Southern African "FRIEND" - The Application of Rainfall-Runoff Models in the SADC Region

DA Hughes

Report to the Water Research Commission
by the
Institute for Water Research
Rhodes University

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SOUTHERN AFRICAN "FRIEND" - THE APPLICATION OF RAINFALL-RUNOFF MODELS IN THE SADC REGION

Final Report to the Water Research Commission on the project:

"Flow Regimes from International Experimental and Network Data (FRIEND) for Southern Africa"

by the

Institute for Water Research
Rhodes University
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DA Hughes
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EXECUTIVE SUMMARY

Objectives and research programme

The Southern African FRIEND project is a contribution to the international FRIEND (Flow Regimes from International Experimental and Network Data) programme which is part of the UNESCO Fourth International Hydrological Programme, in which the central objective is hydrology and water resources for sustainable development. The main research participants in the Southern African FRIEND project are the University of Dar Es Salaam (Tanzania), the Institute for Hydrology (UK), the National Hydrological Services of the SADC member countries and the Institute for Water Research (IWR), Rhodes University (South Africa).

Given the long history of involvement of the IWR in the development and application of rainfall-runoff models, it was inevitable that when the opportunity arose to contribute to the Southern African FRIEND project, the field of research selected would be related to the use of such techniques in the region. While this topic has been quite extensively covered and models frequently used in some parts of the region, notably South Africa, there are many countries of the region where the potential of time-series modelling to solving water resource related problems has not been adequately addressed. The IWR contribution to the Southern African FRIEND project was aimed at improving the experience base of the use of models in the region, identifying some of the problems associated with their application and building capacity in the field of hydrological modelling within the region. This first phase of the project (3 years from 1994 to 1996) has been relatively short and the research programme necessarily limited to achievable objectives. The overall aim was to :

> *'develop procedures and guidelines for the application of appropriate deterministic catchment models within the southern African region for a variety of water resource assessment purposes'.*

Specific objectives were identified as :

- Collate information on the previous application of models in the region.
- Select appropriate daily and monthly time-step models for testing.
- Compile appropriate test data sets of rainfall, runoff, evaporation and physical characteristics for catchments throughout the region.
- Determine the general applicability of the selected models to the different sub-regions of southern Africa through model calibration and identify any model, or data availability, related shortcomings.
- Carry out specific tests of the applicability of the models to simulating the impacts of land-use change on flow regimes.
- Prepare guidelines for the estimation of model parameter values at sites (gauged and ungauged) within southern Africa.

- Package the models and associated data preparation and analysis procedures in a software form suitable for use within the region.

- Provide training to build capacity in the understanding and use of rainfall-runoff models in southern Africa.

There is a large body of literature on the application of models within South Africa. Some of this is contained within published scientific papers, some in research reports and some in consultancy type reports. A large proportion of this information is readily available once the publication source (for scientific papers and reports) or client (for consultancy reports) is known. Information on the application of models elsewhere in the region is less readily accessible and while many examples are known to exist, access to the results of the studies appears to be more difficult.

The monthly time step Pitman Model (Pitman, 1976; Pitman and Kakebeeke, 1991) has been applied extensively within South Africa and has also been applied in Swaziland, Lesotho, Botswana, Zambia and Namibia. It is accessible as part of several software packages that have been designed with efficient application in mind and was therefore the logical choice for the coarser time-step model to be used. During recent years, the IWR has been developing a daily time-step (or less) model that attempts to reach a compromise solution between complex, fully distributed, physically-based models and simplified lumped approaches. The result is a semi-distributed model (VTI model - Hughes and Sami, 1994) that contains representations of the processes thought to prevail in catchments within the southern African region (semi-arid to humid). It also includes routines to simulate surface-ground water interactions as well as various forms of water abstractions and has been applied successfully to a number of South African catchments.

The compilation of the test data sets relied heavily on cooperation with the main hydrometric agencies within the partner countries and experienced individuals within those agencies to identify those catchments with the most reliable data and complete information that could be made available for modelling purposes.

The main part of the research programme involved setting up, calibrating and verifying the two models on the test data sets. The intention was always to apply the monthly model to as large and representative a number of catchments within the region as possible. Data availability constraints were anticipated as being more likely to restrict the number of catchments than the time and manpower resources available to the project. With respect to the daily model, which has more stringent data requirements and demands greater resources to apply, data availability and manpower resource constraints were equally restrictive and the model could only be applied to a sub-set of those used for monthly model testing. The assessment of the applicability of the models had to consider factors relating to data availability, ease or difficulty of parameter estimation and calibration, calibration and verification results, as well as the appropriateness of the models conceptual structure to the real hydrological processes prevailing within different parts of the region. As the impacts of land-use change on hydrology and catchment water yields were perceived to be important issues within the region, the research programme was designed to carry out some limited assessments of the application of the two models to simulating the impacts.

The models are already packaged within the HYMAS software system which allows several models to be operated within a common suite of data preparation and analysis programs that are not only designed for simulated data, but also for carrying out a variety of hydrological and water resource assessments using observed data. Current research programmes within the IWR are extending the capabilities of this software.

With respect to training and capacity building, part of the research programme was designed to offer opportunities for collaborative work with interested individuals or organisations within the region, as well as more formal short-term training courses in the application of the techniques being used (the models and application software).

The modelling system (HYMAS) and the models

The report provides some background to the HYMAS modelling system and briefly describes the facilities that are available. They are designed to allow several models to be operated within a common software environment that includes most of the facilities to establish modelling projects, prepare data files for parameter and time series information, run the models and examine the results in a large variety of different ways. A more complete description of HYMAS and guidelines for its use are contained within the user manual, which is distributed with the software or available from the Institute for Water Research at Rhodes University. The models that were used in the project are also briefly described and these are the Pitman monthly model, the VTI daily model, the reservoir simulation models (daily and monthly) and the Patching model.

The FRIEND database

The report outlines the background to the development of the Southern African FRIEND daily flow time series database and provides some further information about the South African stations (290 in total) that have been included. Several graphs are used to compare the characteristics of the included stations with those of the SA flow database as a whole and these illustrate that, as far as possible, the stations on the FRIEND database are reasonably representative. Some brief remarks are also included about the nature of the data that were made available to the project team, while more specific comments are made within the appendices for each individual country.

Summary and discussion of results

The main results are presented in some detail in 11 appendices, one for each country and an additional one for the simulations of the impacts of land use change. The results summary and discussion chapter are designed to provide a succinct overview of the main results obtained from the application of the two main models (Pitman and VTI). With respect to the Pitman model the results can be further condensed into the following points :

- The model was simple to apply and more successful in the wetter parts of the region when the data provided were adequate. This is partly a result of the fact that there is more 'information' contained within the observed flow data which can be used to guide the calibration process.

- The changes that were made to the model during the project were mainly carried out to improve the model's applicability to semi-arid areas and these were moderately successful. However, there are still some deficiencies in the model formulation that make it difficult to apply in arid and semi-arid areas and these are exacerbated by the limitations of the input data (mainly rainfall) that are normally available for such areas.

- The project has highlighted a well known and understood (and obvious) problem with the application of any hydrological model. This problem relates to the quality and resolution of the input data and it is clear that without adequate rainfall data, either the simulation results can be expected to be poor, or even if the results are adequate they may be achieved for the wrong reason which suggests that the calibrated parameter set may not be transferable to other periods or catchments.

- While it was originally intended to attempt some regionalisation of model parameters, the deficiencies in either the rainfall data, or the number of catchments that could be used meant that such a study would have produced inconclusive results. However, the potential for future regionalisation studies, similar to those that were carried out for South Africa and form part of the WR90 reports, is discussed in this report. It was concluded that, in at least some of the countries, the potential would appear to be quite good, given that more catchments can be included.

The main points relating to the application of the VTI model are :

- This model is inevitably more difficult to apply, partly because it has a far greater parameter space and there was rarely sufficient information on catchment physical characteristics to quantify some of the parameters *a priori*.

- In general terms it was found that if the Pitman model could be calibrated with reasonable success, then so could the VTI model, while the reverse was also found to be the case. This is an indication that one of the main problems lies with the quality, or representativeness, of the input data - a problem common to the application of any model. Results statistics based on monthly volumes of flow are usually very similar for the two models, with the VTI model sometimes demonstrating slight improvements.

- The problems with applying the model to semi-arid areas are similar to those of using the Pitman model. Although the VTI model has a channel transmission loss function, it is very empirical and difficult to calibrate when the processes involved are not well understood and there is no real information available about observed losses.

- A lack of information about levels of water abstraction and catchment land use changes presented a problem for both models but is more relevant to the daily model. There were some catchments where the observed flow regimes suggested that such influences were present, but without more data could not be quantified and were therefore difficult to properly account for in the calibration procedures.

- The ground water functions of the VTI model are very important with respect to simulating the low flow regimes of perennial rivers, but there is frequently very little information about the properties of the aquifers underlying the catchments. While this component of the VTI model is relatively simple to calibrate, there is no guarantee that the parameter values used to simulate the observed response are representative of the true aquifer properties.

The reservoir simulation models were applied in very few cases and only when a large dam was present within a catchment which could not be simulated satisfactorily by the internal small dam routines included in both the Pitman and VTI models. The reservoir models are relatively simple water balance routines and can be successfully applied given that the inflows and abstraction patterns can be adequately quantified. The monthly reservoir model was used with one of the Namibian catchments to assess the impact on estimations of yield of using inflows simulated by different models compared with observed inflows.

The Patching model represents a very simple tool to extrapolate from daily flows gauged at a site to other periods at the same site, or to ungauged sites using regional flow duration curves. The model was applied in several areas during this project and the results were very encouraging. Further developments in the methods of applying this model are continuing within the Institute for Water Research.

Final conclusions and recommendations

The final conclusions further emphasise that, although the models can be considered generally applicable within the region, there are limitations with respect to both the time series input and the physical catchment characteristic data that appear to be available. The amount and quality of such data represented the major limitations to testing the models and determining guidelines for their future application. It is likely that more data are available than were used within the project and that for more localised and focused modelling exercises, better data could be collected and used. However, the project has highlighted the difficulties of accessing data that is suitable for rainfall-runoff model applications within the region and this is an issue that should be addressed in the future.

The report makes some recommendations for training in the use of time series data and models and concludes that a thorough understanding of time series data is a prerequisite to learning how to apply models and that the Pitman model represents an appropriate example for teaching the operation of rainfall-runoff models. The use of daily models, such as the VTI model, is more difficult and the training requirements consequently far greater. It is suggested that a sound background in physical hydrology is a prerequisite and that the model structure needs to be understood quite well before successful calibrations can be achieved.

The report also makes some recommendations about future database development and suggests that there is a need to expand the culture of information sharing within the region. A first step in developing an improved regional database on information relevant to rainfall-runoff modelling could be to catalogue, in detail, what is available, who it is available from and what the conditions and costs of access are. This would have to be a cooperative effort by the state and none-state agencies of all the countries in the region, as well as some international agencies (WMO, UNESCO and FAO for example) and would apply to both time series and spatial data. The positive response that water resource engineers and managers in South Africa have had to the production of the WR90 (1994) reports, the regionalised data and model application guidelines contained within them, could be a lesson for the rest of the region. This report has indicated that there is the potential to extend this approach to many parts of the rest of the region and it is therefore recommended that such studies be carried out.

1. INTRODUCTION

The Southern Africa FRIEND (Flow Regimes from International Experimental and Network Data) project originates from the world wide FRIEND initiative that is part of UNESCO IHP IV (fourth International Hydrological Programme). It involves all the countries of the SADC (Southern Africa Development Community) and the UK, through the Institute of Hydrology and their central involvement in FRIEND projects of other regions.

The Institute for Water Research at Rhodes University and its predecessor, the Hydrological Research Unit, have been involved in research in the field of rainfall-runoff modelling since 1974. Much of the early work concentrated on the comparative application of continuous models to simulating the runoff response to rainfall in small, semi-arid catchments of the Eastern Cape Province of South Africa (Roberts, 1979; Görgens, 1983). Later work expanded into modelling the hydrology of the humid, mountain catchments of the southern Cape (Hughes and Görgens, 1981, Hughes, 1982 and 1985), the testing and development of isolated-event flood models (Hughes, 1984 and 1989; Hughes and Beater, 1989) and the application of stochastic modelling approaches to semi-arid areas (Herald, 1989). The developments in, and increasing use of, personal computers during the 1980s and the recognition that no single modelling approach can satisfy a wide range of hydrological problems led the IWR to promote a more integrated approach to catchment modelling. This resulted in the development of a Hydrological modelling software package (HYMAS), designed for DOS based PCs and incorporating many of the pre- and post-processing routines that are essential to the efficient application of hydrological time-series models (Hughes, et al., 1993). The models that were included in the early version of the system varied from some standard approaches, widely used in South Africa, to others developed and tested within the IWR. This system has now been extended to include additional models and data analysis routines (Smakhtin, et al., 1995, for example).

It was inevitable, therefore, that when the opportunity arose for the IWR to contribute to the Southern African FRIEND project, the field of research selected would be related to the application of rainfall-runoff models in the region. While this topic has been quite extensively covered and models frequently used in some parts of the region, notably South Africa, there are many countries of the region where the potential of time-series modelling to solving water resource related problems has not been adequately addressed. Some of the reasons for this may be related to the difficulties associated with accessing the required information to set up and operate models, some to the lack of human resource development in the field of model application and some to the lack of access to modelling software in the past. The positive experience of the use of models in the South African context and their clearly demonstrated value for water resource planning and decision making, suggests that there is a great potential for similar approaches to be applied more extensively in the rest of Southern Africa, where many of the water resource problems are similar. The IWR contribution to the Southern African FRIEND project is aimed at improving the experience base of the use of models in the region, identifying some of the problems associated with their application and building capacity in the field of hydrological modelling within the region. This first phase of the project (3 years from 1994 to 1996) has been relatively short and the research programme necessarily limited to achievable objectives. However, it is hoped that the initiative will continue into the future and gain momentum as more hydrologists within the region perceive the benefits of modelling approaches and become adept in their application.

1.1 Aims and objectives.

The overall aim of the rainfall-runoff modelling component of the Southern African FRIEND project was therefore to

> *'develop procedures and guidelines for the application of appropriate deterministic catchments models within the southern African region for a variety of water resource assessment purposes'.*

The following more specific objectives were identified :

- Collate information on the previous application of models in the region.
- Select appropriate daily and monthly time-step models for testing.
- Compile appropriate test data sets of rainfall, runoff, evaporation and physical characteristics for catchments throughout the region.
- Determine the general applicability of the selected models to the different sub-regions of southern Africa through model calibration and identify any model, or data availability, related shortcomings.
- Carry out specific tests of the applicability of the models to simulating the impacts of land-use change on flow regimes.
- Prepare guidelines for the estimation of model parameter values at sites (gauged and ungauged) within southern Africa.
- Package the models and associated data preparation and analysis procedures in a software form suitable for use within the region.
- Provide training to build capacity in the understanding and use of rainfall-runoff models in southern Africa.

1.2 Research Programme.

The constraints of time and staff resources available to the project meant that the following limitations were placed on the research programme :

- Only conceptual/deterministic type models that the research team had immediate access to and were reasonably familiar with have been applied. No statistical, stochastic or system type models have been used. The project was never meant as a comprehensive comparative assessment of a wide range of models.

- Only existing models, were to be applied and it was never the intention to develop new models. However, it was accepted that limited improvements to existing models may be carried out where the need for this was clearly identified. The main area of software development was to be associated with making the models more accessible and easier to operate across a range of applications.

- The project team had to rely on the various countries hydrometric agencies for provision of information, or data, on the characteristics of the catchments, observed time series of rainfall, runoff and evaporation and patterns of water use. No resources were available to the project team to allow them to visit individual catchments and supplement available information with further surveys or observations.

- Similarly, the project team was not in a position to check the reliability and accuracy of the time series data provided.

The activities that were planned at the start of the project and designed to fulfil the objectives are outlined below :

- There is a large body of literature on the application of models within South Africa. Some of this is contained within published scientific papers, some in research reports and some in consultancy type reports. A large proportion of this information is readily available once the publication source (for scientific papers and reports) or client (for consultancy reports) is known. Within the current report the main trends in the application of hydrological models within South Africa will be summarised. Information on the application of models elsewhere in the region is less readily accessible to the project team. While many examples are known to exist, access to the results of the studies appears to be more difficult (for example, consultancy reports are often confidential and reports compiled for state agencies are frequently not publicised).

- The constraints on the selection of appropriate models for testing have already been referred to. There is such a large number of models that could be selected, it would be an enormous task simply to decide which are the most appropriate without a much greater experience base. The monthly time step Pitman Model (Pitman, 1976; Pitman and Kakebeeke, 1991) has been applied extensively within South Africa and has also been applied in Swaziland, Lesotho, Botswana, Zambia and Namibia. It is accessible as part of several software packages that have been designed with efficient application in mind. It was therefore the logical choice for the coarser time-step model to be used. During recent years, the IWR has been developing a daily time-step (or less) model that attempts to reach a compromise solution between complex, fully distributed, physically-based models and simplified lumped approaches. The result is a semi-distributed model (VTI model - Hughes and Sami, 1994) that contains representations of the processes thought to prevail in catchments within the southern African region (semi-arid to humid). It also includes routines to simulate surface-ground water interactions as well as various forms of water abstractions and has been applied successfully to a number of South African catchments. While the selection of the VTI model was less obvious than the Pitman model, the project team were familiar with its structure and application and the software required was immediately available. It was also considered that the results of attempts to apply any daily model of this type (semi-distributed, quasi physically-based) within the region would be relevant to other similar models (such as the ACRU model of Schulze, 1995).

- It was anticipated that the compilation of the test data sets would rely very heavily on cooperation with the main hydrometric agencies within the partner countries and experienced individuals within those agencies to identify those catchments with the most reliable data and complete information that could be made available for modelling purposes. Part of the research programme would necessarily involve developing software to translate a variety of different data storage formats into a common one suitable for input to the models. This task was facilitated somewhat by the adoption of HYDATA (hydrological database software provided by the Institute of Hydrology, UK) within the region as a common data storage facility.

- The main part of the research programme involved setting up, calibrating and verifying the two models on the test data sets. The intention was always to apply the monthly model to as large and representative a number of catchments within the region as possible. Data availability constraints were anticipated as being more likely to restrict the number of catchments than the time and manpower resources available to the project. With respect to the daily model, which has more stringent data requirements and demands greater resources to apply, data availability and manpower resource constraints were equally restrictive and the model could only be applied to a sub-set of those used for monthly model testing. The assessment of the applicability of the models had to consider factors relating to data availability, ease or difficulty of parameter estimation and calibration, calibration and verification results, as well as the appropriateness of the models conceptual structure to the real hydrological processes prevailing within different parts of the region.

- As the impacts of land-use change on hydrology and catchment water yields were perceived to be important issues within the region, the research programme was designed to carry out some limited assessments of the application of the two models to simulating the impacts. This was considered to be largely a matter of assessing the extent to which changes to the models parameter values can be considered to reflect changes in the catchment characteristics associated with the type of land-use changes that typically occur in the region. To carry out such tests it is necessary to have access to reasonably detailed information on the nature of the land-use changes, as well as their impacts on the flow regime.

- The recently published updates of the Water Resources of South Africa volumes by the Water Research Commission (WR90, 1994) contain guidelines for the application of the Pitman model to the whole of South Africa, Lesotho and Swaziland. While this project does not have access to the resources to carry out a similar study for the remainder of southern Africa, the results of the Pitman model simulations will be integrated, as far as possible, with the existing regionalisation of parameter values. This approach should provide a basis for the future northward extension of the guidelines that are available for the south of the region. The situation is more complex for the daily model and the approach to recommending guidelines for the use of the VTI model will be different.

- The models are already packaged within the HYMAS software system. This allows several models to be operated within a common suite of data preparation and analysis programs that are not only designed for simulated data, but also for carrying out a variety of hydrological and water resource assessments using observed data. Current research programmes within the IWR are extending the capabilities of this software.

- With respect to training and capacity building, part of the research programme has been designed to offer opportunities for collaborative work with interested individuals or organisations within the region, as well as more formal short-term training courses in the application of the techniques being used (the models and application software).

The introduction to this report provides some of the background to the study on rainfall-runoff modelling that forms one component of the initial Southern African FRIEND project. It has also highlighted the objectives of the project and some of the constraints that have contributed to the design of the programme of research work carried out in order to meet the objectives.

1.3 Format of the report

The following chapter provides some background to the modelling system (HYMAS) that was used to perform all the simulations, as well as brief descriptions of the models that have been used. This chapter is not designed as a full manual to either HYMAS or the models as these are available separately from the author, or other staff in the IWR at Rhodes University.

The third chapter provides some general information about the databases that were established as part of the overall Southern Africa FRIEND programme and raises some general points about data availability and quality within the region that are pertinent to the application of rainfall-runoff models.

The fourth chapter summarises the results of the model applications that are more fully presented and discussed in the appendices (A1 to A11), while the final chapter attempts to draw some overall conclusions and list some recommendations with respect to future model use, training and capacity building and database development.

The appendices contain the bulk of the detail and results about the applications of the models to individual catchments within each country. They contain information about the availability of data that were used in the project, comparisons of observed and simulated data and comments about the successes or failures of the models.

2. HYMAS AND THE MODELS USED

This chapter of the report is designed to provide some background to the modelling system and the individual models used in the rainfall-runoff sub-programme of the Southern African FRIEND project. Further details about the models and the software system (and their availability) can be obtained from the references provided, or by contacting the project team in the Institute for Water Research at Rhodes University.

2.1 HYMAS - History of development and general philosophy.

HYMAS (HYdrological Modelling Application System) was initially developed during the period 1989 to 1993 through an earlier Water Research Commission funded project (Hughes, et al., 1993). The basic philosophy of the design was to create a DOS based PC package that could be used to apply a range of hydrological estimation tools, and specifically rainfall-runoff models, within a common pre- and post-processing environment. A large part of the motivation was based on previous experience of applying models and the difficulties of becoming familiar with many different approaches to setting parameter values, compiling input data and examining the results used by different model developers. It was considered that if a suite of models or techniques, which would be applicable to a wide range of hydrological and water resource related problems, could be packaged together, the time taken to develop such a system would be more than compensated for later when it was put to use. A further factor was that, if the design was carefully thought out at the start of the project, it would be relatively simple to add in additional features at later stages and therefore would become a 'living product' rather than a static one that would soon become obsolete.

In the context of the two main projects carried out within the IWR, that followed the initial creation of HYMAS, the development effort has been more than justified. One of these projects (1993 to 1996) was designed to look at the low flow regimes of a number of large basins within South Africa (Smakhtin and Watkins, 1997) and has made extensive use of HYMAS for simulation purposes, as well as for observed data analysis. The low flow project has also contributed a substantial number of additional routines to HYMAS, particularly in the area of duration curve, low flow frequency, baseflow and recession analyses (Smakhtin, et al., 1995). The second (FRIEND) is the subject of this report and all the hydrological simulation modelling has been carried out using HYMAS. One of the objectives of the FRIEND project, referred to in the first section of this report, was to package the models and associated software in a form suitable for use within southern Africa. Effectively, this package was already available at the start of the project and only had to be slightly revised to make it more generally applicable with respect to the nature of the data available within the region.

The current version of HYMAS contains a wide variety of routines to establish and modify individual modelling or analysis projects, prepare distributed time series and parameter data, run any of 10 models and examine, summarise or analyse observed or simulated data. It is in daily use within the IWR for a variety of research and consultancy projects and is available free of any purchase costs to all other participants in the Southern African FRIEND project.

