beneficial and would further increase the value of the systems produced.

8 Assessment and outlook

J.R. Meigh, M.J. Fry, H.A. Houghton-Carr and D.A. Hughes

8.1 Achievements of the project

The key achievements of the second phase of the Southern Africa FRIEND project can be summarised briefly as:

- Several improved tools for water resources assessment and management have been developed, tested and implemented in the region. The application of the WR90 approach in Zambia and Botswana has shown the way towards improved assessment of the resource, and is a step towards the extension of this technique to the entire region (Chapter 2). Such assessments are an essential underpinning to all water resources planning. Drought assessment and management abilities have been enhanced through the ARIDA software, using approaches that are appropriate to the particular hydrological characteristics of Southern Africa (Chapter 3). Drought management is particularly significant in relation to the frequent occurrence and potentially massive impacts (especially for the poor) of drought in the region. Further development of abilities to manage water resources, especially low flows and abstractions was made through the GIS water resources software (LF2000-SA) (Chapter 4). This work has provided an advanced and powerful tool, which is also very accessible and easy to apply. So far, it has been implemented only in Malawi, but it has great potential for further application across the region. Finally, considering the huge potential importance of climate change due to global warming, work in Swaziland has shown how rapid assessments of the water resources impacts can be made in an integrated way (Chapter 5).

- The project has continued to support region-wide databases and data sharing in Southern Africa, which is vital in a region with many transboundary rivers. The work concentrated on spatial data that are relevant to water resources, and on supporting and enhancing the GIS skills that are needed to make effective use of these data (Chapter 6).

- Transfer of technology and capacity building were important components of all aspects of the project, with the involvement and participation of water resources professionals in the region being integral to the activities listed above. Support for a post-graduate student at a university in the region led to the application of the WR90 water resources assessment approach in Zambia (Chapter 2). Specific training activities were also carried out through regional workshops to disseminate the work done in each component (Chapter 7).

- The project has furthered the ongoing collaboration and co-operation between the hydrological agencies and other organisations in the region on water resources issues, helping to build trust through working together on capacity building exercises, and through sharing data, ideas and problems.

In terms of the main hydrological issues in the region and the overall objectives of the project, as discussed in Chapter 1, it can be seen that work has concentrated on developing practical tools and strengthening institutional capacity to manage water effectively in the face of scarcity and high levels of variability of the resource. The new tools and techniques have been developed with the particular needs of the region in mind through a process which includes direct feedback from the users, to ensure that they are adapted to their needs. The FRIEND project is also a significant aspect of the ongoing process of international co-operation, which it is hoped will eventually lead to improved water sharing across the region, a very significant need in a part of the world where a high proportion of the resources are held in common between several countries.

It is worthwhile to view the achievements of the project in terms of their contribution to broader international development objectives. It is widely recognised that the effective management of water resources is essential to sustain the livelihoods and well-being of the population and to alleviate poverty. This is set out in the UK Government's White Paper *Eliminating World Poverty: A challenge for the 21st century* (DFID, 1997), and has been supported by many international meetings and agencies. By helping to improve the assessment and management of water resources in Southern Africa, the FRIEND programme will, in the long term, bring benefits to the poor. Effective and sustainable management is an essential prerequisite to the provision of access to all for domestic use, reduction of water-borne diseases, and improved livelihood options through the use of water for food production and small-scale industrial activities (Figure 8.1).