2.2 HYMAS - Brief description.

Figure 2.1 illustrates the main menu items within HYMAS, which range from a variety of basic utilities, though a number of pre-processing facilities and model running options to the results analysis procedures. A full description of all these options is not included in this report as reference can be made to the user manual which is available from the Institute for Water Research and is normally distributed with HYMAS as WordPerfect v5.1 files.

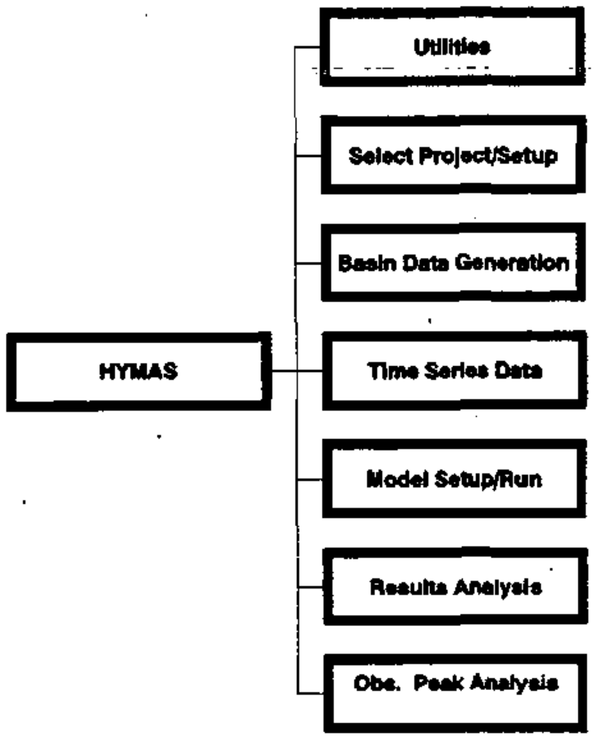


Figure 2.1 Hymas main menu options.

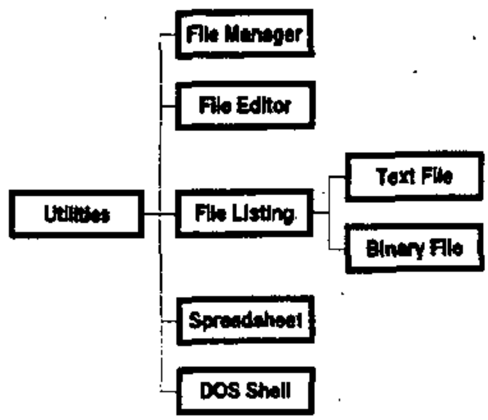


Figure 2.2 Utility options in HYMAS.

The *general utilities* (figure 2.2) that can be accessed from the HYMAS menu usually include a file manager, file editor, facilities for listing files and access to a spreadsheet package. Most of these access proprietary licensed software which is not distributed with HYMAS. However, it is a relatively simple task to modify a single text file to allow HYMAS to access whatever utilities a specific user has access to. Alternatively, the DOS Shell option allows users to leave HYMAS temporarily and run whatever software they choose. The binary file listing option has been included as many of the data files used in HYMAS are in binary format and this program allows users to view different format binary files.

The *select project/setup* options (figure 2.3) include the routines that are used to initiate a new modelling or data analysis project and to retrieve existing ones. A project in HYMAS is defined through a single reference file that includes data (input and output) and model file specifications for most of the disk access information that HYMAS requires to run any of the other processes. This approach allows a user to establish directories and names for all files to be used within a specific application at the start of the project and then leaves HYMAS to pass these specifications on to any of the data processing or model operation programs that are called from the menu. The *batch processing* option allows several projects (such as nested operations of one or more models applied to a large area) to be linked together and includes facilities to specify the sequence of operation of the projects and any file management (renaming, joining, etc.) processes that are also be required. The *change configuration* option allows a user to customise the colours of the menus and to modify the default directory structure.

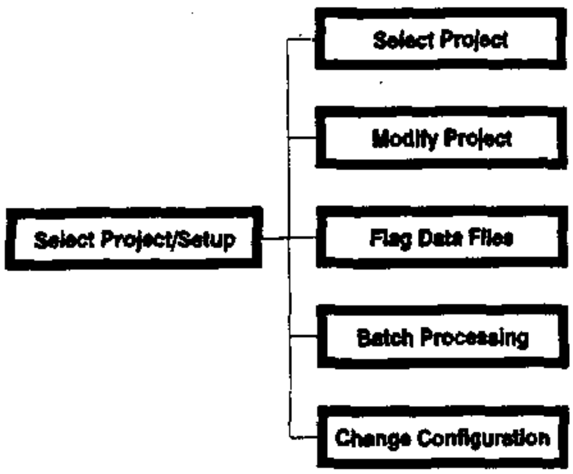


Figure 2.3 Setup options.

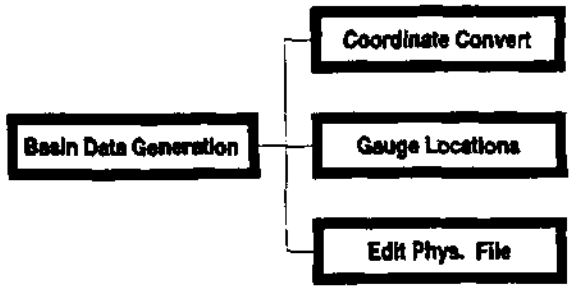
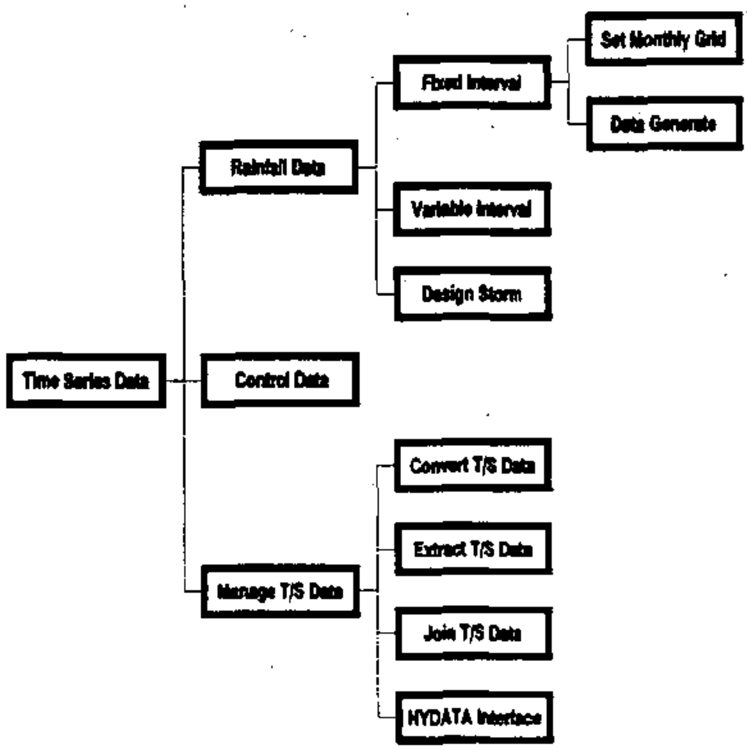


Figure 2.4 Spatial catchment data options.

The spatial catchment data options (*Basin Data Generation* - figure 2.4) are included to assist with establishing the locations of sub-area centres (for the sub-catchment distribution system), raingauges and for entering and editing basic sub-catchment description information. The *coordinate convert* option allows either individual longitude and latitude values to be converted to LO coordinates, or for files containing lists of raingauges and sub-area centres and their longitude and latitudes to be converted to the correct HYMAS formats for later processing. The latter files are required when building mean sub-catchment rainfall data files for input to the models. The *edit physiographic file* option refers to a file containing indices of physical sub-catchment characteristics (topography, soils, geology, vegetation, etc.) which are used for some models to assist with parameter estimation. The actual indices contained within these files are a mixture of directly measurable characteristics (such as catchment and channel slopes, drainage density, etc.) and index data (such as % area underlain by soils of various depths, % area covered by different density vegetation covers, etc.). They have been selected in a pragmatic way and are associated with the level of information that might generally be available across a broad sample of catchments in different regions.

The *time series data* (figure 2.5) options include all the facilities for processing raw data files of different original formats and converting them into files suitable for use with the HYMAS models or data analysis procedures. The *rainfall data* processing sub-options refer to three types of data that are treated separately. The variable interval data processing routine allows users to prepare rainfall input data from breakpoint data files using a flexible time interval that is partly determined by setting rainfall intensity thresholds and is only relevant to the more detailed approach to running the VTI model. As soon as a threshold is exceeded the time step is decreased and the model simulates some internal processes in greater detail. The approach is more fully described in Hughes (1993), but is used relatively infrequently due to the lack of rainfall data available at intervals of less than one day. The design storm routine accesses a model parameter file to determine the storm depth, duration and any delays to be used and distributes the total rainfall according to pre-defined storm profiles (contained within a text file that can be modified if necessary).



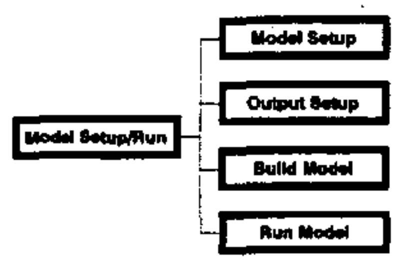


Figure 2.6 Model setup and run options.

Figure 2.5 Time series data options.

The most widely used options are related to fixed interval rainfall data and two sub-options are available. The first (*set monthly grid*) refers to a procedure that is frequently followed for South African catchments to refine the process of mean sub-catchment rainfall data generation. The normal procedures use an inverse distance squared weighting procedure applied to all the individual raingauge data available. There are, however, disadvantages to this approach where the gauges are not representatively located in areas with substantial spatial variations in monthly rainfall totals. The Department of Agricultural Engineering at the University of Natal, Pietermaritzburg have compiled a gridded (1' x 1') database of median monthly rainfall for the whole of South Africa (Dent, et al., 1989), which also includes Swaziland and Lesotho (these data can be accessed through the Computing Centre for Water Research). The set monthly grid option allows the grids of a sub-set of this database to be associated with each raingauge and the sub-catchments in a spatial distribution system and an additional set of sub-catchment/raingauge weighting factors are created. These are then applied, together with the inverse distance squared factors, when the *data generate* option is selected. The latter allows the user to specify the start and end time of the period of data to be used, the type of original data file, the time intervals of the input and output data (monthly or daily) and the maximum number of gauges to be used to generate each mean sub-catchment rainfall time series. If a median monthly grid file has not been processed, additional weighting factors can be entered manually and applied to ensure that the mean annual sub-catchment rainfalls generated are representative. A variety of different original data file formats have been allowed for, largely based on the experience of setting up data files for the FRIEND project. They include South African Weather Bureau format, CLICOM (WMO) daily and monthly formats, simple spreadsheet text file formats (year and 12 monthly totals, or year, month and up to 31 daily values) and blocked spreadsheet formats (each month of data headed by a separate descriptive line and the data appearing in several following rows).

The *control data* option allows the mean monthly data that are required for some models to be entered. These data sets include mean monthly potential evaporation, pan factors and abstraction data, as well as some values to control the seasonal variations of parameters.

The *manage time series* options are included for the purposes of compiling other forms of observed time series data (streamflow, evaporation, dam volume and abstractions) from original data files into HYMAS binary format files which are coincident in time with the rainfall input files. As with the rainfall data, many of the file format options that have been allowed for have been derived from experience during the FRIEND project which has helped to make the available options more comprehensive. The *HYDATA interface*, which allows streamflow data to be exchanged between HYMAS and HYDATA, was established because the latter software package (developed by the Institute of Hydrology in the UK) was accepted as the common approach to storing the flow data within the Southern African FRIEND project and is used by many of the regions national hydrometric agencies. If HYMAS is to be used just for the analysis of observed streamflow data and no rainfall file has been created, all of the original data will be extracted. When several projects are linked a facility is often required to combine data files (*Join T/S Files* - figure 2.5). This is required when the flow time series output from two or more catchment simulation projects are required to be joined as a single time series input to a downstream reservoir simulation project.

The *model setup/run* options (figure 2.6) are used to establish and edit parameter data files, modify the amount of information appearing in the output files, create unique model types and actually run a model. The *model setup* option contains the main parameter entering and editing routines. In the case of some models, default parameter values are estimated from the physical catchment data previously referred to. The parameter values, for each sub-catchment in the distribution system, can be edited through a spreadsheet type chart. There are various facilities to allow the same value(s) to be copied from one sub-catchment to others and for scaling a group of parameter values. Also included are facilities to establish periods (time-slices within the complete modelling period) over which parameters change, as well as the value of that change. The purpose of these are to allow dynamic catchment influences to be included in the simulations. Examples could include the effects of afforestation, clear felling, expanding irrigation abstractions or the increase in full capacity of a reservoir. Changes can be set up to increase or decrease linearly over a defined period, or to be immediate.

When the models are run, data files are created that contain the values for input, internal state and output variables for each sub-catchment and at each time step. These data files can be quite large for projects involving daily time steps and many sub-areas. The *output setup* option allows users to specify which of the output variables to retain in the data file, thus reducing disk space usage if less output detail is required than nominally allowed for. Some of the models have optional routines available for carrying out certain model components. These are stored as compiled object code and can be combined in different ways to create a final executable model made up of the individual users choices (*build model*).

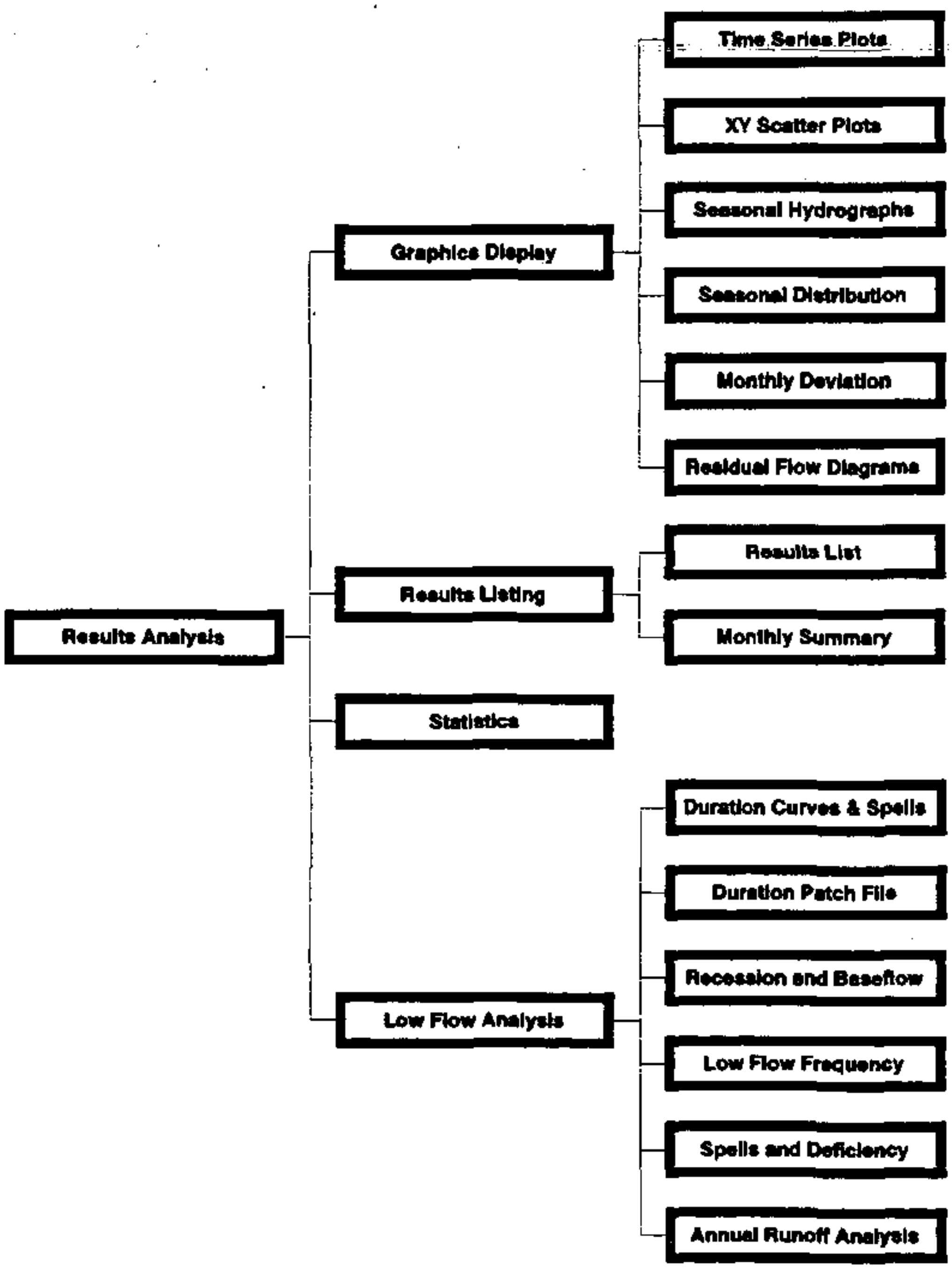


Figure 2.7 Results and observed data analysis options in HYMAS.

The option in the main menu with the largest number of sub-options is *results analysis*, which includes all the facilities to assess model results and analyse both observed and simulated data (figure 2.7). There are four main categories of results analysis procedures; those primarily concerned with graphical displays of time series data; those with listing data from results output files; those with calculating summary statistics of model results and the group of procedures concerned with low flow analysis.

The *graphics display* options include facilities to display any of the results variables (input, state or output) as a pair of *time series plots*, over any length of period within the complete model period. Several data sets can be displayed on the same axes (assuming they have the same units of measurement) for comparative purposes. Thus, this facility is useful for comparing observed and simulated values, comparing rainfall and runoff response and for determining which component of a model is responsible for generating most of the response during different periods. It is frequently useful to view the relationship between two variables (the obvious example application being the relationship between observed and simulated data). The *XY scatter plot* option allows two variables to be selected and prompts the user to choose the type of transformation (none or logarithmic), ordinary or cumulative data and the period of data to be used. Data from all, or a subset of months of the year can also be selected. The display consists of a scatterplot of all data specified and a table of values including mean, standard deviation, maxima, minima, regression equation coefficients and the coefficient of efficiency (all for non- and log-transformed data). If the time interval is selected as one of the variables to plot and the cumulative data option is chosen, the facility can be used to display single mass curve plots for the purposes of detecting historical trends. Similarly, if more than one set of observed data of the same type are available, double mass curve analysis can be performed. *Seasonal hydrographs* refers to a facility to plot overlaid daily time series of output variables for selected months of each year of a defined period. The purpose is to be able to examine variations in seasonal response and to identify differences between typically wet and dry years. The *seasonal distribution* option allows the mean monthly distribution of model output and observed data to be examined, while the *monthly deviation* option plots the relationship between either the standard deviation, coefficient of variation or skewness of daily values within a month versus the total monthly value of a variable. While the latter can be used for any of the observed or simulated variables, it is primarily designed for streamflow.

Results listing allows simulated variables to be written to the screen, a printer, a text file or other files with specified formats, so that the data values can be examined in more detail or imported into external software. For daily data, a further option is available to output summary monthly values (means or totals). The most common use of these facilities are for generating files for import into more sophisticated graphical presentation software.

The *statistics* programs are all model specific and not available for all the models included. For the VTI model the program generates total, or net change, values for all the output variables, while for the Pitman monthly model the output consists of calendar month and annual means and standard deviations of the output variables. The statistical output for the reservoir simulation model provides annual means and standard deviations of the main water balance components, carries out a financial analysis (based on some cost parameters) and provides tables of the percentage of time that certain storage states and drafts (as a % of required draft) are equalled or exceeded.

The *low flow analysis* routines are all referred to in greater detail in the report generated by a partner project carried out within the Institute for Water Research (Smakhtin and Watkins, 1997), but are summarised below for completeness. The *duration curves and spells* is possibly of the greatest relevance to the FRIEND project and is mainly used to display duration curves of output, or observed data (principally used for streamflow data). For daily data, options are available to plot from 1 to 90 day duration curves, either as ordinary flow values or standardised, though division by mean daily flow. For monthly data, 1 to 3 month duration curves can be selected. In both cases, all or part of the complete data file can be used and all, single or groups (seasons) of calendar months can be included. The keyboard arrow keys can be used to move up and down the duration curve and the % point and flow values are displayed on the screen. Critical values can be selected and used in the subsequent spell analysis, which displays histograms of the frequency that such values are exceeded and not exceeded for a range of durations. The flow values for 18 points on the duration curve can also be written to a printer or file. The next option (*duration patch file*) is used to create data files of calendar month and annual 1-day duration curve values for use with the 'Patching' Model (see later section and Hughes and Smakhtin, 1996).

Recession and baseflow analysis refers to the procedures that calculate the recession coefficient and baseflow index of daily time series data. Various methods can be used and Smakhtin, et al. (1995) or Smakhtin and Watkins (1997) provide further details and some examples. The *Low flow frequency* option carries out annual series frequency analysis of the data based on a set of user-selected low flow durations (1 to 183 day moving average periods). The results are given as sample probability plots and values, as well as those based on the best fit to a Wiebull distribution, although it is recognised that this distribution may not be the most appropriate to use. *Spells and deficiency* is different to the spell analysis carried out as part of the duration curve option in that annual series of maximum spell duration and deficiency volume are subjected to frequency analysis. The thresholds for the spell analysis are selected from a group of fixed values representing percentages of either mean daily or monthly flow. The analysis (as with most of the low flow procedures) can be carried out for specific months or seasons and for any part of the entire time series. The final option in this group (*annual runoff analysis*) allows annual total values to be displayed (or written to a file) as actual values or as cumulative departures from the mean annual value. This facility was initially added to allow cycles and trends to be identified and to check whether two time series (from separate gauges) covering different periods could be considered to be representative of longer periods.

2.3 The models in HYMAS.

Nine models have been included in the current version of HYMAS and those that have been used within the FRIEND project are described in more detail in the following sections.

The *VTI model* (Variable Time Interval) is a semi-distributed catchment hydrology model which includes surface-ground water interactions and can operate with time intervals of between 5 minutes and 1 day. It is normally used as a daily model due to the lack of availability of finer time interval rainfall data.

The *Pitman model* is a monthly time-step, semi-distributed catchment hydrology model.

The *RAFLES model* is a daily time-step, semi-distributed version of the model created by Stephenson and Paling (1992), which uses simplified hydrodynamic equations for overland flow and Green-Ampt infiltration and includes routines for erosion and sedimentation. The model remains largely untested and has not been used in this project.

The *P-Export Model* (Hughes and van Ginkel, 1994) represents an initial attempt at creating a simple model to simulate the daily runoff and nutrient loads from an urban area. The model uses a modified SCS approach for the hydrology and storage-depletion principles for the water quality component. It is still largely untested and has not been used in this project.

The *Design Flood model* is a simple approach using Nash-Muskingham routing procedures to convert a design storm rainfall into a flood hydrograph. As flood modelling was not part of the IWR's contribution to FRIEND it has not been applied.

The *Patching Model* (Hughes and Smakhtin, 1996) represents a pragmatic approach to patching and extending daily time series, making use of the principle that there is frequently a high degree of similarity between the equivalent duration curve % points (based on calendar month duration curves) for flows in different rivers within the same region. This model has been applied in some of the Southern African FRIEND countries and is explained in a little more detail later.

The *Monthly Reservoir Simulation Model* (Hughes, 1992) is a reservoir water balance model that allows several linked dams to be simulated together and is usually used in conjunction with the Pitman monthly model to provide a more complete suite of models to simulate basin-wide water resource availability. In the context of the FRIEND project, it has only been used in Namibia to determine the impact on reservoir yield of using the simulation results from different models as inflows.

The *Daily Reservoir Simulation Model* is a daily version of the previous model, the main other difference being the inclusion of a simple spillway overflow routine that also allows the reservoir level to exceed full capacity. It has only been used in some of the South African catchments, but not elsewhere, as the majority of the catchments were selected on the basis of the absence of major upstream abstraction influences.

The *Daily Rain Tank model* is designed to simulate the water balance of a rain tank, given information on the size of the roof, gutter and roof surface characteristics, tank size and patterns of required water use. The model uses a time series of daily rainfall data as input and estimates the assured yield for various tank sizes and performs a simulation for a specific yield and tank size. It was mainly set up to assess the feasibility of using rain tanks as a supplementary water supply in developing communities in South Africa.

One further model is currently being added to HYMAS and that is the *IFR model* (Hughes, et al., 1997), which represents an attempt to simulate the likely time series of flows that will result from the implementation of the recommendations of an Instream Flow Requirements workshop to determine the environmental flow needs of a river.

All of the above models are calibrated manually and no automatic parameter optimisation procedures are currently available in HYMAS.

2.4 Pitman model.

The Pitman model was first described in the report by Dr Bill Pitman (Pitman, 1973) and in its various versions has become the most widely used monthly time-step, rainfall-runoff model within southern Africa. The basic form and conceptualisation of the model has been preserved through all the subsequent versions that have been re-coded by the original author and others, but at the same time additional components and functionality have been added. The current 'official' version of the model is now referred to as WRSM90 (Pitman and Kakabeeke, 1991) and is available as a complete water resource modelling system that allows basins to be sub-divided and includes the simulation of reservoirs and water transfers. The version that was initially included in HYMAS has also preserved the original core conceptualisation, but some functions have been added and others modified in certain ways. However, the extent to which a simulation result will differ from that obtained from the original model depends on the way in which the user quantifies the new parameter values (i.e. it is still possible to obtain the same result). During the course of the FRIEND project a few additional changes have been made and a further version of the model included in an attempt to cater for a relatively unique hydrological response observed under Namibian arid to semi-arid conditions. The model is not described in detail in this report as Pitman (1973) provides a more than adequate description. This report will concentrate on the HYMAS version and the changes that have been incorporated. Some observations will also be made about the application of the model and quantification of parameter values.

2.4.1 Brief description of the model.

Figure 2.8 provides a diagrammatic illustration of the model components (including the changes made for the HYMAS versions), while table 2.1 lists the parameters and provides brief explanations of their purpose.

The two inputs to the model are a monthly time series of *precipitation* and either a similar time series of *potential evaporation*, or mean monthly values. In South Africa the potential evaporation data are commonly S or A pan values corrected for open water evaporation. The main part of the model operates over four iterations and the monthly rainfall depth has to be distributed accordingly. This is achieved using a symmetric S-shape, cumulative mass curve and the HYMAS version of the model includes an RDF parameter to determine how much rain falls in each iteration step. In the original model this value is fixed at 1.28 and the effect of a range of RDF values for four rainfall depths is illustrated in figure 2.9. It is clear that lower RDF values give rise to more even distributions over the month.

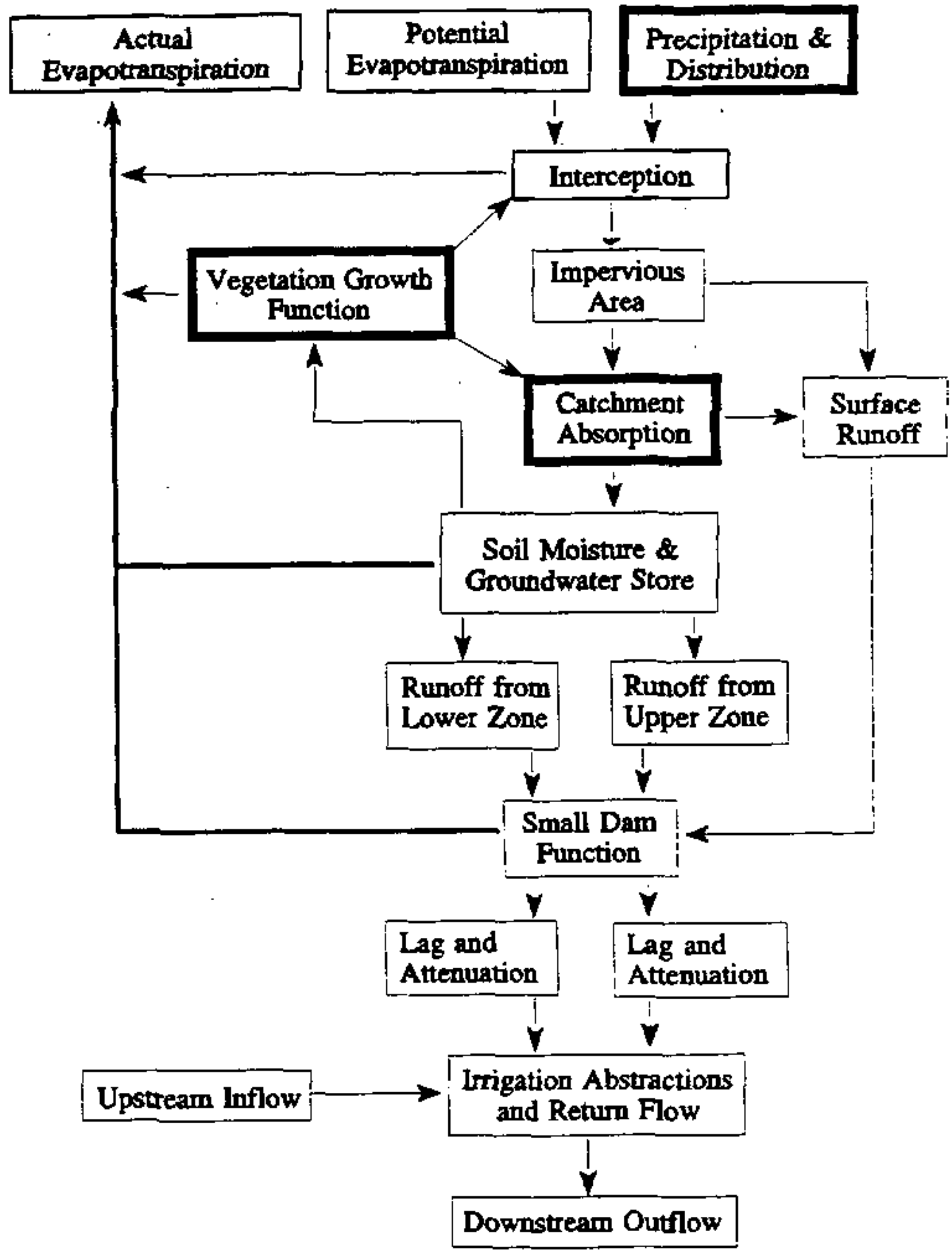


Figure 2.8 Flow diagram representation of the version of the Pitman model which forms part of the HYMAS system. The bold type boxes highlight the areas where the model has been changed during the FRIEND project to improve the applicability of the model.

Table 2.1 Pitman model parameters (some are additions to the original model version and those highlighted are related to the functions added during this project).

Parameter	Units	Description
RDF		Rainfall distribution factor controlling the distribution of total monthly rain over 4 iterations.
PI (Veld & Forest)	mm	Interception storage parameters for natural veld and for forest cover.
AI	Fract.	Impervious part of sub-area.
ZMIN	mm mnth^{-1}	Minimum catchment absorption rate
ZAVE	mm mnth^{-1}	Mean catchment absorption rate.
ZMAX	mm mnth^{-1}	Maximum catchment absorption rate.
ST	mm	Maximum moisture storage capacity.
SL	mm	Moisture storage capacity below which no runoff occurs.
FT	mm mnth^{-1}	Runoff from moisture storage at full capacity.
GW	mm mnth^{-1}	Maximum groundwater runoff.
R		Evaporation-moisture storage relationship parameter.
POW		Power of the moisture storage-runoff equation.
FF		Ratio of forest/natural veld potential evapotrans.
VPOW		Power of the vegetation decay function.
MDAM, DAREA	Ml, %	Maximum dam storage and % sub-area above dams.
A, B		Parameters in non-linear area-volume relationship for dams.
DUSE	km^2	Irrigation area supplied from dams.
TL, GL	months	Lags of runoff components (TL for surface & soil runoff, GL for g'water runoff).
IARR, IWR	km^2, Fract.	Irrigation area and return flow fraction.
EFFECT	Fract.	*Effective rainfall fraction (to reduce irrigation demand)*
RUSE	Ml y^{-1}	Non-irrigation direct demand from the river.

The *interception* function is controlled by parameter PI, which can have different values for the proportion of the catchment covered by natural veld and that covered by forest. Seasonal variations in these values are also allowed for by specifying mid-winter and mid-summer values and assuming a sine curve variation between these extremes. In the version modified for arid areas, PI values are specified for good and poor vegetation cover conditions, rather than for seasonal extremes.

Surface runoff is generated from two possible functions (figure 2.8). The first is a simple impervious area function, where the proportion of the catchment that is impervious and directly connected to river channels is specified as a parameter (AI). The second function is represented by a triangular frequency distribution of catchment absorption (infiltration) rates, defined by ZMIN, ZAVE and ZMAX. The inclusion of the ZAVE parameter in the HYMAS version allows the triangular distribution to be asymmetric. Rainfall totals less than ZMIN do not generate any surface runoff, higher rainfalls generate progressively greater runoff volumes and the part of a rainfall total that is greater than ZMAX all contributes to runoff. The normal HYMAS version allows for seasonal variations in these parameters, while in the arid area version, ZMIN and ZMAX values are quantified for good and poor vegetation cover conditions.

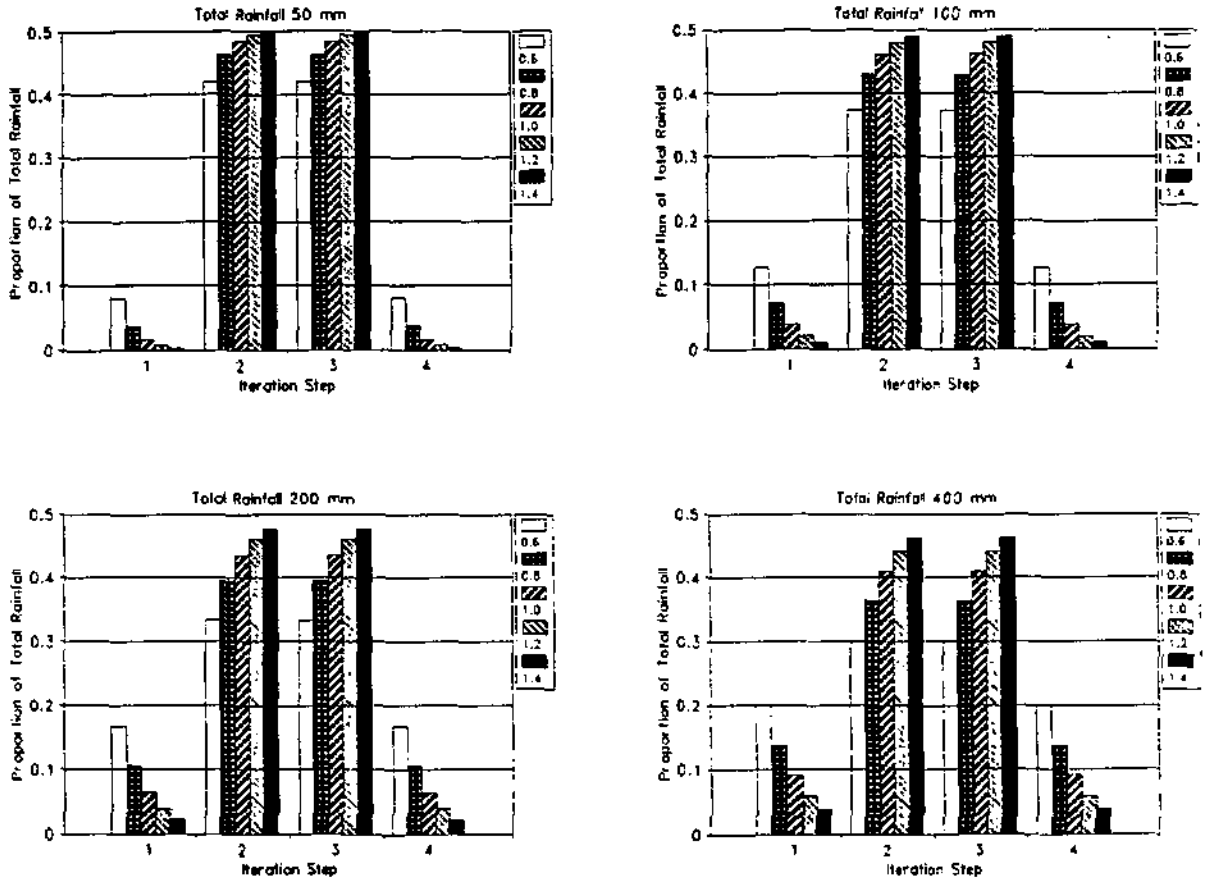


Figure 2.9 Illustration of the effect of the new Rainfall Distribution Factor (RDF) parameter for 5 values of the parameter and 4 monthly rainfall totals.

The proportion of the rainfall that is not intercepted, or contributing to surface runoff, increments the level of water in the *moisture store* and if the maximum value (ST) is exceeded, the balance becomes part of upper zone runoff. In the original model these are referred to as soil moisture storage and runoff, however, there is no groundwater store in the model and if actual baseflows are generated as drainage from a groundwater store, ST must represent this as well as the potential soil water storage. *Evapotranspiration* losses are controlled by parameter R (within the range 0 to 1) which determines the depth of water lost in relation to the potential evaporation value for the month and the current moisture storage status. A low value of R indicates that moisture can continue to be lost even at low storage states, while a value close to 1 suggests that losses during low potential evaporation months (relative to the maximum) will cease at relatively high moisture storage states. This parameter can also change seasonally, or with vegetation cover in the arid area model version.

Runoff from the moisture storage is controlled by a power function (POW parameter) relationship with storage level, with SL determining the lowest level at which runoff still occurs. FT represents the maximum runoff depth which occurs at maximum storage, ST. GW is a parameter used to differentiate between runoff from more rapidly draining storages (the soil perhaps) and slower ones (groundwater perhaps). If the calculated runoff rate is below GW all of the runoff is considered to be slowly draining, while if greater, GW mm month^{-1} is slow and the remainder considered to be more rapid.

In the arid version of the model the moisture storage state for the current and last two months is used to estimate a potential vegetation growth factor through a weighted average of the result of a power function of the relative moisture state.

$$VG_i = [(S_i - SL) / (ST - SL)]^{VPOW} \quad \text{.......... Eq. 2.1}$$

and

$$VG = 0.5\ VG_0 + 0.3\ VG_1 + 0.2\ VG_2 \quad \text{.......... Eq. 2.2}$$

where VG is the vegetation growth factor,
VG_i is the contribution to VG for month i (minimum value = 0),
S_i is the moisture storage state for month i,
0, 1 and 2 refer to the current, previous and last but one month,
and VPOW, SL and ST are model parameters (see table 2.1).

A single wet month, preceded by two dry months, will therefore have less effect than a sequence of moderately wet months. If the vegetation growth factor, calculated in any single month, is greater than the current relative vegetation cover (VCOV; a value between 0 and 1), then the current cover is set equal to the growth factor (VG) and the decay time re-initialised to zero. If VG is less than VCOV, then the decay time is incremented by 1 month and VCOV reduced by a non-linear decay function which is controlled by the VPOW parameter. The effect of different VPOW values on the decay is illustrated in figure 2.10 (left side). The initial cover refers to the cover value at the last time it was re-set to VG (at a higher value) and it can be seen that the total decay time allowed for is four years. The right hand side of figure 2.10 illustrates a 5 year sequence of estimated vegetation cover characteristics for the Etemba catchment in Namibia, with ST = 325, SL = 0 and VPOW = 2.0.

The VCOV value is used to determine what the current value for parameters PI, ZMIN, ZMAX and R should be, within the range defined by their good and poor vegetation cover values. It is clear that, apart from parameter VPOW, the effect of the vegetation cover function (and its effect on the other functions) is also influenced by the values of ST and SL, as well as other model components and notably surface runoff, in that this controls how much water is added to the moisture store. The addition of the cover function has therefore substantially added to the complexity of the model and, potentially, the difficulty of calibration.

All the runoff components are routed through a small dam function that assumes that runoff from the proportion of the catchment above the small dams (DAREA) must first satisfy available storage before being able to contribute to outflow from a sub-area. Water is lost from these dams through abstractions, controlled by parameter DUSE (table 2.1) and a monthly distribution of depth of irrigation water demand, and by evaporation, controlled by a non-linear relationship between area and volume and the monthly potential evaporation demand. The rapid runoff components are the first to be used to satisfy the small dam storage.

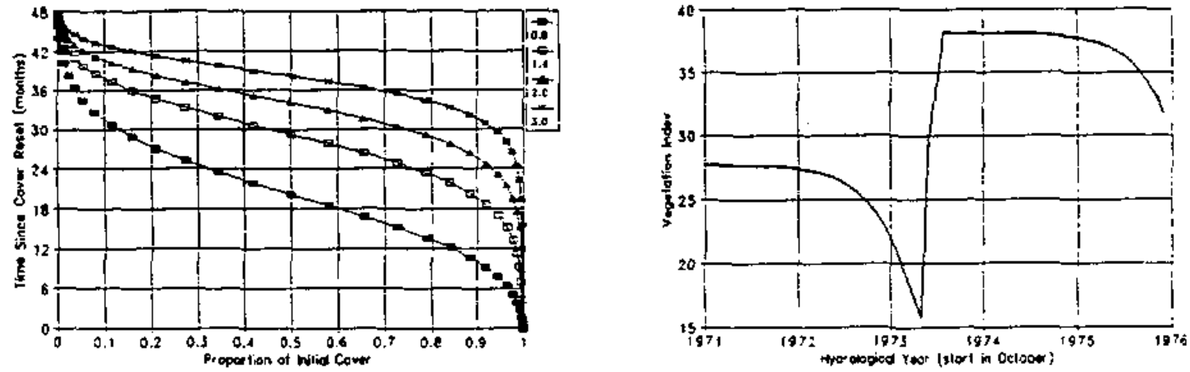


Figure 2.10 Illustration of the effect of different VPOW parameters on the decay of vegetation cover over time (left diagram) and an example of the estimated vegetation cover (or vegetation index) for the Etemba catchment (Namibia) for the period October 1971 to September 1976 (right diagram).

Any flow which is not taken up by dam storage is then subjected to lag and attenuation, the slow and rapid flow components using the same function but with different parameters (TL and GL). The total routed flow is then added to any upstream inflow (from higher sub-areas or from external file inputs) to produce the final runoff before river abstractions. The HYMAS version of the model differentiates between direct abstraction from the river for irrigation and non-irrigation purposes. Irrigation abstractions are based on the irrigation area parameter (IARR) and a monthly distribution of irrigation demand depth, which is reduced by the effective proportion of the rainfall (EFFECT) in each month. A proportion of the irrigation water (IWR) is assumed to return to the river during the same time interval. The non-irrigation direct demand is based on an annual demand value (RUSE) and a distribution that specifies the proportion of the annual value that is required each month.

2.4.2 Calibration issues and approaches.

Pitman (1973) provides guidelines for users to assist them in their approach to calibration and these are reproduced as table 2.2 in this report. In general terms ST and FT are the recommended parameters to concentrate on in humid to semi-arid areas with high to relatively high baseflow components, while ZMIN and ZMAX should be the main calibration parameters used in drier climates. Many of the other parameters (POW, SL, PI, R, TL an GL, for example) can be maintained at 'standard' values in most situations, although this report suggests that some of them can be useful to 'fine tune' a calibration. Clearly, the water use parameters should not be used for calibration and should be set at values that most closely reflect the real situation.

Table 2.2 Effects of INCREASING model parameter values on the properties of the simulated runoff time series.

Parameter	Property of simulated runoff		
	Mean Annual Runoff	Standard Deviation	Seasonal flow distribution
POW	Decreased	Increased	More Peaked
SL	Decreased	Increased	More Peaked
ST	Decreased	Little Effect	More Uniform
FT	Increased	Decreased	More Uniform
GW	No Effect	No Effect	Dry season flows increased
AI	Increased	Decreased	Early wet season runoff increased
ZMIN	Decreased	Increased	More Peaked
ZMAX	Decreased	No Effect	No Effect
PI	Decreased	Increased	More Peaked
TL	No Effect	No Effect	More Uniform and lagged
GL	No Effect	No Effect	Dry season runoff increased
R	Increased	Decreased	More Uniform

Some further guidelines, that have emerged from the FRIEND project, can also be suggested. In semi-arid to arid areas, relatively high rainfall months can be used to determine the minimum value that ST should be set at. As FT is normally set to zero in such areas where sustained baseflows do not occur, it is difficult to calibrate the value of ST, because it has very little effect on runoff in most months. However, a low value of ST can cause the storage capacity to be exceeded during relatively high rainfall months and result in very high runoff volumes being generated. If these excessive runoffs are not reflected in the observed flow data, ST can be increased to a point at which the capacity is exceeded less often. The use of the new parameter RDF also has an influence on this effect as reducing RDF from the default value of 1.28 produces a more even distribution of rainfall over the four model iterations and suggests that ST is likely to be exceeded less often.

Parameter SL has been commonly set to 0 in most previous applications of the model, however, there are occasions when parameters POW, FT, GW, TL and GL are not flexible enough to generate a satisfactory baseflow response. This has been found to be the case in some catchments where the soil/ground water storage is quite high, but also where there seems to be a limit to the amount that can drain out of this storage.

The overall conclusion about the calibration approach is that initially it is always better to follow the procedures recommended by Pitman (1973) and to concentrate on parameters FT, ST, ZMIN and ZMAZ (depending on the flow regime type). The calibration of these parameters should allow the gross response characteristics to be reproduced satisfactorily. Only after this has been completed should the other parameter values be adjusted to refine the shape of the baseflow response and the balance between runoff generation during wet and dry seasons or years.

When calibrating with several sub-areas and where very little is known about the different characteristics of the sub-catchments, a detailed examination of the spatial/temporal rainfall variations and how these effect runoff patterns can be very useful to guide the calibration process and decide which parameter values should be changed on which sub-areas. However, it should also be recognised that, without further information about the likely runoff characteristic (possibly inferred from topography, geology, soils and vegetation information) variations between sub-catchments, it is never an easy task to try and establish parameter value variations that are meaningful.

It is always very useful to examine the observed streamflow response before any calibration is started and attempt to interpret the flow regime in terms of an understanding of the model, its individual components and how these can be used to represent actual process responses. This represents the 'hydrological' approach to calibration, where the perceptions of the model user about the real catchment hydrology are used to guide the calibration exercise. The implication is that the user must therefore develop a reasonably detailed understanding of the model and how it is trying to represent hydrological processes. The alternative is a purely 'numerical' calibration exercise where only an understanding of the numerical effect of changing parameter values is required to make the calibration process more efficient. While the latter may achieve a satisfactory result for a single catchment, the former should be of more value when calibrating a series of catchments and when it is important to achieve some consistency in the way in which the streamflow response is simulated.

2.5 VTI model.

The basis for the variable time interval approach is explained in Hughes (1993), while the version of the model used here is more completely described by Hughes and Sami (1993), although some modifications have been made since the publication of that paper. The description given in this report will be confined to the main conceptual base of the model. An illustration of the models structure is given in figure 2.11, while table 2.3 lists some information about the model parameters.