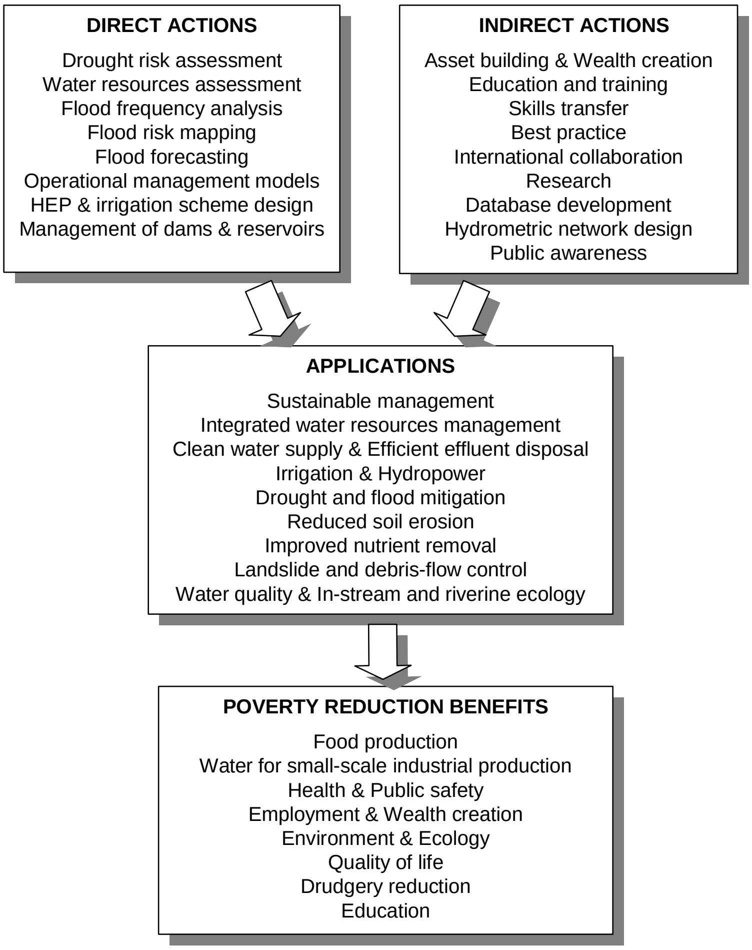

Figure 8.1 *FRIEND links to poverty reduction and sustainable development*

8.2 Priorities for future work

Despite the achievements of the project, there is still much to be done. The Southern African region remains one in which institutional capacity and the skills base need to be continually improved in order to contribute to improved water resources planning and management, with their eventual impacts on poverty and the people's livelihoods.

Within the specific context of Southern Africa FRIEND, it is proposed that future work should concentrate on three areas, as follows:

An enhanced capacity building programme

Research results are only useful if they are available to those who will best use them, at the time they need them, in a format they can use, and with findings that are comprehensible and adaptable to local circumstances. Future capacity building activities should place greater emphasis on the dissemination of training to ensure maximum potential impact in terms of numbers of people reached. The focus should be in four key areas:

- *Self-help training.* This is a relatively simple and inexpensive way of keeping practitioners' skills up-to-date. Staff can extend their knowledge and expertise whilst spreading their study over weeks or months so that it does not interfere with their normal day-to-day activities. Self-help training material should be developed and released via CD-ROM, the internet and through courses at local universities to make it available to a wider audience.

- *Training for trainers.* Regional training workshops should concentrate on educating those responsible for teaching hydrology, focussing on new methods for hydrological design and water resources assessment. Participants would include established university and technical college lecturers and senior staff within operational hydrological agencies who are responsible for staff development. This would help to support the training of junior staff and to propagate knowledge through organisations.
- *Curriculum development.* International co-operation between water resources institutes and academic staff would help to redefine and improve the hydrology modules of undergraduate and post-graduate courses in the region. Several universities have expressed a need for such support.
- *Support to post-graduate studies.* Continued assistance to students undertaking post-graduate research on relevant topics at universities in the region is needed.

Region-wide surface water assessment

Lack of reliable information on the availability of water resources remains a major problem in Southern Africa. The current project (Chapter 2) has made significant advances in developing improved methods of water resources assessment, and this work could be very effectively continued and enhanced through involvement in the major PCN 14 project which has been identified by the Southern African Development Community. PCN 14 aims to improve the ability of the member states to make water resource assessments that are environmentally sustainable and based on broad strategic water resource planning, using information and approaches that are reliable and mutually accepted within the region. By supplementing this initiative, the FRIEND programme would be extremely efficient in generating further beneficial outcomes. Work should focus on the following areas, which have been identified as being of high importance:

- Improving the capability to assess water resources for ungauged catchments throughout the region by developing an appropriate and consistent model parameter estimation scheme and parameter regionalisation procedures through the use of GIS techniques.
- Enhancing temporal assessment of water resource availability by disaggregation of the monthly flow series derived under PCN14 to a daily time step. This is relevant to such issues as the assessment of run-of river water supply potential, assessment of spate irrigation potential, design of micro-hydropower schemes, and for setting environmental flow requirements.
- Improving technical and institutional capacity within SADC government agencies to enable them to develop integrated water resource management plans and provide a framework for resolution of transboundary water disputes.

The PCN14 project is a major, locally-driven, regional initiative, and its methods and results will become a standard component of water resources management in the region. This means that the enhancements discussed here would also be very widely disseminated and would become standard tools used in water resources management across the region.

Integrated water resources management tool for Southern Africa

The current project (Chapter 4) has provided an advanced and powerful tool, which is also very accessible and easy to apply. This is the LowFlows 2000 Southern Africa software (LF2000-SA). So far, it has been implemented in Malawi, but it has great potential for further application across the region. The software integrates surface water resources assessments with water use, allowing the assessment of the impacts of existing and planned abstractions and other alterations to the hydrological regime in both gauged and ungauged locations. This provides an effective tool to support decision-making. Extension of the software to make it applicable in other countries in the region would be valuable, and could be achieved through the use of digital elevation models and the outputs from other water resources assessment work (such as that under PCN 14, discussed above), and the incorporation of a number of additional facilities.

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