2.5.1 Model description.

The rainfall input to the model consists of depths over time intervals of between 5 mins. and 1 day, which are dependent on a set of rainfall thresholds defined by the user. The thresholds are used to automatically determine at what depth the time interval decreases. For example, setting thresholds of 10mm for 1 day, 6 and 1 hour intervals and defining a minimum interval of 15 mins. would produce the following pattern of intervals :

Rain < 10 mm day^{-1}	:	1 day step
10 mm $6h^{-1}$ > rain > 10 mm day^{-1}	:	6 hour step
10 mm h^{-1} > rain > 10 mm $6h^{-1}$	:	1 hour step
rain > 10 mm h^{-1}	:	15 minutes step

The purpose of this approach is to enable the modelling time interval to more closely correspond to the real rates at which hydrological processes operate. It is clearly necessary to have observed raingauge data with a time resolution at least as high as the finest time interval selected. In all the applications used for the FRIEND project only daily resolution data were available and the variable interval components of the model were not used. In such cases, additional internal iterations are applied to prevent some of the components from transferring water, over a complete day, at rates which are solely dependent upon storage levels, or transfer rates set at the start of a wet day.

Figure 2.11 indicates that the model contains functions to represent the majority of the processes considered to be important in humid to semi-arid catchments. Estimates of *potential evaporation* are made by distributing monthly mean corrected pan evaporation values equally over the days of a month and using a sine curve distribution for intervals of less than one day. Losses from interception, depression and small dam storages as well as saturated soil surfaces are assumed to occur at the potential rate. *Interception* is estimated using a modified Rutter model (Rutter, et al., 1975) with parameters based on the proportion of the catchment lying under several broad vegetation cover classes.

A *rainfall intensity dependent runoff generation* routine makes use of a decaying infiltration rate function (Kostiakov, 1932) of the form :

Infiltration rate = $k * c * TIME^{(k-1)}$ . . . . Equation 2.3

where TIME is the cumulative time since the start of a rainfall event. Infiltration rates over a sub-area at any specific time are defined by Log-Normal distribution functions, rather than single values, by using two values (mean and standard deviation) for each of the parameters k and c. The area contributing to runoff is then equivalent to the cumulative frequency at the point on the distribution where the infiltration rate equals the rainfall intensity value in a specific time interval. The calculation of the runoff rate assumes that rainfall exceeds the infiltration rate by differing degrees over the contributing area. The parameters of this component (k and c means and standard deviations) are estimated from relationships with soil texture and other soil properties as explained in Hughes and Sami (1993).

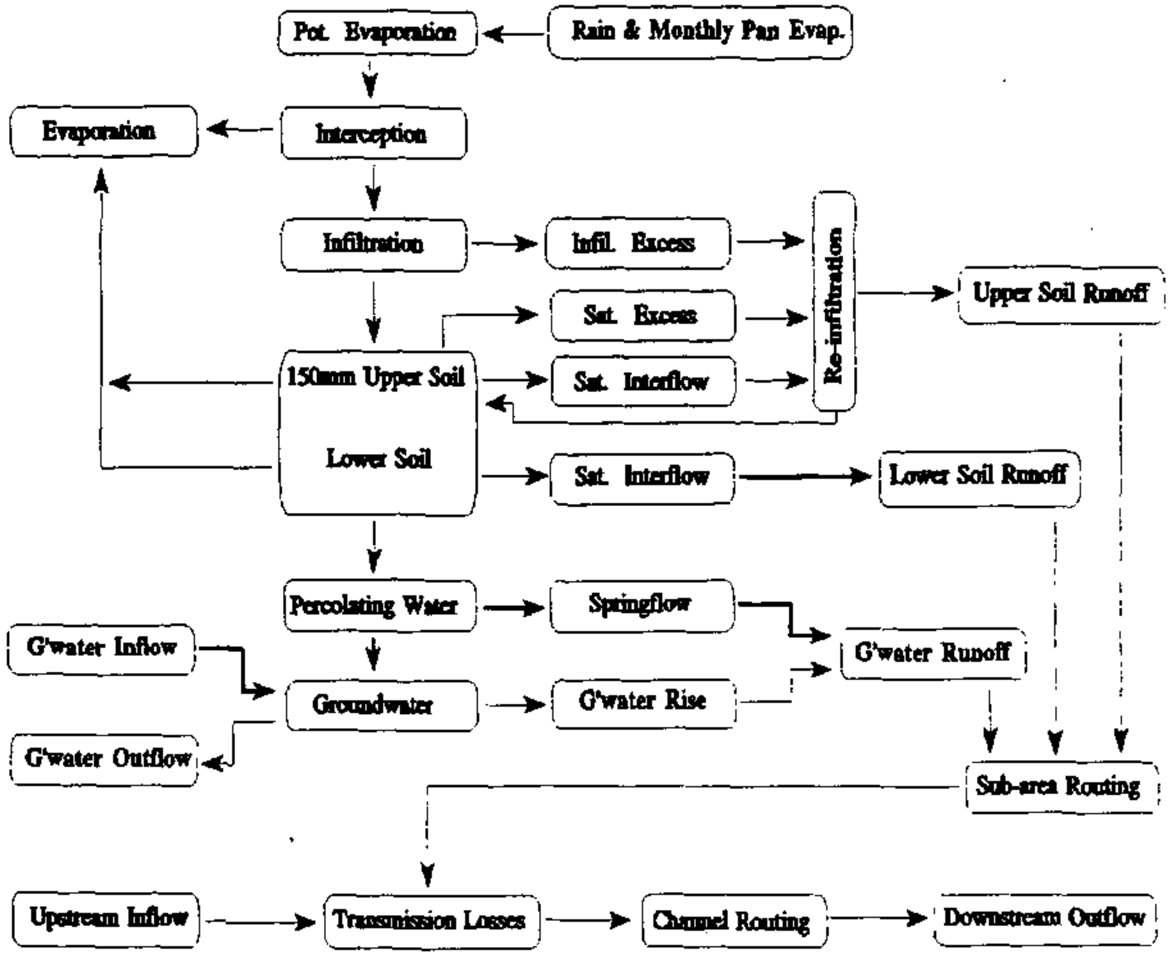


Figure 2.11 Flow diagram representing the VTI model structure.

A distribution function approach is also used in the main *moisture accounting and runoff generation* component. The total soil profile is divided into two layers (upper layer = 150 mm, lower layer = mean soil depth - 150 mm) and the water contents of both represented by Normal distribution functions. All soil water contents are expressed relative to porosity and the means of the distributions (upper and lower soil zones) are determined from water balance calculations (Δmean = rain + drainage - evaporation - runoff), while the standard deviations vary with the means according to a relationship defined by a soil parameter. The proportions of the catchment that can be considered to be saturated or contributing to vertical drainage are then estimated from the part of the distributions lying above relative water contents at saturation (0.98 * porosity) and field capacity (a parameter) respectively.

Before using the saturated proportions to estimate the quantities of three runoff components, two further factors are calculated during each time step of modelling. These are 'lateral' (LDF) and 'vertical' (VDF) distribution factors which represent attempts to account for the spatial and vertical position of the saturated parts of the two soil layers. They have been included on the assumption that catchments in different climatic areas, or with different soils or slopes, may have the same degree of soil wetness, but the spatial or vertical position of the saturated areas will strongly influence the nature of the runoff patterns. The LDF factor is updated in each time interval from an estimate of the lateral drainage rate using the soil moisture content, hydraulic conductivity, porosity and catchment slope parameters. High LDF values imply concentration of soil water in the valley bottom areas and are typical of consistently wetted soils with high lateral drainage rates. Low values imply soils which are generally drier, or where drainage rates are low relative to the rate of drying through evapotranspiration. The VDF factor is updated in each time interval by a function of the proportions of the two layers contributing to vertical drainage. VDF values are generally low (concentration in the lower parts of a soil layer) at the start of rainfall events, gradually increase as the upper zone becomes wet and decrease as vertical drainage decreases after an event.

A combination of the current groundwater level, the saturated proportion of the lower soil zone and the LDF value are used to determine the size of a conceptual soil 'seepage face', which represents the saturated part of the catchment surface in the valley bottoms directly connected to stream channels. Apart from the intensity controlled runoff component, the model simulates three other soil moisture controlled runoff components :

- Saturation excess runoff from rain falling on the saturated surface of the upper soil zone, including the 'seepage face'.
- Saturated sub-surface flow re-emerging from saturated parts of the upper soil zone.
- Saturated lower layer sub-surface flow from the conceptual soil 'seepage face'.

The intensity controlled runoff component and the first two of the above are subjected to a re-infiltration function based on the proportion of the upper soil layer that is not contributing to any form of surface runoff.

The amounts of drainage from the upper soil layer to the lower layer and from the lower layer to groundwater are determined from the time interval, the proportions of the two layers distribution functions that lie above field capacity (adjusted by the LDF and VDF values) and hydraulic conductivities for the soil and groundwater bodies.

Actual evapotranspiration from the saturated proportion of the upper soil layer occurs at the potential rate. Additional losses from the un-saturated part of the upper layer, as well as all the lower layer are determined from functions of a seasonally varying crop factor, soil texture and the relative moisture contents of the layers.

A *groundwater-surface water interaction* component is included to account for :

- Drainage from the lower soil zone into a storage which represents percolating water that has not yet reached the water table.
- The re-emergence of percolating water as springs above the normal water table (perceived as a short circuit in the recharge process caused by preferential flow paths and can also account for the presence of perched water tables).
- Increments to groundwater resulting from recharge and the resultant rise in the water table.
- Groundwater seepage resulting from intersection of the water table with the ground surface.
- Transfers into and out of aquifer storage by groundwater flow between sub-catchments.

The algorithms are based on a set of parameters that define the geometry of the water table relative to the surface and the properties of the aquifer (storativity, transmissivity and aquifer depth, for example).

Any runoff generated within a sub-area, first has to satisfy available depression and small dam storage, before being routed through a non-linear storage discharge equation of the type $S = K.Q^n$ (where S is storage, Q discharge and K, n parameters) using the solution algorithm recommended by Hughes and Murrell (1986). The output from this *sub-area routing* component is combined with any flow generated from upstream sub-areas, subjected to *channel transmission losses* and *routed down the channel* network to the next downstream sub-area or the catchment outlet. Channel routing is carried out using the same non-linear storage discharge function as for sub-area routing, but with different parameters and including a time delay.

In addition to the natural hydrology components, the model also includes facilities to account for losses to small dams, abstractions directly from rivers and from groundwater.

In summary, the VTI model represents a compromise solution between fully distributed, strongly physically based approaches and simpler, lumped approaches. While the model is designed to be operated using a relatively coarse sub-catchment distribution system, it includes algorithms based on frequency distributions and some largely empirical factors (LDF and VDF) to represent variations within sub-areas.

Table 2.3 Parameters of the VTI model

Parameter	Brief description or explanation
Sub-area shape (L/W ratio)	Ratio of catchment length to width, used to define part of the geometry of the groundwater storages.
Mean slope	Used for the soil and g'water flow hydraulic gradients.
Crop factor	Summer and winter values used to define the relationship between potential and actual evapotranspiration.
Proportion of veg. cover	Summer and winter values used in the interception function.
Leaf Area Index	Summer and winter values used in the interception function.
Canopy capacity	Summer and winter values defining the limit of the interception store.
Storm duration factor	Summer and winter values used to distribute daily rainfalls.
Infiltration curve k	Summer and winter values of the k parameter in the infiltration equation.
k variability	Used to define the standard deviation of k in the infiltration equation.
Infiltration curve C	Summer and winter values of the C parameter in the infiltration equation.
C variability	Used to define the standard deviation of C in the infiltration equation.
Upper soil store (mm)	Maximum moisture storage in the upper soil zone.
Lower soil store (mm)	Maximum moisture storage in the lower soil zone.
FC/Porosity ratio	Relative moisture content at field capacity (upper zone).
Slope/valley soil depth ratio	Estimate of spatial distribution of shallow and deep soils.
Soil hydraulic conductivity (mm h^{-1})	Used to determine rates of soil water drainage (upper zone).
G'water hydraulic conductivity (mm h^{-1})	Used to determine recharge rates and g'water drainage
Texture distribution factor	Defines the differences between hydraulic conductivity and field capacity between the upper and lower soil zones.
St. Dev. of soil moisture content (mm)	Defines the shape of the distribution of moisture content over the sub-area.
Max. depresssion storage (mm)	Max. depth of channel pool storage (i.e. fed from initial runoff, not rainfall on slopes).
Max. dam storage (Ml)	Maximum potential storage of runoff in small dams.
% area above dams	Defines the proportion of the sub-area that can supply small dams.
A & B	Two parameters in the non-linear relationship between dam area and volume.

Parameter	Brief description or explanation
Demand from dams (Ml d^{-1})	Average daily abstraction from small dams (seasonal variations defined elsewhere).
G'water distribution vectors	Defines the direction of flow of g'water below the sub-area (2 directions are possible).
Effective planar slope	Correction to the sub-area slope used for g'water geometry definition.
G'water drainage vector	Vector result of vertical and horizontal flow components of g'water percolating down to the water table.
Max. regional g'water slope	Used to define the g'water geometry and the g'water outflow to other sub-areas.
Aquifer storativity	Defines the amount of storage available in the aquifer together with the g'water geometry.
Aquifer transmissivity (m^2 d^{-1})	Used to determine g'water outflows to other sub-areas.
Max. depth to aquifer (m)	Defines the rest water level when the g'water gradient is zero.
G'water demand (Ml d^{-1})	Average daily abstraction from g'water (seasonal variations defined elsewhere).
Initial percolating store (fraction)	Defines the starting storage level of the percolating g'water store.
Initial g'water depth (m)	Defines the starting level of aquifer storage.
Sub-area routing K	Parameter in the storage-discharge routing function (summer and winter values).
Sub-area routing n	Parameter in the storage-discharge routing function.
Channel losses parameter (power)	Power parameter in the transmission loss function.
Flow infiltration area (km^2)	Area over which transmission losses can take place.
Mannings n / sqrt(channel slope)	Used in the transmission loss function and to estimate gradients for some soil and g'water outflow functions.
Channel infiltration k	k parameter in the channel infiltration curve equation.
Channel infiltration C	C parameter in the channel infiltration curve equation.
Channel infiltration-storage power	Parameter to define the relationship between infiltration rate to transmission losses and available storage.
Channel routing delay (h)	Travel time delay from the sub-area centre to the catchment outlet.
Channel routing k	Routing parameter in the channel storage-discharge relationship.

2.5.2 Use of the VTI model

While many of the parameters are based on commonly measured variables of catchment hydrological processes, it should be recognised that semi-distributed models of this type treat the simulation of individual sub-areas in a lumped modelling approach. This means that direct measurement of parameters is not really possible due to the spatial heterogeneity that occurs in any hydrological process at the scale of typical sized sub-areas (a few km^2 to over 100 km^2). Quantifying parameter values is therefore never a simple task, while at the same time it is important to generate total streamflow response for the right reasons and with more or less the correct balance between the individual components (surface, soil and groundwater runoff). The perceived hydrological response of the catchment and how this response can be represented by the model, should be the main consideration when calibrating the model. Otherwise the calibration exercise becomes purely numerical, the use of such a detailed model becomes counter productive and the extrapolation of the results to a period other than that used for calibration could be highly unreliable. There are many simpler models, with far fewer parameters, that can be applied if a purely numerical (rather than hydrological) calibration procedure is to be followed (see also the points raised in the section on the Pitman model). The advantage of such models is that they can frequently be fitted automatically, using parameter optimising techniques, and that they do not rely upon an understanding of the actual processes prevailing within a catchment. The disadvantages are that the calibrated parameter set may be totally unique to the time series period used for calibration, it is unlikely that the internal components of the model can be interpreted with respect to actual catchment processes and such models are difficult to use for future scenario (land use change, climate change, etc.) planning.

The extent to which simpler numerical models, compared to more physically realistic models, can be applied successfully in ungauged catchments is still unclear. The usual procedure for such applications of the simpler type of model is to carry out calibrations for all possible catchments with observed data and develop regional parameter relationships which can possibly be transferred to ungauged sites. This has frequently been found to be an unsuccessful exercise for the very reason that the model parameters do not have any real physical meaning and it is therefore difficult to know what they should be related to when trying to develop regional relationships. However, more physically realistic models are constrained by the problem that there is frequently not enough information known about catchment physical properties to evaluate the parameters in a reliable way and that many such models also have some highly empirical parameters that cannot be easily evaluated, even if extremely detailed information is available. This dilemma has plagued the science of hydrological simulation modelling throughout its history and is likely to be an issue for many years to come.

With respect to the VTI model (and models of a similar type), its successful application relies upon developing a reasonable understanding of the hydrological processes prevailing within a catchment and how to reproduce these through the model. The implication is that the potential user should have a sound appreciation of physical catchment hydrology, the model structure and the effects of changing parameter values. The latter can only really be developed through experience with the use of the model. In terms of the FRIEND project, where most of the calibrations were carried out without any catchment site visits, there will always be a measure of uncertainty about whether the real catchment processes have been adequately represented.

As with the Pitman model, a detailed study of the observed rainfall and runoff response, prior to the start of the calibration process, can prove to be invaluable. Essentially, this procedure involves looking for 'signals' in the observed response that suggest the operation of certain types of hydrological processes and then deciding how these can be reproduced with the model. Some types of signals that are appropriate to look for are :

- Do small, but high intensity rainfall events during the dry season generate a streamflow response ? - this may help to define the infiltration parameter values.

- What is the nature of the baseflow response of the catchment ? - Is there a dominantly seasonal response that suggests long term drainage from ground water storage ?

- What is the shape of the shorter term baseflow response immediately following more rapidly responding high flow events ? - The latter can help to determine the soil storage and drainage characteristics.

- The balance between runoff response at the start of a wet season and later in the season can be useful to define the moisture storage characteristics and the extent to which early wet season rainfall can satisfy soil moisture deficits. It can be particularly useful to examine relatively dry years, where less rainfall occurs and moisture deficits take longer to be satisfied.

None of these will necessarily allow the parameters to be quantified, however, they can be very valuable to guide the user in the choice of which parameter, or groups of parameters, to concentrate on to improve the simulation results once the initial parameter values have been estimated. A procedure that is adopted within the IWR is not to calibrate some of the parameters, but to reconsider the way in which the catchment characteristics have been evaluated in the light of the initial simulation results, to revise their values and allow HYMAS to derive new estimates for the parameter values. For example, if the results indicate that the soils should be deeper, or should have higher hydraulic conductivities, the user can try and justify revising the estimates of the soil characteristics by re-examining the available soils information.

2.6 Other supporting models.

2.6.1 Reservoir simulation models.

While both the Pitman and VTI model have components that are designed to simulate the effects of small reservoirs, there are frequently situations where a more detailed approach to modelling impoundments is warranted. Neither of the two catchment models can deal with a reservoir that is located on a main channel and which has inflow contributions from upstream sub-catchments in the distribution system. This is because the small dam routines in both models can only receive inflows from all, or a portion of, the sub-area in which they are located. The simulation of the effects of larger dams is therefore carried out using either the monthly or daily reservoir models in a linked modelling approach.

Both of these models are relatively simple water balance approaches, although can be used to simulate several closely linked impoundments, with associated transfers of water between them, which complicates the setting up and operation of the models, but allows more complex systems to be simulated. Abstraction and compensation flow release patterns are defined on the basis of monthly distributions with some operating rule control linked to the stored volumes of water.

The main difference between the daily and monthly versions is that the full supply level in the monthly model is never exceeded and any excess inflow becomes spillage within the same month. Spillage, within the daily model is controlled by a relatively simple hydraulic flow equation based on the water level calculated from the
volume through a user defined depth-volume relationship.

$$\text{Overflow } (m^3) = \text{head}^{1.5} * \text{SPILLC} * \text{SPILLW} * 86400 \quad \text{Eq. 2.3}$$

where head is the depth above full capacity, averaged over the start and end of the time interval,
SPILLC and SPILLW are the spillway coefficient and width respectively and are model parameters,

and 86400 represents the conversion factor from flow rate to volume over 1 day.

The models can be calibrated against time series of observed outflows and/or observed stored volumes and can accept observed or simulated values as inflows. Similarly, the outflows can then be used as upstream inflows to one sub-area of a rainfall-runoff model established for a downstream catchment.

2.6.2 Patching model

The Patching model (Hughes and Smakhtin, 1996) was designed as a pragmatic approach to filling gaps in existing daily streamflow records and extending daily flow time series. However, current research is concentrating on extending the application of the model to the regional simulation of daily flow sequences. It has been applied in the FRIEND project to a limited subset of the catchments, specifically where daily rainfall data were not made available and the VTI model could not be used. The model is based upon the use of a spatial interpolation algorithm between flows at different sites (within the same catchment, or in different catchments within the same hydrologically similar region).

In an attempt to account for some of the non-linearities in streamflows at different sites, even within similar parts of the same basin, the spatial interpolation algorithm has been based on the daily flow duration curves for each month of the year. The first step in the procedure is to generate tables of discharge values for each site and month of the year for 17 percentage points of the flow duration curves (DTQ_i, where $i = 1$ to 17 corresponding to 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99%). Up to five possible 'source' stations are then identified and each assigned weights (W_j, $j = 1$ to 5) associated with the degree of similarity between these flow regimes and the 'destination' site (the one to be patched or extended). An estimate of the streamflow on any day at the 'destination' site is then made by identifying the percentage point position (DP_j) on the duration curve table (for the relevant month) of the streamflows on the same day at the 'source' sites (QS_j) and reading off the flow value (QD_j) for the equivalent percentage point from the 'destination' site's duration curve table. The procedure is illustrated in figure 2.12 for a single 'source' site.

Each estimate of the 'destination' site flow value (QD_j) is then multiplied by the 'source' site weight (W_j) and the sum of these values divided by the sum of the weights. If any of the 'source' sites have missing data then these are ignored for those periods.

$$QD = \Sigma(QD_j * W_j) / \Sigma W_j \quad \text{Eq. 2.4}$$

For 'source' streamflows lying between the 17 defined percentage points of the duration tables (DTQ_i), logarithmic interpolation is used to define the position. Thus :

$$DP_j = EXP\{(lQS_j - lDTQ_{j,i}) / (lDTQ_{j,i-1} - lDTQ_{j,i})\} \quad \text{Eq. 2.5}$$

$$QD_j = DP_j * EXP\{(lDTQ_{s,i} - lDTQ_{s,i-1}) + lDTQ_{s,i}\} \quad \text{Eq. 2.6}$$

where DP_j is the duration table percentage point position,
$lDTQ_{j,i}$ the natural log of the closest duration table flow value less than QS_j,
$lDTQ_{s,i}$ the natural log of the flow value at the same percentage point in the 'source' site duration table,

and i-1 refers to the percentage point one step higher than i.

While occurring very infrequently, special cases exist if the 'source' flow is either greater than the flow exceeded 0.01% of the time or less than the flow exceeded 99.99% of the time. In the former case QD_j is estimated as $QS_j * DTQ_{s,1} / DTQ_{j,1}$ and in the latter as $DTQ_{s,17}$. A further special case exists where the duration curve of a 'source' station is flat between two of the data table points (denominator of equation 2.5 = 0). The position (DP_j) is assumed to lie halfway between the two points.

The 'parameters' for each 'destination' site are the catchment area, the site number of up to five 'source' sites and their weighting factors. The output from the model consists of the raw observed flow data (including missing data periods), the 'patched' observed flow (no missing data) and what is referred to here as the 'substitute' flow time series. This represents a time series made up of completely estimated values regardless of whether the original observed flow was missing or not. The purpose of 'substitute' series is to allow the patching process algorithm and associated choice of 'source' sites and weights to be evaluated by comparing them with the original observed data in a similar way that simulated series are compared with observed in conventional modelling approaches.

Further details of the application of this model can be found in Smakhtin and Watkins (1997), where some of the extensions to regional estimations of daily time series of flows are also discussed.

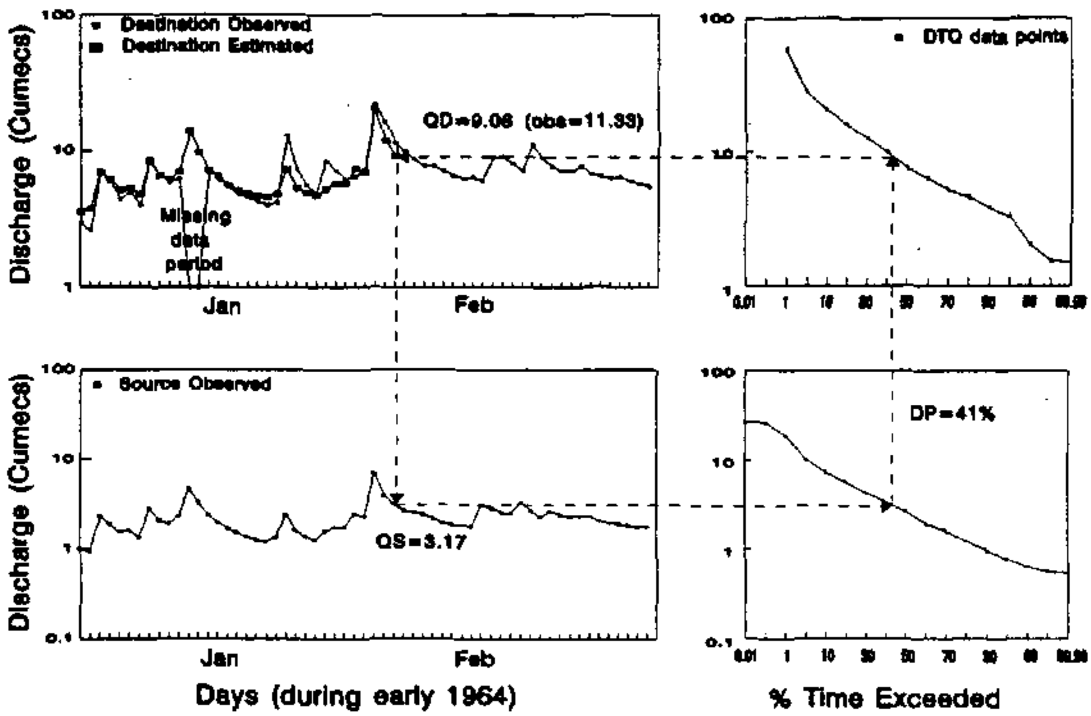


Figure 2.12 Illustration of the patching algorithm for a Swaziland catchment with a single source station. The upper left diagram shows the estimated values for the whole of January for the destination station.

3. THE FRIEND DATABASE

3.1 Introduction

The rainfall-runoff modelling sub-programme of the Southern African FRIEND project is one of five related activities, the other four being the development of regional databases of time series and spatial information, flood frequency studies and low flow or drought studies. This section of the report will provide some information about the two regional database sub-programmes and the way in which they relate to present and future applications of models within the region.

3.2 Time series database

One of the initial activities of the Southern African FRIEND project was to identify a representative set of streamflow measuring stations within the region and begin to bring the daily records of these together into a common database which could be stored at the coordination centre in the University of Dar es Salaam (UDSM), Tanzania. The decision was made to use the HYDATA software, which was made available to all the participating countries by the Institute of Hydrology (IH) in the UK, through ODA funding. HYDATA has facilities for converting various original data formats into its own format, reviewing and editing time series data in various ways, carrying out some analyses (recession, baseflow and duration curves, for example) and outputting the data in various formats. It is currently used by several of the regions national hydrometric agencies as their main hydrological data storage system.

Part of the Rhodes University contribution to the international project was to access the South African Department of Water Affairs and Forestry (DWAF) daily streamflow database, decide on the stations that should be transferred to the FRIEND database, convert the data to HYDATA format and transfer the converted files to the coordination centre. To support the flood frequency sub-programme it was also necessary to obtain the mean daily and instantaneous flood peak data from DWAF and pass these onto the Department of Civil Engineering at UDSM.

As the streamflow database was only planned to be finalised quite late during the first phase of the project (1994 to 1996) and because daily rainfall data and evaporation data were not considered as part of the main database, the IWR at Rhodes needed access to the data prior to the database being constructed. The majority of the data from the other countries (excluding South Africa) were collected during visits made by Dr A Bullock and Mr A Andrews (Andrews and Bullock, 1994) of IH and they made every effort to collect the related daily rainfall, evaporation and spatial data (maps, catchment descriptions, etc.) at the same time. The rainfall-runoff modelling sub-programme was therefore almost entirely reliant on the data and information that were collected during this period, although some data were forthcoming at a later stage as well. Further details of the stations used for testing the rainfall-runoff models is provided in the individual country appendices (A1 to A10).

A total of 691 flow gauging stations have been included in the main database and the distribution from the eleven countries involved is summarised in table 3.1. It is clear that there is a somewhat uneven distribution (given the relative size of some countries), but that the data should provide a reasonable representation of streamflow characteristics within the region. Further details about the catchment sizes, locations and lengths of record for these stations can be obtained from the coordination centre and will be reported in the main international FRIEND report to be published by UNESCO during 1997. A catalogue of all the flow gauges operated or operating within the region is available from the coordinating centre at the University of Dar Es Salaam.

Table 3.1 Contributions of flow data from the participating countries.

Country	Number of stations	% contribution
Angola	19	2.7
Botswana	24	3.5
Lesotho	23	3.3
Malawi	39	5.6
Moçambique	16	2.3
Namibia	50	7.2
South Africa	290	42.0
Swaziland	36	5.2
Tanzania	78	11.3
Zambia	31	4.5
Zimbabwe	85	12.3

3.2.1 South African stations

The South African stations were selected to produce a representative sub-set of the approximately 1500 available from DWAF that also loosely matched several criteria. One initial criterion for inclusion in the FRIEND database was that the catchment area should be less than 1000 km^2, however, that would have excluded a large percentage (38%) of the South African stations and so this criterion was relaxed and only the very large basins left out of the sample (figure 3.1). A second criterion, that the flow regimes should be largely unaffected by abstractions, effectively excludes most of the large basins anyway. However, this second criterion was also difficult to satisfy, as a large proportion of South African rivers are developed for water supply purposes and it is difficult to find stations, except those with very small catchment areas, that are totally unaffected. A previous Water Research Commission Project on instream flow methodologies (King and Tharme, 1994) adopted a similar set of criteria to select some 350 catchments for analysis and their stations provided a starting point for the FRIEND project selection. Figure 3.1 illustrates that the selected stations are biased toward the smaller catchments (< 200 km²) and away from the catchments greater than about 2000 km² in area.

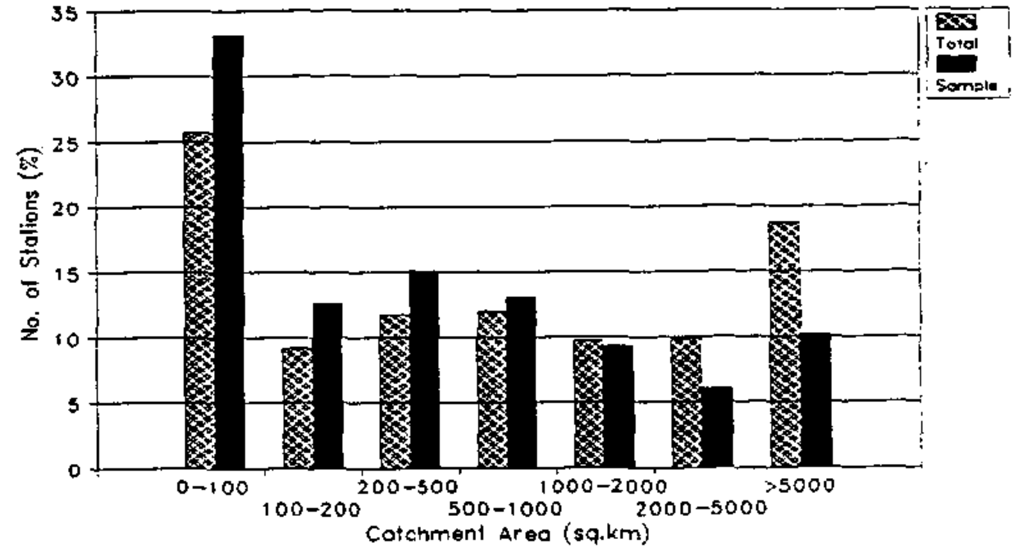


Figure 3.1 FRIEND stations (sample) compared to all South African streamflow stations (total) - by catchment area.

The third criterion was related to record length and suggested that the majority of the selected catchments should have at least 15 years of usable data which is relatively uninterrupted by missing values. Figure 3.2 shows the distribution of total record lengths for the initially selected catchments (344 stations) and the clear bias toward longer records. However, it should be noted that much of the daily flow data for South African gauging stations is based on single daily stage observations prior to the 1960s when automatic recorders came into operation. Figure 3.3 therefore illustrates the distribution of record lengths based on autographic data, and while the modal value is still in the region of 25 to 30 years, there are far fewer stations with long records and many more with usable records of less than 15 years.

The final criterion was that the stations should be geographically representative, given that South Africa covers several different climate types. Figure 3.4 compares the geographical distribution of the complete set of DWAF stations with that of the stations selected for the FRIEND project on the basis of 10 grid squares, each 5° * 5° in size and identified by the central longitude and latitude lines (for example 18/33 represents the Western Cape area). There are relatively few stations in some blocks because they do not include much of South Africa (for example 23/23 is mainly in Botswana) It is clear from the diagram that the selected stations are reasonably geographically representative (relative to the total group of available stations).

Data from a total of 344 stations were passed to the coordinating centre and they selected 290 of those for inclusion in the regional data set (table 3.1).

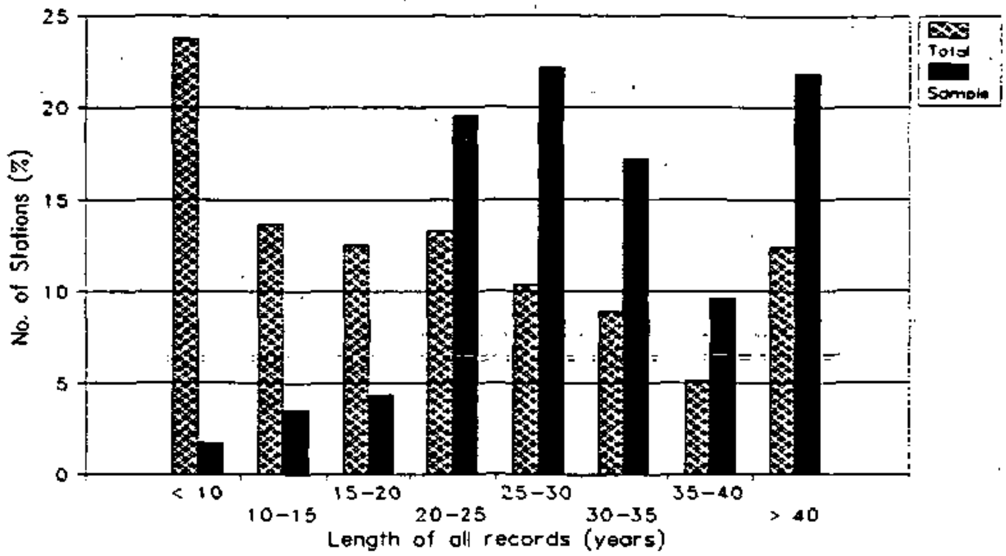


Figure 3.2 FRIEND stations (sample) compared to all South African streamflow stations (total) - by total record length.

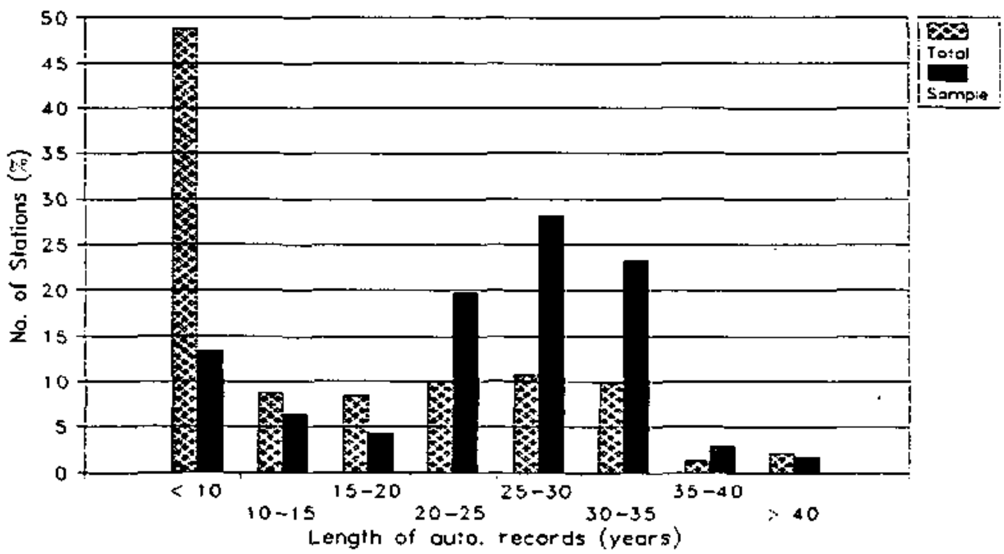


Figure 3.3 FRIEND stations (sample) compared to all South African streamflow stations (total) - by autographic record length.

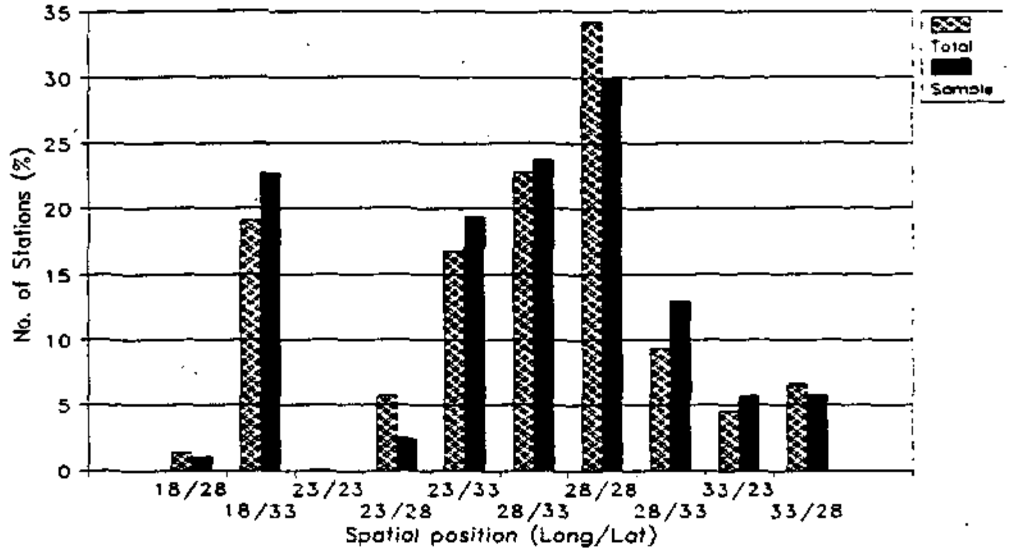


Figure 3.4 FRIEND stations (sample) compared to all South African streamflow stations (total) - by spatial position (the position is defined by the longitude and latitude of the centre of 5° * 5° blocks).

As referred to in the previous chapter of this report, the data transfer (from DWAF to HYDATA format) was facilitated using an interface program written as part of the HYMAS package. The Rhodes research group found this to be the easiest and most efficient way of achieving the objective and it also served a further purpose of providing a facility to extract HYDATA format data for use with the models. Unfortunately, because the rainfall-runoff modelling programme had to proceed in parallel with the development of the database, much of the other countries data was provided in a wide range of formats, all of which had to be catered for in HYMAS. While it would have made the project more efficient if those data had already been part of a HYDATA database, a compensating factor was that it forced the Rhodes team to include more data format exchange facilities within HYMAS.

3.2.2 Time series data availability, resolution and quality

Streamflow data

The streamflow data that were made available was the most complete and all at a resolution of 1 day. However, very little information was provided about the type of gauging structure (if any), or about the methods of stage recording (continuous or discrete readings). While it was the responsibility of the individual countries hydrometric agencies to only include stations for which data error checking had been carried out, no information is available from the central database about the accuracy of the records. It is fairly certain that some of them will be based on discrete daily observations (therefore possibly missing peak flows and under-estimating the true mean daily flow), and particularly the older records before continuous monitoring equipment became more widely used in the region. Other possible problems could be related to inaccurate rating curves, inadequate sized structures or rating curve ranges for measuring high flows, or situations where the shape of the natural section or structure means that low flow fluctuations are difficult to observe accurately. It is anticipated that at least some of the records from all the countries suffer from these problems, but it is a different matter to identify which ones without a detailed analysis of the observation techniques and the records. The latter was certainly beyond the scope of this project.

In most of the South African cases, gauge exceedences can be identified from the flood database and it is often possible to identify the maximum flow rate that can be measured. However, DWAF have recognised that some of the flow gauging records for South Africa do have problems and while a programme of re-rating is under way, it takes time to identify the problem gauges and improve the data. As can be seen from the appendices, some time series from other countries were identified as being probably erroneous (based on several factors), while for most of them it was necessary to assume that they were adequately accurate.

One of the warnings about the future use of the database, is that further error checking, re-rating and other data re-evaluations could be taking place within the hydrometric agencies and that more accurate streamflow information might be available direct from these agencies than from the FRIEND database.

Rainfall

The rainfall data were collected at the same time as the flow data, but in most countries the rainfall databases are operated by a different agency to the flow data. This seems to have caused a number of difficulties in accessing and retrieving the necessary rainfall data to match the catchments that were selected for testing the rainfall-runoff models. In the case of some countries, only monthly data were made available, while in others a relatively poor sample of the total available data was actually provided to the project. These factors resulted in the rainfall data being the major limitation to the project and seriously affected the capability to generate satisfactorily representative mean catchment, or sub-catchment, rainfall inputs. The fact that different agencies collect the rainfall data, and that it was the streamflow data collection agencies who are represented on the overall FRIEND project, meant that it was almost impossible to obtain further rainfall data after the initial data collection exercise within the time frame of the project. This is an issue that needs to be addressed within the region as a whole if hydrological studies, involving both rainfall and runoff data, are to be promoted and their results contribute to better water resource planning and management. Cooperation between all agencies collecting hydrometeorological data is essential.

One advantage that South Africa has over the other countries is the availability of the gridded (1' * 1') median annual rainfall data (Dent, et al., 1989) for the whole country (and including Lesotho and Swaziland). These data were compiled by the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg and available from the Computing Centre for Water Research (located at the same University). They are based on spatial interpolation algorithms using all the available station rainfall data for South Africa and are extremely useful in generating mean catchment rainfalls where spatial rainfall gradients are high and gauge densities relatively low. A similar coverage is available for potential evaporation (Schulze and Maharaj, 1991), although has not been used in this project.

Evaporation

While time series of evaporation data represent a similar issue to rainfall, it was not expected that there would be a large number of stations for which evaporation data were available and the models used have already been demonstrated to work satisfactorily with mean monthly estimates. The amount and type of evaporation data that was provided varied throughout the region and it was not always clear what the source of data was. There are many different ways in which evaporation data are estimated or measured, varying from A and S pans, to estimates based on meteorological data (Penman, Penman-Monteith equations, etc.). For example, some of the data provided were based on pan observations, but it was not made clear whether they were A or S pans. In some cases only regionalised maps of potential evaporation were made available and again it was not always clear what methods were used to develop these maps. It must therefore be recognised that many of the evaporation demand estimates used within the rainfall-runoff modelling programme are of uncertain quality.

Other time series data

Other time series data that are potentially relevant to a study of this type are those related to landuse changes and temporal variations in water abstractions. In general terms, no such data were made available to the project, except for those specific catchments selected for testing the models sensitivity to landuse change. In some South African catchments, reported or measured (by DWAF) water abstraction patterns were available and were collected for the 'Low-Flow' project (Smakhtin and Watkins, 1997) that was operating in parallel with the FRIEND project.

3.3 Spatial database

Part of the overall FRIEND project was to compile thematic coverages (geology, soils, vegetation, rainfall, evaporation, etc.) for the whole region. The responsibility for this was shared between IH, UK and UDSM, Tanzania and the details of this component of the project will be reported in the UNECSO Southern African FRIEND project. The only data that was used by the rainfall-runoff modelling sub-programme were the coverages of gauged catchment boundaries as the remainder were still being prepared during the course of the model testing exercises. Most of the coverages are based on relatively low resolution data (not better than a scale of 1:250 000) and, although they would have been extremely valuable as a unified database for background material, would have been of somewhat limited value for the direct estimation of model parameter values in all but the largest catchments. Some of the source material used to compile these coverages was, however, made available to the rainfall-runoff modelling team and was used qualitatively to develop some of the initial parameter sets.

3.3.1 Catchment description data availability

While the availability of catchment description data is dealt with specifically in each of the individual country appendices, some general comments are pertinent in this section of the report. The availability of this type of information is highly variable throughout the region. In some countries, for example, quite detailed soils, vegetation, geology, hydrogeology, etc.

maps are available, albeit at relatively course scales. In others, reliance had to be placed on very generalised descriptions in books and reports. There is little doubt that more is available than was used, but the resources of the project did not allow for searching various sources to obtain more detailed information. One of the conclusions of the project is that a unified directory of information of this type (from books, maps, reports, etc.) for the whole region would facilitate future studies related to catchment hydrology. Such a directory could include brief descriptions of the nature of the information, its original date, the source from which it can be obtained, any related costs and the details of restrictions on its distribution or use.

One problem which is common to nearly all the countries is the nature of the soils data that is available. It is frequently based on agricultural and crop production criteria, that is not always useful for hydrological studies. Given that soils information (texture, depth and water retention and hydraulic characteristics) is probably the most important input to a model, from the point of view of parameter estimation, it is unfortunate that more data of this type does not exist.

3.4 General comments on information availability and resolution

In general terms, the amount of information available is less than is usually considered sufficient for model testing purposes. However, it should be recognised that the objectives of the sub-programme were not to test the models as such, but to test their applicability to simulating the catchment hydrology of the region. As any experienced hydrological modeller is aware, there is commonly much less information available (or less time to gather more) in practical application situations than in research situations, where models are developed and properly tested. The test applications that are included in this report therefore represent examples of the type of situation that would be faced by hydrologists operating in the region and attempting to apply models for practical, water resource applications. In fact the situation may be even better in many situations as they would normally be dealing with a smaller area and number of catchments and would have more time to ensure that they had access to all possible information for the area of concern, particularly with respect to rainfall.

However, it is apparent that there is a need for better coordination and indexing of the possible sources of information relating to catchment hydrology. The FRIEND project has played a role in identifying some of these sources and of bringing them together. This should become more apparent when the final UNESCO report is published, which will include chapters on all the sub-programmes of the project.

4. SUMMARY AND DISCUSSION OF RESULTS

4.1 Introduction

The results for each country and those for the modelling tests carried out on the landuse change catchments are presented in detail in appendices A1 to A11. These appendices discuss the availability of time series and catchment description data, identify the specific catchments used in the study and provide some brief descriptions of their characteristics. They also outline the calibration procedures that were followed and present the simulation results. The results are presented mainly using a standard set of statistical comparison criteria between observed and simulated streamflows. These criteria are the observed and simulated means and standard deviations of either monthly (Pitman model using Ml = $m^3 * 10^3$, or MCM = $m^3 * 10^6$) or daily (VTI model using $m^3\ s^{-1}$ or $l\ s^{-1}$) flows, the percentage error in the estimation of mean flow and the coefficients of determination (R^2) and efficiency (CE). Two sets of statistics are provided, one for un-transformed data and one for natural log transformed data. While the former are strongly influenced by extremes (high flows and floods), the latter are less so and provide a better indication of the degree to which the models have satisfactorily simulated low to moderate flows.

The coefficient of determination is defined as the square of the correlation coefficient (R) which is the covariance divided by the product of the standard deviations of the observed and simulated flows :

$$R = \Sigma\{(\text{Obs.} - \text{Obs. Mean})(\text{Sim.} - \text{Sim. Mean})\} / n.S_o.S_s \quad \ldots\ldots\ldots \text{Eq. 4.1}$$

where S_o and S_s are the standard deviations of the observed and simulated flows respectively.

This statistic is not sensitive to systematic errors and a high value (close to the maximum of 1.0) can be achieved despite the fact that simulated values generally over- or under-estimate the observed. The coefficient of efficiency is sensitive to systematic error and is defined by :

$$CE = 1 - \Sigma(\text{Obs.} - \text{Sim.}) / \Sigma(\text{Obs.} - \text{Obs. Mean}) \quad \ldots\ldots\ldots\ldots\ldots \text{Eq. 4.2}$$

Values of less than zero imply that the observed mean value provides a better estimation of each individual flow value in the observed time series than do the equivalent simulated values - clearly a situation that suggests a poor simulation. With un-transformed values it is not uncommon to achieve quite a high R^2 statistic and a low or negative CE statistic, while getting quite high values for both statistics using transformed values. This would normally suggest that the peak values are consistently over- or under-simulated and that the relevant model parameters should be adjusted, unless other factors (such as poor measurements of high flows) suggest otherwise.

While there are many other statistics (see, for example, Görgens, 1983) that could be used, for the purposes of the FRIEND study, those included provide an adequate impression of the applicability of the models and the success of the simulations when supported with graphical illustrations of the results.

The appendices also provide example graphics to illustrate the comparisons between observed and simulated flows. These are either in the form of comparative time series plots or duration curves. There are a large number of other comparative analyses that can be carried out using the HYMAS package (see Smakhtin and Watkins, 1997 for some specific examples, particularly related to low flows), but limitations of space in this report has precluded their inclusion.

Only in special circumstances do the appendices provide information on the relative performance of the models over the period used to calibrate the models compared to the validation period. In most cases the results presented cover both periods. This is largely because there was rarely a systematic difference between the results for the two periods and variations in model performance between different periods were usually related to other factors. At least part of the reason for this feature must be that the calibration periods were chosen to be representative, in terms of runoff variations, of the total time series period available. Had the models been calibrated on relatively wet or dry periods, then the differences may have been much greater. The implication is that if the available records are not very representative of the flow regimes of the catchments used, the calibrated parameter sets may not be applicable to other periods. This problem is always present when using limited lengths of observed flow data for model calibration exercises and suggests that further validation (and re-calibration) should take place when more data become available.

The results appendices do not include a section for Angola as the data were only made available to the FRIEND project during 1996 and no rainfall data were supplied. No Pitman or VTI model simulations were carried out for Lesotho, largely because of uncertainties in the project teams ability to define the catchment rainfall inputs in this mountainous and sparsely gauged area and partly because of the simulations that have been carried out as part of the Lesotho Highlands scheme (see LHWP, 1986 and related reports). There has been a certain amount of controversy over the estimation of streamflow regimes in the region and it was considered that it would be better to wait for the existing problems to be resolved before any new attempts at modelling these catchments are made.

4.2 Pitman model

Table 4.1 provides a summary of the results that were obtained from the application of the Pitman model and it is immediately apparent that they are highly variable. In some cases the lower values in the ranges of R^2 and CE statistics represent outliers that can be accounted for by poor input data or similar problems that are unrelated to the model itself. The results can be summarised in several points :

- In general terms and all other factors being equal, the model was simpler to calibrate and performed better in the sub-humid to humid parts of the region, with the most consistent results being obtained for the wetter parts of Zimbabwe, Swaziland and Moçambique. The results for Malawi are strongly affected by the limited amount of rainfall data that was made available and the fact that there seem to be some quite steep rainfall gradients across the catchments. A similar problem existed in some of the Tanzanian catchments. The upper range of values given for the statistics (R^2 and CE generally greater than 0.7) are the sort of values that might be expected from the application of the Pitman model to most South African catchments that do not lie in the more arid parts of the country and for which the rainfall inputs can be reasonably defined. Part of the reason for the better performance in more humid catchments is the fact that there are more 'signals' in the observed data which can be used to guide the calibration process, whereas in semi-arid to arid areas the 'signals' are often confused by extremes. These 'signals' are generally recognisable in the catchments response to different types of rainfall, both short term (i.e. individual months) and longer term (i.e. seasonal variations). The 'signals' include high flow responses, short term recessions and longer term seasonal recessions. The short term recessions are less evident in monthly data, but can be noticeable in monthly flow regimes from relatively large catchments (see comments and figures 4.1 to 4.3 in the discussion on the VTI model).

- The application of the model in semi-arid to arid areas (Namibia and Botswana, for example) is limited by the inability of the rainfall gauging networks in these areas to adequately represent catchment average rainfall and by the fact that inter-monthly distributions of rainfall can be highly variable and therefore not always adequately represented by the fixed procedure used within the model. A further limitation exists in that some of the processes that are active in semi-arid to arid areas are not represented by the normal version of the model. Specifically, there is no transmission loss function and this can affect the way in which the model is set up for different scale catchments. For example, a relatively small catchment simulated on its own may require a different parameter set than if it is part of a larger catchment. This is because some of the streamflow generated in the upstream area may be lost before it contributes to the runoff at the outlet of the larger catchment. There is some evidence (from discussions with other users of the model) that this type of problem can be partly solved by establishing a 'dummy dam' within the downstream areas, such that upstream inflow has to satisfy some storage requirement before generating runoff downstream. A possible problem with such an approach is that transmission loss processes are likely to be more complex, related to flow rates as well as volumes, and more non-linear than the use of this technique suggests. However, it may represent a useful approach which is better than not accounting for losses at all.

- Although the statistics for the semi-arid simulations are usually relatively poor, observed and simulated duration curves are frequently very similar (see figures A4.2, 3 and 4 and A8.2 and 3) over the main range of flows. The Pitman model does seem to simulate more months with flow than observed, but the volumes of runoff in these months is usually quite low and do not constitute a large proportion of the total runoff. From a water resource assessment point of view, the simulation of a long representative time series that reproduces the characteristics of the observed duration curve may be more important than accurate reproduction of individual observed monthly flows. This issue is further discussed in the Namibia appendix where observed and three simulated flow time series were used as upstream inflows to a reservoir simulation model and the yield differences analysed.

- Some aspects of simulating semi-arid to arid catchments have been improved through limited modifications to the Pitman model. The specific situation in the Namibian catchments, of a dynamic vegetation response to variations in the depth of seasonal rainfalls, has also been addressed through further modifications to the original model and the development of the 'NamPit' model. However, while the modifications generated better overall results than the original model, they are still not as good as the results obtained from the NAMROM model which was developed specifically for Nambian catchment conditions. It is also unfortunate the information on the actual processes involved, or the extent of the dynamic vegetation response (quantified through satellite imagery perhaps) is not available. Such information would have been extremely useful in formulating the vegetation cover algorithm and in quantifying the parameters that control its operation.

- The application of the model to the Southern African region, under the circumstances of data availability that prevailed during this project, highlights the fact that it is difficult to obtain acceptable results when there are great uncertainties in the reliability and representativeness of the input data. It is likely that the real amount of rainfall data available from some parts of the region is better than that which was used in this study, where there was little time to try and obtain all that was available and the contacts with the correct hydrometeorological observation agencies were not very well established. However, the conclusion does serve to remind potential users that there is no substitute for adequate rainfall input data. The same applies, to a certain extent, to potential evaporation data, although because of the lower variability and the consideration that other factors can be just as important in determining actual evaporation rates, it appears that long term monthly means can be used successfully. No tests have been carried out to determine whether better results could be obtained if adequately representative time series of potential evaporation data were available. Part of the reason for this is that there are relatively few such observation stations within the region, spatial variations in potential evaporation are not very well understood and it would be difficult to determine whether an available time series could be considered representative or not.

- One of the other issues that affects the success of the simulations is the availability of information relating to changes that affect the streamflow regimes of rivers and their stationarity over long time periods. This may relate to landuse changes, or to the development of impoundments and abstractions direct from the river. Where large and centrally organised schemes exist, some information is often available (particularly in South Africa), but where the effects are more distributed (such as the development of farm dams, small scale but widespread irrigation, etc.), there is often very little information.

Table 4.1 Summary of Pitman model results based on monthly streamflows in Ml ($m^3 * 10^3$). The Namibia results are based on the modified version of the Pitman model and the landuse catchments on the results after parameter slicing.

Country	No. of catchments	Range of areas (km^2)	Range of record lengths (month)	Un-transformed			Ln-transformed		
				Mean % errors	R^2	CE	Mean % errors	R^2	CE
Zimbabwe	14	146 - 3320	66 - 264	-8.7 : 10.8	0.47 : 0.86	0.42 : 0.85	0.2 : 17.5	0.35 : 0.83	0.25 : 0.79
Malawi	5	18 - 1460	31 - 141	-12.4 : 6.5	0.01 : 0.84	< 0 : 0.82	-1.8 : 1.5	0.08 : 0.91	< 0 : 0.86
Swaziland	7	166 - 1305	120 - 268	-5.2 : 10.0	0.45 : 0.81	0.39 : 0.80	0.1 : 2.0	0.59 : 0.86	0.48 : 0.85
Botswana	10	570 - 21216	90 - 228	-8.7 : 11.8	0.39 : 0.77	0.27 : 0.70	-20.9 : 1.7	0.10 : 0.49	< 0 : 0.38
Moçambique	5	3100 - 26314	127 - 159	-9.0 : 6.1	0.37 : 0.84	0.21 : 0.84	-0.7 : 5.1	0.60 : 0.80	0.56 : 0.78
Tanzania	6	140 - 1940	128 - 250	-7.6 : 3.3	0.26 : 0.81	< 0 : 0.78	-0.4 : 12.5	0.19 : 0.87	0.02 : 0.86
Zambia	14	256 - 65983	157 - 235	-20.1 : 6.5	0.05 : 0.79	< 0 : 0.78	-7.1 : 1.9	0.12 : 0.83	< 0 : 0.82
Namibia	9	212 - 14096	219 - 350	-2.5 : 3.5	0.19 : 0.82	< 0 : 0.82	-16.7 : 1.6	0.07 : 0.69	< 0 : 0.68
Lesotho	Not modelled but some results (generally acceptable) available from the LHWP (1986) report								
South Africa	Not modelled in this project but normally good results obtainable in most areas (see WR90 reports for regional parameters)								
Landuse	7	0.21 - 2.88	144 - 276	-12.6 : 39.0	0.47 : 0.94	0.25 : 0.90	-4.3 : 25.9	0.63 : 0.92	0.20 : 0.91

4.2.1 Regionalisation of model parameters

The Surface Water Resources of South Africa 1990 reports (WR90, 1994) include regional parameter values for the countries of South Africa, Swaziland and Lesotho and are designed to be used for the simulation of natural flow regimes. These values can be used as first estimates in calibration exercises, or to generate representative time series at ungauged sites. In the latter case, any user must be aware of the limitations of the recommended parameter values and that they can only be considered applicable to the range of catchment sizes and types that were used in their derivation. For example, in steeper headwater areas the parameter values would be inappropriate, as the regional sub-divisions (quaternary catchments) were carried out at a much coarser scale. Despite these limitations, the guidelines on parameter value estimation are extremely valuable and have enhanced the value and overall applicability of the model in this part of southern Africa (South Africa, Swaziland and Lesotho). The results of this study were based on simulations of a large number of catchments within the region and the first phase of the Southern African FRIEND project did not have access to the resources necessary to repeat such an exercise for the rest of the sub-continent. However, during the calibration exercises, the potential for future regionalisation of parameter values was considered.

For most countries, there were far too few catchments used in the study to be able to make any firm conclusions about regional patterns of suitable parameter values, and frequently this issue was further confused by uncertainties in some of the data inputs (notably rainfall). The potential for regionalisation of parameter values in Zimbabwe would appear to be quite good, given that additional catchments, particularly in the drier western parts of the country, could be included. Although less clear, there also seems to be some potential in Botswana and Zambia. The potential for Zambia might be clarified if more rainfall data were available for those parts of the catchments used where large gaps currently exist. The potential for the other countries is largely unknown, but at the same time it should be recognised that fewer catchments were used.

4.3 VTI model

Table 4.2 provides some summary statistics to illustrate the level of success of applying the daily time-step VTI model to a sub-set of the catchments used with the Pitman model. In some cases the daily model was not applied because daily rainfall data were not made available (Namibia and Malawi) and in others (some Tanzanian catchments, for example) because the Pitman model applications had revealed problems with the data that could not be resolved. In general terms, it can be seen that, except for Botswana, the performance statistics are similar to those generated by the Pitman model. However, it should be remembered that those given in table 4.2 for the VTI model are based on daily data, while the Pitman results are based on monthly data. In fact, in those cases where the Pitman model performs reasonably well, statistics based on monthly accumulations of simulated daily flows from the VTI model are very similar. In other cases, the VTI model often, but not always, generates monthly volumes that are improvements on those generated by the Pitman model, particularly in the low flow components of the regimes. Several observations can be made about the application of the model to the region.

- In terms of the suitability of the available time series data for daily modelling purposes, the situation is very similar to the application of the Pitman model. There are many areas where the data that were made available were less than adequate to represent the likely spatial variations. In some cases this proved to be restrictive and prevented satisfactory calibrations from being achieved. In other areas, there were situations where calibrations could be achieved, but the level of uncertainty regarding the suitability of the calibrated parameter set was quite high because of the uncertainty in the representativeness of the input data.

- There was rarely sufficient information on the physical characteristics of the catchments to be able to express a high degree of confidence in the initial quantification of the parameter values. Where more information is available, it is usual to fix certain parameter values and calibrate those that have less direct physical meaning (or which are more difficult to quantify from physical catchment characteristics). This means that in data scarce situations, the calibration exercise is made more difficult because there are more parameter values that potentially need to be modified. This is always a problem with more complex models that have a large parameter set and where the parameters have strong interrelationships in the way in which they affect the simulation results. The implication is that without a large effort expended on collecting more information, complex physically-based models are difficult to apply to the region as a whole. There tends to be more detailed databases on physical catchment characteristics in South Africa than elsewhere in the region, but many of these even have not reached the stage of being readily available at costs that are low enough to promote their widespread use. In other parts of the region, such databases are being developed, but often at spatial resolutions that are not really adequate for the purposes of simulating the hydrology of small to medium sized catchments (less than 500 km^2) in detail.

- The same comments made about 'signals' in the observed records, with respect to the Pitman model, are even more relevant to the VTI model, in that there are more 'signals' present in the daily data as they are less masked through the effects of accumulating flows into monthly volumes. Figure 4.1 illustrates a two year period for the Sabie River (at X3H006, catchment area = 766 km^2) and it can be seen that there are a number of 'signals' related to peak flow response, short term recessions after events, long term seasonal baseflow (which declines over the two year period due to a relatively dry second year) and small events outside the main wet season. All of these together provide a great deal of information which can be used to calibrate different components of the model. Figure 4.2 provides a similar illustration for the semi-arid Tati River (at gauge 4511 (catchment area = 570 km^2), which shows that many of the 'signals' are still present although there is no long term baseflow. Figure 4.3 represents a time series for the even more arid Mosetse River in Botswana (at gauge 5211, catchment area = 1026 km^2). In this case the 'signals' are less evident, or more confusing, and difficult to relate to the operation of the model components.

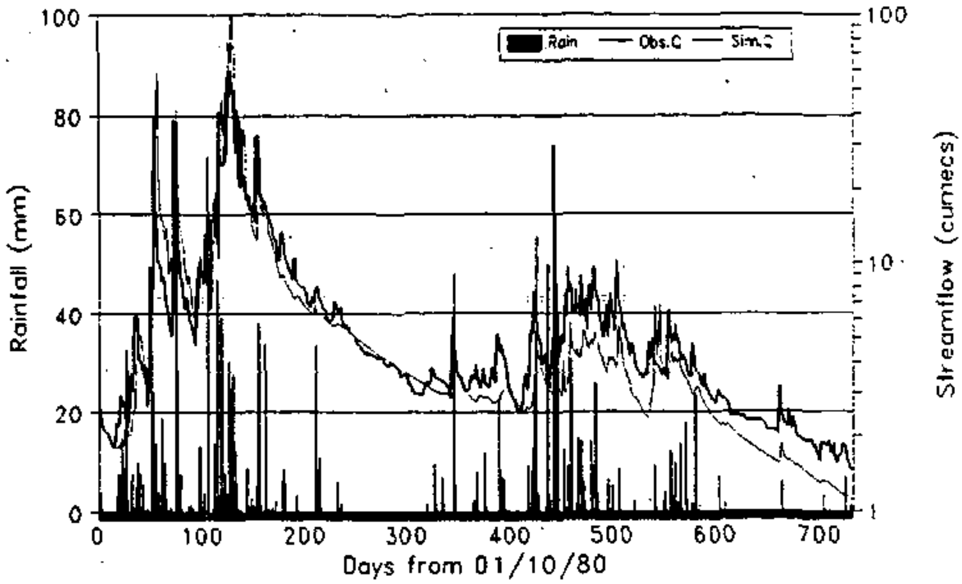


Figure 4.1 Daily rain and flow (observed and simulated) time series for the Sabie River, Mpumalanga, South Africa at station X3H006.

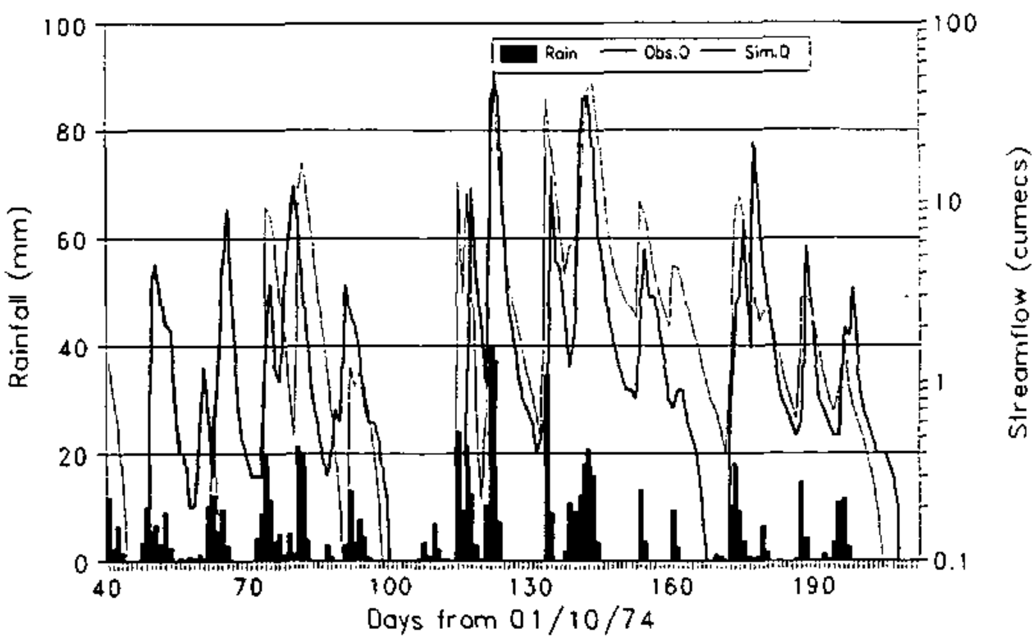


Figure 4.2 Daily rain and flow (observed and simulated) time series for the Tati River, Botswana at station 4511.

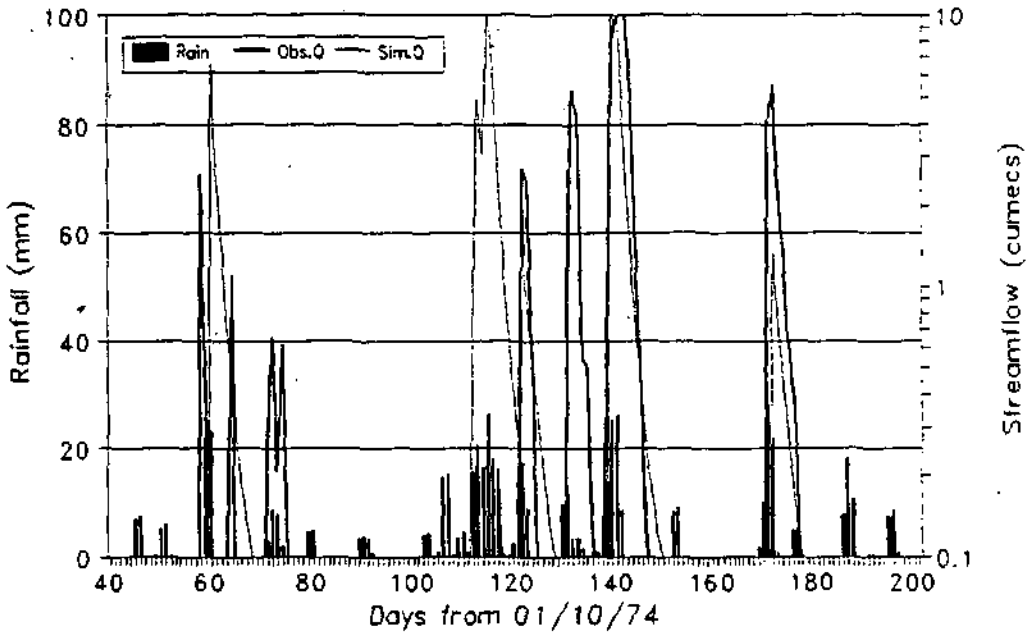


Figure 4.3 Daily rain and flow (observed and simulated) time series for the Mosetse River, Botswana at station 5211.

- The ground water functions are very important in controlling the pattern of baseflows in permanently flowing rivers, and it might therefore be concluded that detailed information on aquifer properties would be required. However, many of the ground water conditions found within Southern Africa are represented by similar examples found in South Africa, where the research team have developed a reasonably good conceptual understanding of the mechanisms involved. It was therefore found that the ground water parameters could be calibrated relatively quickly and successfully from an approximate idea of the lithology of the aquifer and a brief study of the observed low flow response. Nevertheless, it would still be useful to have more information to ensure that the ground water situations are being represented correctly within the model. It is more difficult to ensure that the ground water regimes of ephemeral rivers in semi-arid to arid areas are being adequately represented, because although the research team have experience of applying the model in such areas of South Africa, there are fewer or no 'signals' in the flow regime to help with developing a conceptual picture (figures 4.2 and 4.3).

- The comments made about landuse change and water abstraction information discussed under the Pitman model, apply to an even greater extent to the VTI model. Within some of the South African streamflow data sets, the influence of irrigation abstractions occurring during the week but ceasing on weekends is quite evident. However, the model operates on the basis of mean monthly abstraction patterns. While this influence is relatively easy to ignore and should not affect a visual assessment of the correspondence between observed and simulated flows, it can affect the low flow statistics. A more serious effect is caused by inter-annual variations that have no clear pattern or trend (clear trends can be accommodated using the time-slice options).

- The appendix that discusses the results of the simulations on small experimental catchments that have well documented landuse changes demonstrates that both models can simulate some of these effects with reasonable success, given the constraints of the information provided and the difficulties of defining rainfall inputs in relatively upland and steep topography. It is unfortunate that there are not well documented and gauged catchments within the region where other landuse or abstraction scheme changes have occurred, so that the models could be tested under such situations as well.

- The daily model suffers from similar problems in semi-arid to arid areas as the monthly model and reproduction of individual observed daily flows is rarely satisfactory. However, figures A4.8 and 9 illustrate that duration curves can be reasonably well reproduced, even during a validation period when the fit statistics are very poor.

4.3.1 Regionalisation of parameter values

The issues related to regionalisation of the VTI model parameter values are quite different to those related to the Pitman model because many of the VTI model parameters are supposed to be estimated from catchment characteristic information. The main issues or questions are therefore :

- Do these parameter estimation techniques work satisfactorily in the region?

- Is there sufficient information available about catchment characteristics in the region to be able to make use of the estimation procedures?

- Can regional estimates be provided for the other parameters that cannot be directly estimated?

These are clearly interrelated questions, particularly if the answer to the second question is no and consequently no answer can be given to the first question. In general terms, the amount of detailed catchment data that is readily available is not adequate, but that does not mean that for specific model studies within smaller parts of the region it could not be made available, or obtained from relatively limited fieldwork programmes.

Table 4.2 Summary of VTI model results, based on daily flows (the landuse catchments on the results after parameter slicing).

Country	No. of catchments	Range of areas (km^2)	Range of record lengths (month)	Un-transformed			Ln-transformed		
				Mean % errors	R^2	CE	Mean % errors	R^2	CE
Zimbabwe	6	146 - 3320	66 - 264	-3.5 : 20.0	0.45 : 0.77	0.32 : 0.70	6.0 : 73.7	0.34 : 0.79	0.22 : 0.77
Malawi	No daily rainfall data made available to the project								
Swaziland	7	166 - 1305	120 - 268	-4.3 : 9.0	0.51 : 0.82	0.45 : 0.80	-0.2 : 4.7	0.62 : 0.87	0.60 : 0.84
Botswana	10	570 - 1026	214 - 228	-2.7 : 33.0	0.15 : 0.49	< 0 : 0.43	3.9 : 248.7	0.11 : 0.31	< 0 : 0.22
Moçambique	5	3100 - 26314	127 - 159	-9.2 : 4.5	0.44 : 0.71	0.33 : 0.71	-7.1 : 3.8	0.48 : 0.82	0.19 : 0.80
Tanzania	5	140 - 1940	128 - 250	-15.2 : -0.2	0.14 : 0.67	< 0 : 0.40	-20.8 : 300.0	0.10 : 0.82	< 0 : 0.82
Zambia	1	65983	120	5.0	0.75	0.67	-3.0	0.64	0.51
Namibia	Not modelled								
Lesotho	Not modelled								
South Africa	Many	< 10 - 5000	> 120	Variable, but generally at least as good as, if not better, than the examples from the other countries.					
Landuse	7	0.21 - 2.88	144 - 276	-15.4 : 19.2	0.41 : 0.86	0.15 : 0.85	-4.3 : 11.7	0.61 : 0.90	0.38 : 0.89

The experience of running the model in various parts of South Africa (which covers many of the combinations of climate\soil\vegetation\geology characteristics found in the other regions) suggests that where a reasonable impression of catchment characteristics is available, the parameter estimation routines can provide values which will generate acceptable simulation results. Clearly, these can always be improved upon through calibration.

Although relatively easy to calibrate, perhaps the hardest parameters to estimate, *a priori*, are those that determine the ground water response in the wetter parts of the region which have permanent flow regimes. Small changes in some of these parameters can also make large differences to the resulting low flow regime. Part of this problem lies in the fact that hydrogeological characteristics are difficult to quantify without extensive surveys which usually involve expensive drilling programmes. The other problem is that most of the hydrogeological data that are available are related to the extraction of water from boreholes, which is not always relevant to the broader scale aquifer properties that affect recharge and the ground water flow contribution to surface runoff. There is therefore scope for further regional studies of recharge rates (Bredenkamp, et al., 1995) and low flow regimes (see for example Drayton, et al., 1980) that are linked to broad geological conditions and the way in which these are represented in the model by the relevant parameter values. The results of such studies may bypass the need for more detailed hydrogeological information which is unlikely to become generally available for a long time to come. Regional information on such as recharge can be extremely useful to ensure that the simulations are generating component values that are within the correct range, and if not the parameter values can be revised.

4.4 Other models (used in this project)

All of the models referred to in this section are included as part of HYMAS and therefore the project team have some experience of their application and a clear understanding of their structure.

4.4.1 Reservoir simulation models

The reservoir simulation models (daily and monthly) have been applied in several situations, mainly where large scale impoundments, on the main channel, occurred within a modelling project and could not be satisfactorily simulated using the internal dam and abstraction routines of the Pitman and VTI models. All of these examples occurred within the South African data set (Luvuvhu and Mooi Rivers, for example) and the reservoir simulations were not tested against observed time series of dam volumes and not always against observed outflows. However, the models have been used in other situations where observed data are available for an assessment of the results and they have been found to perform satisfactorily, given that the reservoir characteristics and patterns of abstraction can be defined (Hughes, 1992).

In the case of one Namibian catchment (Friedenau), the observed inflow and stored volume data were used together with averaged patterns of monthly abstractions to establish the monthly reservoir model. The same reservoir model setup was then used to assess the yield estimations that would have arisen from using simulated inflows from the NAMROM, NamPit and standard Pitman models.

4.4.2 Patching model

The patching model (Hughes and Smakhtin, 1996) has been established as a simple tool to extrapolate from gauged daily streamflow records to other periods at the same site (for patching or extension of records), as well as for providing daily time series at ungauged sites using regional flow duration curves. This latter application of the model is still under development but initial results suggest that it has a great deal of potential, particularly when some regionalised monthly flow data are already available. The model has been used in several situations within the FRIEND project including areas of South Africa (Smakhtin and Watkins, 1997), Swaziland, Lesotho and Malawi. The results are encouraging and suggest that the model could have a great deal of potential in the future. The advantages of the approach are the simplicity, the limited resources required to operate the model and the limited amount of catchment information that is required. All of these are pertinent to the Southern African region where there is limited available capacity to operate and run complex daily models.

4.5 Other models (not used in this project)

One of the stated objectives of the project was to collate previous experience of the application of models within the region. It was immediately apparent that the previous application of models is heavily biased toward South African catchments (where research into rainfall-runoff modelling development and application has been extensively carried out since the early 1970s) and toward the various versions of the Pitman monthly model.

Clearly the *Pitman model* has been used extensively within South Africa and there are many applications that have never been widely reported (i.e. part of unpublished consultancy reports). There are also several examples of the Pitman model being applied within the other countries of Southern Africa. It was used on more than one occasion within Botswana (SMEC, 1991), in its original form as well as in a modified form, although the exact nature of the modifications are not clear. It was also used extensively during the Lesotho Highlands project (LHWP, 1986) and there are additional reports of its application within Zimbabwe, Zambia and Tanzania. Unfortunately, none of the details, the calibration procedures followed, nor the results of most of these applications outside South Africa have been published in a readily accessible form. It has therefore been difficult to learn from these experiences and integrate the results into this report.

The SMEC (1991) report on the Botswana catchments refers to the application of the *Monash model* (Porter and McMahon, 1971), a semi-distributed daily time-step model, and that in general terms it performed somewhat better compared to the Pitman monthly model results.

The *NAMROM model* is referred to in the appendix on Namibia and results of applying this very specific model have been discussed in Mostert, et al. (1993) and de Bruine, et al. (1993). It was developed specifically for Namibian conditions and includes components to cater for the negative serial correlation found between seasonal rainfall and runoff and attributed to dynamic vegetation responses. It also contains a simplified function to account for downstream transmission losses. It is, however, more empirical (and less conceptual) than the Pitman model and has not been tested outside Namibia. Appendix A8 suggests that the model is generally better able to simulate the monthly flow regimes of the semi-arid

Namibian catchments than is the Pitman model, even after the modifications that were made during this project.

One daily model that is becoming extensively used within South Africa is the *ACRU model*, which is a semi-distributed, daily model that has been developed by the Agricultural Catchments Research Unit in the Department of Civil Engineering at the University of Natal, Pietermaritzburg (Schulze, 1991 and various ACRU reports including Schulze, et al., 1989 and Schulze, 1995). It has a wide range of features that allow it to be used for water resource estimation as well as crop yield and landuse change scenario modelling. The developers have supported the actual model development with additional routines to facilitate the estimation of parameter values using cross-references to databases of standard parameter values for different soils, vegetation covers, landuses, cropping practices, etc. The user may therefore select the most suitable characteristics and have many of the parameter values estimated automatically. There are several examples cited in Schulze, et al. (1989) and later conference papers of the models success within South Africa. However, there do not seem to be any published reports of the results based on daily data (most use monthly volume comparisons with observed data) and therefore comparisons with the VTI model results contained within the FRIEND report are difficult to make. Additional model development work is still proceeding, with new components being added and others being improved. There is little doubt that the model has a great deal of potential to be useful in the field of water resource evaluation and management within the region.

There are some indications that the *MIKE SHE model* (marketed by the Danish Hydraulic Institute) has been applied within the region and DHI have used the model in three Zimbabwe catchments in a comparative study with the NAM (lumped conceptual type model) and WATBAL (semi-distributed) models (Refsgaard, 1995). The results appear to be favourable with respect to the simulation of monthly flow volumes and the daily duration curves. No fit statistics are provided for daily data. The IWR at Rhodes University is currently evaluating the SHE model and its data requirements with respect to the southern African region, but the project is still in its infancy and no conclusions have been reached yet. The model certainly is more complex to establish than the other models referred to here and it follows that the level of staff and data resources that will be required to apply the model will be greater. This may place severe restrictions on its value for use within the region, given the constraints that have already been noted in relation to the application of simpler models. However, it may still be useful for specific large project tasks where the effort required to set the model up will be rewarded in the long term.

4.6 Conclusions

The general conclusion is that the models can be considered applicable to the region. Where the input data are reasonably representative of the conditions prevailing, the models can be calibrated and generate satisfactory results. There are situations in the more arid parts of the region where the models cannot really be considered to be applicable, largely because of the operation of transmission loss processes that are not well represented in the models. However, this conclusion must be considered in the light of the fact that there seem to be many areas where the available input data are less than representative and therefore, either the models cannot be satisfactorily calibrated, or little confidence can be expressed in the suitability of the parameter values to represent the processes of streamflow generation. The main reason for this is that the parameter values may be as much a reflection of the lack of representativeness of the input data, as they are of the catchment response. Under such circumstances, the reliability of the results is suspect and it is doubtful whether the calibrated parameter values have any real meaning and therefore cannot be used to extrapolate streamflow records for longer periods than have been observed, nor can they be considered to be representative of the type of catchment response found in the region.

One of the recommendations which is referred to in the following chapter of the report is that before the models are used within parts of the region, a more detailed assessment be undertaken within the specific area of concern. This, of course, will only be possible if there are additional data (rainfall and streamflow, particularly) that were not available during this project. If such data are available, then it is likely that the results of the modelling exercise could be as good as the upper ends of the range reported here (tables 4.1 and 4.2). If not, then the results could be very variable. This is not exactly a surprising conclusion and is likely to apply to any model that is used. It is really stating the obvious - that the success of simulating the rainfall-runoff processes in a catchment is highly dependent on defining the rainfall part of the equation. If that cannot be defined then either the runoff cannot be simulated correctly, or if it can, it is possibly simulated for the wrong reasons. In the latter situation, the results may look reasonable, but that does not mean that they are necessarily of any value.

5. FINAL CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of main conclusions

The structure of this report is such that most of the results are summarised in the previous chapter, which is already a condensation of the results (detailed in the appendices) obtained from applying the models to data from the individual countries. It is therefore not considered necessary to repeat these at length in this concluding chapter. However, for the sake of completeness, the major results will be briefly emphasised, despite the fact that some of the statements made previously will be repeated.

- In general terms, neither model (nor any others probably) can be applied successfully when the rainfall data used for input are not adequately representative of the true catchment inputs. This lack of representativeness may apply to mean or median annual depths, or may relate to shorter term inputs (monthly or daily) and their spatial variability. There are several parts of the region where this becomes a serious issue in terms of the rainfall data that was made available to the project. While it can be suggested that a greater amount of rainfall data is likely to be available, if full access to the individual countries databases were possible, this project cannot state that categorically. There are certainly areas where present day and historical patterns of rainfall gauging are not sufficient to represent the true patterns of catchment input. These areas tend to be in the drier and more remote (mountain) parts of the region, although not exclusively so.

- A further problem with the available rainfall database, from the point of view of generating long time series of streamflow from calibrated models, is the fact that many of the records from raingauges in a region are not coincident in time or have extended periods of missing data. Compiling stationary mean catchment rainfall inputs is therefore made more difficult.

- The availability of a country-, or region-, wide gridded database on mean or median monthly rainfalls, as exists for South Africa (Dent, et al., 1989), can be an extremely useful source of information to supplement an otherwise sparse network of stations for which time series exist. More sophisticated and accurate weighting procedures can then be used than simple averages, or area weighted averages. Of course, it is essential that the basis for generating the gridded database is scientifically sound, does not generate anomalies and that it is at an appropriate resolution (the South African database has a resolution of 1'*1').

- Both models were found to be much more difficult to apply in the arid and semi-arid parts of the region. Part of this problem is related to the difficulties of adequately defining the rainfall inputs in such areas where the rainfall tends to be highly spatially variable (particularly on a daily basis) and there are usually low density gauging networks. Part of the problem may also be related to the fact that spatial variability in the sources and sinks of surface runoff is frequently very high and that the spatial resolution used in the modelling is too low to be sensitive to the variability.

However, there is also little doubt that there are some deficiencies in the model formulations with respect to their application to arid areas. The main deficiencies seem to be in the absence of a transmission loss function within the Pitman model and the fact that although there is such a function within the VTI model, it is highly empirical and the parameters are difficult to quantify. More information is required about the processes involved in transmission losses and how to incorporate these into different types of models.

- The previous point referred to losses in arid and semi-arid ephemeral rivers, but the point is also valid for rivers in somewhat more humid areas, or at least that have their sources in wetter areas. Where such rivers flow through drier areas downstream they can often become seasonal, particularly if water supply schemes or landuse changes upstream reduce the dry season flows. Where alluvial deposits occur in the valley bottoms, the seasonal exchange of water between the alluvial aquifers and the river can be a very important process that determines the nature of the low flow regime and can also be important to the ecology of the valley bottom itself. These river-aquifer exchange processes do not seem to be very well understood and are difficult to incorporate into a model. However, they could be important in assessing the impact of planned upstream water resource developments on downstream users or downstream environments.

- Apart from the above conclusions, the models were found to be generally applicable to the region and can be applied successfully. The VTI model requires much greater resources in terms of information, experience, time and effort but does not seem to generate much better results in terms of monthly streamflow simulations. It is therefore suggested that the monthly model is the better model to use where the required resolution of flow information is no higher than monthly volumes.

- The parameter estimation procedures for the VTI model that are included in HYMAS appear to be appropriate, given that a reasonable amount of information is available to describe the characteristics of the catchment and that an experienced user of the model can interpret this information in the context of the models conceptual structure. At the very least, this means that a reasonable level of confidence can be expressed in the appropriateness of some of the parameter values and that the calibration procedure can concentrate on those parameters that do not have such direct associations with measurable catchment characteristics. One of the problems in the southern African region is that such information is not always readily available and it is necessary to resort to a less controlled form of calibration when few parameter values can be determined *a priori*. Under such circumstances, calibration can be extremely time consuming and there is also doubt about whether the simulations have been achieved for the correct reason.

- Soils characteristic data (depth, texture, etc.) are critical to the *a priori* estimation of several parameters in the VTI model. What soils information is available is frequently of limited value as it is not orientated toward the use for hydrological purposes, but rather for agricultural purposes. While this is understandable in a region where primary food production is of great importance, a hydrological classification of soils would be of great value for water resource studies.

- With respect to the VTI model, the ground water parameters can be very important in determining low flow patterns, but information on aquifer properties is difficult to find and interpret for the purposes of quantifying parameter values. There is the possibility that a more detailed study of this aspect of the VTI model calibration procedure could be worthwhile if coupled to a broad regionalisation of aquifer types and their properties.

- There are no direct relationships between the Pitman model parameters and physical catchment characteristics although such information is still very useful to assist in calibrating the model, particularly the size of the main moisture storage parameter (ST). Catchment description information can also be helpful in determining relative differences in some parameter values between sub-areas in the distribution system of a single catchment and in carrying out calibrations for several catchments within a region.

- No firm conclusions have been reached in this project about the regionalisation of parameter values for the purposes of applying the models at ungauged sites. This is particularly relevant to the Pitman model, as such a procedure already exists for South Africa and includes Swaziland and Lesotho. More catchments need to be included in the modelling exercise before any regional patterns are likely to emerge. However, in some of the countries, there does seem to be a potential for regionalisation.

- Both models appear to be appropriate for simulating afforestation or clear felling landuse changes, although most of the examples used relate to pine species. A wider range of plantation species types needs to be included before clear guidelines on the modification of parameter values to account for these influences can be determined. It should be emphasised that neither model is currently capable of simulating the effects of different management treatments such as planting methods, the influence of fertilizer applications or irrigation. They are not crop growth models and the rate of canopy or root development (and therefore the rate of change of the relevant model parameters) would have to be determined external to the models. The models do seem to be sensitive to thinning practices, although the few catchments used, where such treatments are documented, has precluded the development of clear parameter estimation guidelines. The models do not seem to be very sensitive to the influences of wildfires and more detailed assessments of such influences and how to modify parameter values to account for them would be required.

- No other types of landuse change were represented in the available data sets and it was therefore not possible to assess the models capabilities in this respect. The application of the models to the South African catchments frequently involved the inclusion of abstraction impacts (from small and large dams and directly from the river) and both models can account for these influences, given that data are available to define them adequately.

- Simpler estimation procedures that do not require rainfall data as input, such as the patching model referred to in this report, appear to have a lot of potential in this region where data and experience in the use of more complex techniques are limiting.

5.2 Recommendations for training

5.2.1 Use of time series data

This aspect of the training recommendations relates to the collection of hydrometeorological time series data, its management, storage, retrieval and analysis. It is really beyond the scope of this component of the Southern African FRIEND project to make recommendations about the collection, management and storage of time series data, beyond emphasising the importance of this in relation to providing data inputs to hydrological and water resource simulation models. The problems that occurred during the hydrological studies that were carried out prior to the implementation of the Lesotho Highlands project (LHWP, 1986) are a testament to the need for careful data collection and storage as well as the need for checking the quality and accuracy of data used to plan such large and economically sensitive schemes.

Without much more thorough analyses, it is difficult to gauge the level of accuracy of the streamflow, rainfall and evaporation data that are available in the region, although this project has clearly identified some areas where there are potential problems. The implications are that trained staff are required to carry out such tasks when the available historical records are used in analyses that are going to generate results that form the basis of water resource planning and management decisions. One course, held at the coordinating centre at the University of Dar Es Salaam during the first phase of Southern African FRIEND, did address certain of these issues and concentrated on building capacity in the use of the HYDATA software.

A further aspect of training in relation to time series data is the analysis of such data and the extraction of indices or summary data (low flow and flood indices, duration curves, frequency analysis, etc.). While this is also more related to the other components of the FRIEND project, it is also very important from the point of view of the rainfall-runoff modelling sub-programme. These techniques are frequently used to judge the performance of a model and the results generated by a model should never be seen as an end in themselves, but as inputs to further analyses. The HYDATA course already referred to included some components of time series analysis, as did another course on rainfall-runoff modelling.

5.2.2 Rainfall-runoff model applications

The *Pitman* model is considered to be a highly appropriate model for training in the general application of conceptual type rainfall-runoff models. Such models include some representation of natural hydrological processes but do not attempt to include strongly physics-based equations, the parameters of which should be evaluated from field measurements. The Pitman model contains representations of the main hydrological processes such that it can be used to teach the concept of the need for hydrological understanding as a prerequisite for the application of conceptual models. It is also sufficiently detailed and incorporates parameter interactions such that it can be used to illustrate many of the problems and difficulties experienced in calibrating a model. However, at the same time it has a straightforward structure that can be learnt and understood in a relatively short period of time by anybody with the type of background normally required for a hydrologist or water resource practitioner. It is also not too complex that a detailed understanding of physical hydrological processes is required to use it and its information requirements are relatively easy to satisfy. It can therefore be set up and applied successfully in many situations and if it is not successful, the reasons are often clear (lack of adequate rainfall data, for example). The other advantage of the model is that it has been clearly demonstrated to have a practical value in assisting in the solution of water resource management issues.

There are a number of different software versions of the model, the HYMAS version and the current 'official' version (Pitman and Kakebeeke, 1991), being two which have been referred to in this report. It is this author's opinion that it does not matter which version is used in a training situation as the basic structure of them all is very similar and close to the original version (Pitman, 1973). The main differences are the methods used for data input and output and the way in which the results are analysed and presented. Most of the versions in use today within South Africa also allow the Pitman model to be operated in a sub-catchment, or semi-distributed, way and combined with other water resource simulation tools such as reservoir simulation models. The Pitman model is therefore appropriate for investigating large water resource schemes using a systems modelling approach where various water use and development scenarios can be evaluated. Transfers between sub-catchments and reservoirs can be handled as part of the system and the main limitations are the definition of the operating rules. The level of sophistication with which these can be defined vary with the software product being used and potential users are directed to the developers manuals.

Daily models are inevitably more complex and normally require greater levels of expertise and understanding of physical hydrology to use successfully. The training requirements are consequently greater and they frequently have much more stringent data requirements. The better a catchments hydrology is understood and the more information that is available about the physical characteristics of a catchment that affect the streamflow response to rainfall, the easier it usually is to run a model (once the basic conceptual model structure and meaning of the parameters is understood). The implications of not being able to meet a models information requirements, both in terms of the calibration procedure, and in terms of the interpretation of the results, need to be clearly appreciated. All of these aspects complicate the process of training a new user in the application of such as the *VTI* and *ACRU* type models. There are, of course, simpler (more conceptual and less physically-based) daily time-step, rainfall-runoff models that incorporate fewer aspects of physical hydrology (there are also more complex ones as well). These can be successfully applied in certain circumstances, but extrapolation, temporally or spatially, can be more difficult and the reliability of the results somewhat less predictable. The training requirements for the simpler type of daily model are similar to those for the Pitman model, but the experience of their use (and therefore their value) within the region is much less.

Spatial and temporal interpolation approaches, such as the *Patching model* (Hughes and Smakhtin, 1996) are considered by the author to have a great deal of potential for the southern African region. They are relatively simple and quick to setup and operate and require little training in their use beyond the appreciation and understanding of the characteristics of streamflow time series and duration curves. They also have the advantage of not requiring rainfall data.

One course on the use of rainfall-runoff models was provided during the first phase of the Southern African FRIEND project and was held at the coordinating centre in the University of Dar Es Salaam (UDSM). A range of models and modelling approaches were introduced to the participants, including HYMAS (as a model operating system), the Pitman and VTI models as well as some other, less parameter intensive, approaches used at UDSM in conjunction with automatic optimising procedures.

5.2.3 Other types of data and the interrelationship of information

This report has frequently emphasised the need for better coordination in the availability of different types of data that are relevant to managing catchments water resources. The situation is very similar to integrated catchment management, where an holistic view of all the factors associated with development (surface and ground water abstractions, landuse practices, urban development, etc.) need to be taken into account if a catchments resources (not only water) are to be managed effectively and sustainably. Similarly, if a rivers flow regime is to be understood, all the factors that contribute (rainfall, evaporation, ground and surface water runoff, landuse and vegetation cover, geology, soils, etc.) should be considered. This is only effectively possible if the various agencies responsible for collecting such information operate together to achieve a common goal. There is, as yet, a very weakly established culture of information sharing within the southern African region, even within a single country. Part of the consequence is that many groups, who could make use of some information and add value to it, often do not even know of its existence, let alone know how to access such information. This situation appears to apply between different state agencies within single countries, between countries and also between international organisations working within the region.

There is therefore a need to expand the culture of information sharing and to increase the awareness of the availability of different types of data and how to gain access to it. Only then will it be really possible to identify where the gaps are and establish programmes (where financially beneficial and possible) to fill such gaps.

5.3 Recommendations for the future application of models within the region

5.3.1 Recommendations for future database development

The previous sub-section on training identified the need for an improvement in the appreciation of the need for information sharing within the region. This applies not only between countries and international agencies, but also between state and private (or parastatal) agencies within each country. The information being referred to is time series of rainfall, streamflow, evaporation, water abstractions, ground water levels, etc., as well as spatial information on topography, geology, soils, vegetation, landuse (and changes), etc. The FRIEND project has certainly had an influence on the understanding of the availability of such data and has added further information through its various sub-programmes. However, time and staff resource limitations have meant that much of the data contributed is at a scale which is not always appropriate for detailed catchment studies. These data have value for the region as a whole but may be less than appropriate for individual water resource development projects. At the same time it is the belief of the author that a great deal more information exists than can be currently considered readily available. The first step in the development of a regional database of relevant information could therefore be a cooperative effort (by all countries and international agencies) to catalogue in detail what information is available and what the conditions and costs of access are. It should then be possible to identify what the future information requirements are, set priorities and establish programmes for its collection and storage. It is also necessary for the various users of such information to clearly state their requirements in terms of accuracy and resolution

A great deal of money and other resources are expended collecting and collating this type of information and it is essential that the best use is made of it and that, where possible, value is added to raw data to make it of greater use to others. The best way to make use of the data is to ensure that it can serve several client bases rather than a single one (such as the original agency that collected it). The issue of payment for data or information should be able to be resolved, but only when the true value of the raw and further processed data can be properly appreciated.

5.3.2 Further research in model application guidelines

The limited number of catchments used in the study precluded a full regionalisation of parameter estimation guidelines for the Pitman model, but the potential for the success of such an approach appears to justify further efforts. It is suggested that individual countries should take the initiative of carrying out such studies within their own areas, but coordinated within the southern Africa region as a whole. Projects of this nature would be ideal for postgraduate students and would therefore have the added benefit of building capacity in the application of models. The eventual integration of the results of such a programme could lead to an extension of the currently available parameter estimation guidelines for South Africa to the whole sub-continent. The value of these as water resource estimation tools in South Africa has already been demonstrated. The positive response that water resource engineers and managers in South Africa have had to the production of the WR90 (1994) reports and the regionalised data contained within them could be a lesson for the rest of the region. This report has indicated that there is the potential to extend this approach to many parts of the rest of the region and it is therefore recommended that such studies be carried out.

With respect to daily models, it is more difficult to make any firm recommendations and it is likely that the best approach is for individual potential users to apply the model, or estimation technique, that they are most familiar with. Further research on developing application guidelines for the use of a single specific model may not therefore be justifiable. It may be better to develop a register of those individuals or groups who have access to suitable models and sufficient experience in their use, who could be called upon to carry out the necessary simulations when required. It is suggested that there are fewer demands for daily streamflow data than monthly and that daily simulation modelling is a much more specialist area of expertise.

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Appendix A1 ZIMBABWE Catchments

A1.1 Availability of time-series data.

Flow data.

Daily flow data are available for a large number of catchments of various sizes and reasonably well distributed throughout the country. Many of the records have quite substantial gaps due to missing data, but it has been possible to select a representative group of catchments that generally have over 10 years of more or less continuous data. The data were supplied via the Institute of Hydrology, UK in HYDATA format. The records are available for the early to mid 1960s to the late 1980s.

Rainfall data.

While the available flow data did not place any particular restrictions on the number and selection of catchments to be used for modelling, the available rainfall data did. At the time during the project when the data were being collected, Zimbabwe's rainfall database had been reputedly lost due to a computer failure. The rainfall data available to the project team were therefore in the form of copies of the original daily recording sheets which had to be typed in. These data were made available by Dr Andy Bullock of the Institute of Hydrology, UK and entered into computer data files by the project team. The rainfall records vary substantially in length but start in the mid 1940s, at the earliest, and end in the mid 1980s. Dr Bullock did not have access to the complete database and it was therefore necessary to select catchments for which a sufficient number of representative raingauge records were available.

Evaporation data.

24 stations with daily data for as much as 20 years were available and these were used to develop a regional pattern of mean monthly potential evaporation values which were used for input to the models.

The final selection yielded 14 catchments with a total of 58 raingauges available to define the rainfall input. They are illustrated in figure A1.1 and table A1.1 indicates that the catchment size ranges from 146 to 3320 km^2.

A1.2 Availability of catchment description data.

Very generalised information on geology, soils, vegetation cover and landuse was available from a rather dated source (Collins, 1965). This publication includes descriptions of the various characteristics as well as maps at a scale of 1:2 500 000. In addition, topographic maps at a scale of 1:250 000 were available.

These sources are sufficient to identify the major differences between catchments but are of limited value in terms of specifically detailed information on the hydrological characteristics of the soils (texture, depth and structure) and underlying geological formations. There was also, unfortunately, no detailed information made available about the extent or patterns of water abstractions and usage. Collins (1965) includes a map of the surface water resources of the country which includes some approximate information about the extent of storage (expressed as a % of mean annual runoff) in the main drainage basins and the major dams and some farm dams are indicated on the 1:250 000 topographic maps. However, neither source is of much value in terms of trying to quantify water use.

A1.3 Selection of catchments and brief descriptions.

The selection of the 14 catchments (figure A1.1) was largely based on the availability of rainfall data.

A37 (Kana River) and **A41** (Tshongokwe River) are located in the western part of Zimbabwe to the north of Bulawayo. Mean annual rainfall is of the order of 630mm. The catchments are underlain by sandstones and sands of the Kalahari System, resulting in unstructured, deep sandy soils. The topography is characterised by gentle slopes and relatively low drainage densities. Vegetation cover consists of woodland with poor ground cover due to the low moisture retention character of the soils. Landuse (1965 data) consists of exploitation of the indigenous trees for forestry. None of the four available raingauges lie within the catchments.

B15 (Lumani River), **B29** (Mchabesi River), **B56** (Tuli River) and **B77** (Shashani River) are located to the south west of Bulawayo with mean annual rainfalls varying from below 600mm to over 650mm. The B15 to B56 group of catchments are reasonably well represented by raingauges, many located within the catchment boundaries. However, none of the gauges are very close to catchment B77. The catchments are underlain by granites and the soils predominantly sandy. The topography is relatively steep, the rivers draining the elevated Midlands area towards the Shashi and the Limpopo rivers. The catchments lie in the tree savanna region where the predominant landuse appears to be semi-extensive livestock production

C6 (Ngesi River) is located in the central part of the Midlands, to the south of Harare. Slopes are low and they are underlain by sandstones and shales of the Karoo System. Mean annual rainfall is of the order of 720mm and the soils are hydromorphic sands. Information from five raingauges in reasonable proximity to the catchment is available. The natural vegetation is savanna woodlands and the landuse semi-intensive livestock production supported by limited fodder and cash crops.

D24 (Poti River) and **C83** (Gwebi River) are located to the north and north west of Harare, respectively. Mean annual rainfall is over 880mm and the soils are generally sandy, developed on granite. Some parts of these catchments also have more silty soils developed on basement schist outcrops. The very upper parts of C83 drain the northern suburbs of Harare and could be marginally affected by increasing stormwater drainage during the period of record. D24 has steeper topography than C83, the former being located on the margin of the elevated Midlands and draining toward the Mazoe River. The natural vegetation cover is similar to C6, but the landuse is more orientated toward intensive cropping (maize and/or tobacco) with some livestock production.

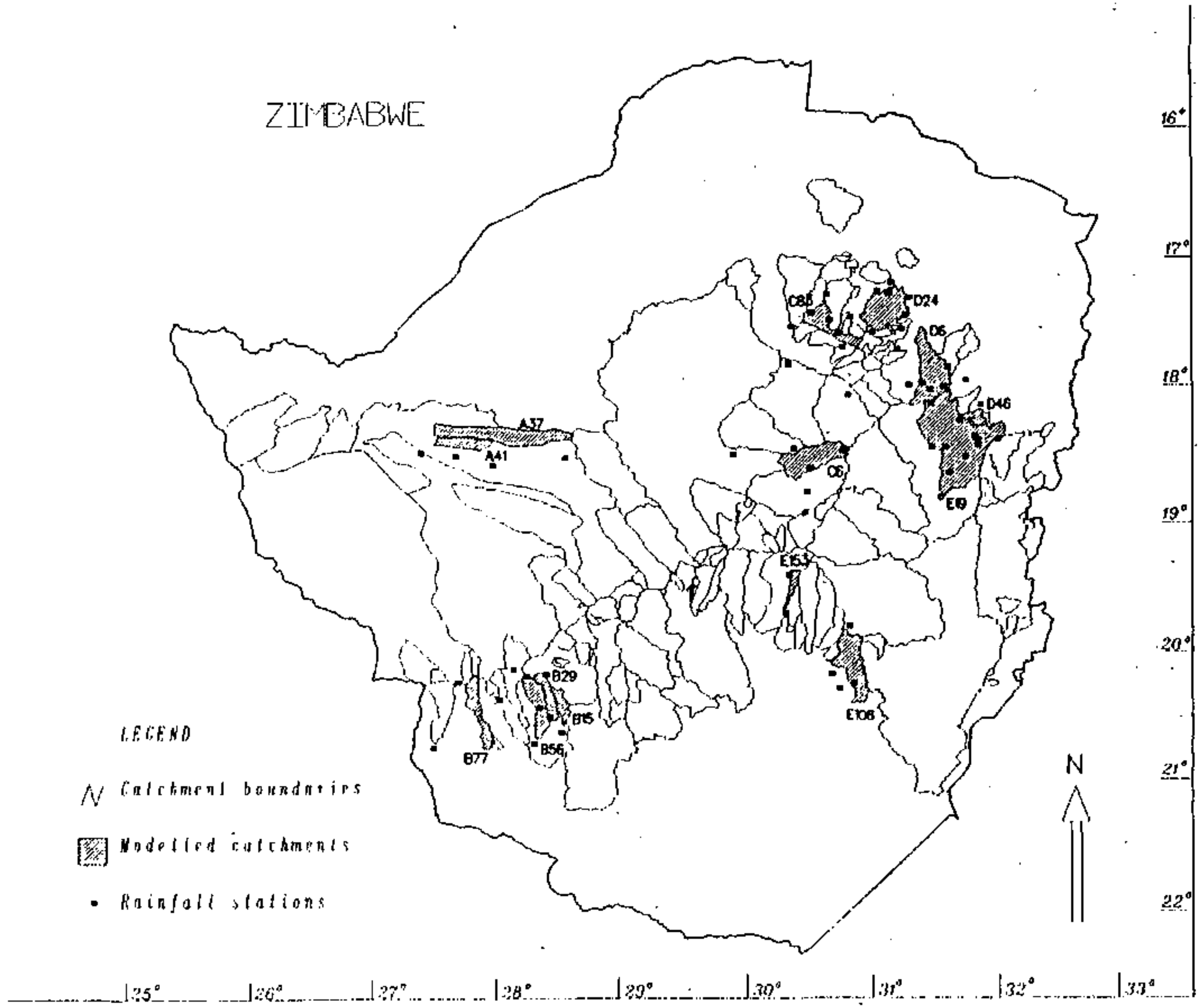

Figure A1.1 Gauged catchments in Zimbabwe and those selected for use.

D6 (Shawanoya River), **D46** (Mwarazi River) and **E19** (Macheke River) represent a group of catchments draining the east-west ridge extending from the mountains of the Eastern Highlands to Harare. The upper reaches of these catchments are therefore moderately steep. They are all developed on granite with relatively frequent occurrences of dolerite dyke intrusions. The soils are generally sandy, but locally in association with the dolerite dykes, can be clayey. Rainfall varies from 910mm around D6 to lower than 800mm in the lower reaches of E19. The whole area is well represented by the available raingauges. Vegetation and landuse are similar to D24 and C83.

E108 (Chiredzi River) and **E153** (Umshagashe River) are located on the margins of the higher ground of the Midlands and drain towards the Sabi/Lundi river basin. The available raingauge information is reasonably well situated with respect to the catchments and the mean annual rainfall is of the order of 750mm (E153) to 820mm (lower parts of E108). They are underlain by granites and E153 is characterised by sandy soils, while E108 by somewhat finer textured soils. The natural vegetation is savanna woodlands and the landuse semi-intensive livestock production supported by limited fodder and cash crops.

A1.4 Calibration procedure (Pitman Model).

The original intention was to try and transfer parameter values from similar areas in South Africa based on the information provided within the Surface Water Resources of South Africa update volumes (WR90, 1994). The closest area is the Northern Province and the Limpopo - Oliphants region (Volume I). Unfortunately, it is difficult to find parts of this region which have sufficiently similar characteristics (climate, geology, soils and vegetation) to consider anything close to a direct transfer of parameters. Consequently, the best that was possible was to follow a similar approach to that which appears to have been used in WR90. Despite variations in catchment size, topography, geology, soil type and depth, as well as vegetation cover, several model parameters have fixed values throughout the Limpopo-Oliphants region. These parameters are PI (interception parameter, value = 1.5mm), R (evaporation-soil moisture relationship parameter, value = 0.5), SL (minimum soil moisture storage for runoff to occur, value = 0mm) and TL (runoff lag/delay parameter, value = 0.25 months). Wherever possible, these parameters were therefore kept at the same values for the Zimbabwe catchments.

Some other principles were that those catchments with sandier and more freely draining soils would have higher POW values and possibly higher ZMIN and ZMAX values. As most of the catchments are described as having relatively sandy soils and with at least reasonable vegetation cover, ZMAX values were expected to be high. Without more detail about soil and weathered substrata depths it is difficult to determine *a priori* principles for setting the value of ST and FT and therefore, together with ZMIN and ZMAX, these were the main calibration parameters used to establish correspondence between observed and simulated streamflow volumes. Because of the occasional incidence of extreme monthly rainfall totals, once ZMIN and ZMAZ have been established, setting ST was found to be relatively straightforward. It was generally set quite low initially and then increased until the excessive runoff caused by the exceedence of rainfall over the storage capacity was removed. This is an important observation as without a relatively extreme rainfall included in the calibration period, it was found difficult to establish a representative value of ST. None of the modifications made to the original Pitman model were applied during the Zimbabwean calibrations and no attempt was made to incorporate abstractions of any kind.

The subdivision of the gauged catchments into sub-areas was mainly based upon the positioning of the available raingauges to obtain the best representation of sub-area rainfall input. E19 was subdivided the most (6 sub-areas), while many of the smaller catchments were not subdivided at all.

Table A1.1 lists the data periods used for modelling, the number of observed months of data, catchment area, mean annual rainfall and pan evaporation depths, as well as the final parameter values adopted as representative. In general terms, at least 5 years of the total available observed streamflow was used for calibration and the remainder reserved to ensure validation of the calibrated parameter values. For those catchments that have longer observed records, up to 10 years were used for calibration.

A1.5 Simulation Results (Pitman Model).

The results of the calibrations are provided in table A1.2 using the standard set of comparative statistics. Figures A1.2 to A1.4 provide graphical examples of the degree of success of the calibration exercises. It should be noted that these do not always represent the optimum results that can be achieved with the model, mainly due to the principle of fixing certain parameter values. In some cases, particularly those that experience a relatively high percentage of months (about 20%) with zero flow conditions, slightly better calibrations could be achieved by varying PI, R and TL. Similarly, including some of the model modifications that were developed during this project and designed mainly for arid areas also gave slightly better results. However, it should be noted that no information on water abstractions has been included and, if present, would mostly affect the low flow months where most of the calibration problems existed. The parameter values given in table A1.1 and the results in table A1.2, therefore represent a 'regional compromise'.

The highlighted parameter values in table A1.1 identify the situations where, keeping to the original calibration principles did not generate acceptable results and where these could only be achieved by departing from those principles. The need for a non-zero SL value for B77 and C6 to remove some low flows in dry winters is difficult to explain with the information available. The use of a non-zero SL can slightly improve the results in many of the more southerly and drier catchments, but to a much lesser extent than in B77 and C6. The cause may be related to different groundwater flow characteristics or to abstraction influences on the flow regimes. The very high ZMIN value for A41 may be indicative of much sandier soils within this catchment than for the closely adjacent A37 (both underlain by Kalahari sands). Certainly, the topographic map suggests a discontinuous main channel for much of the upper part of A41, which may be indicative of less surface runoff.

In general terms the simulation results are reasonably good and there is no indication that the correspondence between simulated and observed flows deteriorates between the calibration and validation periods. The results for the more southern and western catchments are not as good as for those catchments in the vicinity of Harare, and this may be a reflection of the denser network of raingauges available for D24, C83, D6, D46 and E19.

Table A1.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Zimbabwe catchments. The bold figures indicate parameter values that deviate from the original calibration principles.

Catchment	Start year	End year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	POW	ST	SL	FT	ZMIN	ZMAX	PI	R	TL
A37	1964	1978	168	1370	620	1950	4.0	435	0	12	40	1300	1.5	0.5	0.25
A41	1964	1978	143	502	640	1950	4.0	540	0	18	**160**	1400	1.5	0.5	0.25
B15	1960	1983	264	267	623	1650	3.0	250	0	10	50	750	1.5	0.5	0.25
B29	1960	1983	200	363	620	1650	3.0	320	0	15	50	750	1.5	0.5	0.25
B56	1960	1983	164	645	594	1650	3.0	300	0	18	50	750	1.5	0.5	0.25
B77	1968	1983	155	558	674	1700	3.5	520	**120**	25	25	1100	1.5	0.5	0.25
C6	1960	1983	264	1040	714	1600	3.5	720	**250**	20	25	1100	1.5	0.5	0.25
C83	1970	1983	108	656	882	1600	3.5	250	0	20	25	750	1.5	0.5	0.25
D6	1960	1983	239	1170	910	1550	3.5	420	0	35	50	1100	1.5	0.5	0.25
D24	1960	1983	252	1060	918	1550	3.5	580	0	35	50	1100	1.5	**0.3**	0.25
D46	1968	1983	155	202	831	1450	3.5	480	0	35	50	1100	1.5	0.5	0.25
E19	1960	1983	197	3320	798	1450	3.5	510	0	35	50	1100	1.5	0.5	0.25
E108	1966	1983	204	1040	815	1700	3.0	250	0	40	25	725	1.5	0.5	0.25
E153	1974	1984	66	146	743	1650	3.0	200	0	40	25	525	1.5	0.5	0.25

Figures A1.2 to A1.4 illustrate some of the results in more detail; the logarithmic scales for the time series diagrams have been used to emphasise the differences between observed and simulated medium to low flows. Figure A1.2 illustrates an example of a good fit over virtually the full range of flows down to the 95% exceedence level. It is quite likely that the difference between observed and simulated flows below this point is related to abstractions which have not been modelled. There is certainly evidence from the topographic maps of a relatively dense network of farm dams within this catchment.

Figure A1.3A illustrates the results for catchment D46 using a 9 year time series. The main problem seems to be in the seasonal recessions, particularly after moderate to dry years (1970, 1971 and 1973), and this feature is also reflected in the duration curves (Fig. A1.3B). It would be difficult to attribute all of this effect to abstractions, however, it should be noted that the observed duration curve is based on only 155 months compared to 180 months of simulated data and that most of the missing observed months are in the medium to low flow periods.

Figure A1.4 illustrates the results for one of the drier catchments to the south (B77) where the model was not capable of simulating the length of time that zero flow conditions were observed (despite using the parameter SL). The time series graph (Fig. A1.4A) illustrates that zero flow conditions do not necessarily occur during dry seasons which follow dry summers (1973, for example), as might be expected, but can follow some of the wettest summers (1974, for example). Although the differences between the duration curves is apparently very great, it only represents about 3.5% of the mean annual runoff and could be at least partly attributed to water usage within the catchment, although few farm dams are shown on the topographic maps. It is difficult to draw any final conclusions about the influence of abstractions without more information.

A1.6 Calibration procedure (VTI Model).

The initial parameter values were established by setting the physiographic variables to values which reflect the information contained within Collins (1965), or that could be extracted from 1:250 000 topographic maps. As this information is only of a very general nature, the values of the physiographic variables could only provide rough guidelines. It is recognised that more detailed information is probably available for at least some of the catchments. However, the time and manpower resources available to this project were such that it was necessary to rely on readily available material, or that provided by the national hydrometric agencies.

Inevitably, the major components of the model had to be calibrated to achieve anything close to an acceptable agreement between observed and simulated daily flows. The components that were concentrated on were those related to the size and texture of the soil moisture storage and the hydraulic conductivity and geometry of the groundwater storage. The former largely controls the surface and soil baseflow runoff components, while the latter the slower baseflow component released from groundwater storage. To a large extent, the vegetation (controlling interception and evapotranspiration losses) and flow routing parameters were left unchanged from the values estimated from the physiographic variables.

Table A1.2 Pitman model simulation results, Zimbabwe catchments.

Catchment	Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
A37 - Obs.	2384	4588				6.42	1.70			
- Sim.	2345	3833	-1.6	0.52	0.50	6.57	1.71	2.3	0.58	0.51
A41 - Obs.	548	1139				4.92	2.31			
- Sim.	546	1162	-0.3	0.45	0.33	5.10	2.05	3.6	0.35	0.25
B15 - Obs.	2220	5180				6.21	2.36			
- Sim.	2010	5159	-9.4	0.62	0.58	6.22	1.88	0.2	0.55	0.55
B29 - Obs.	2346	5762				6.52	2.20			
- Sim.	2194	6068	-6.5	0.86	0.85	6.78	1.58	4.0	0.49	0.48
B56 - Obs.	4652	9841				6.94	2.28			
- Sim.	4310	9788	-7.3	0.71	0.69	7.15	1.67	3.0	0.42	0.41
B77 - Obs.	2391	6346				5.30	2.86			
- Sim.	2182	5176	-8.7	0.64	0.63	6.23	2.12	17.5	0.68	0.56
C6 - Obs.	4679	12374				6.57	2.41			
- Sim.	4699	11034	0.4	0.47	0.42	6.87	2.44	1.2	0.55	0.46
C83 - Obs.	10537	29137				7.00	2.28			
- Sim.	11680	24177	10.8	0.79	0.79	7.32	2.33	4.6	0.83	0.79

Table A1.2 (Contd.) Pitman model simulation results, Zimbabwe catchments.

Catchment	Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
D6 - Obs.	20907	36943				8.61	1.81			
- Sim.	19184	37286	-8.2	0.88	0.88	8.59	1.69	-0.2	0.74	0.73
D24 - Obs.	12480	22729				8.06	1.97			
- Sim.	12663	24125	1.5	0.82	0.80	8.42	1.52	4.5	0.76	0.72
D46 - Obs.	2830	6475				6.55	1.70			
- Sim.	2905	6364	2.6	0.88	0.88	6.84	1.49	-12.3	0.78	0.75
E19 - Obs.	38927	65494				9.48	1.73			
- Sim.	38779	71200	-0.3	0.90	0.88	9.64	1.36	1.7	0.61	0.60
E108 - Obs.	16218	28692				8.15	2.22			
- Sim.	15967	29476	-1.5	0.74	0.72	8.44	1.65	3.5	0.51	0.49
E153 - Obs.	2523	5433				6.59	2.25			
- Sim.	2309	4483	-8.5	0.79	0.78	6.85	1.79	3.9	0.29	0.21

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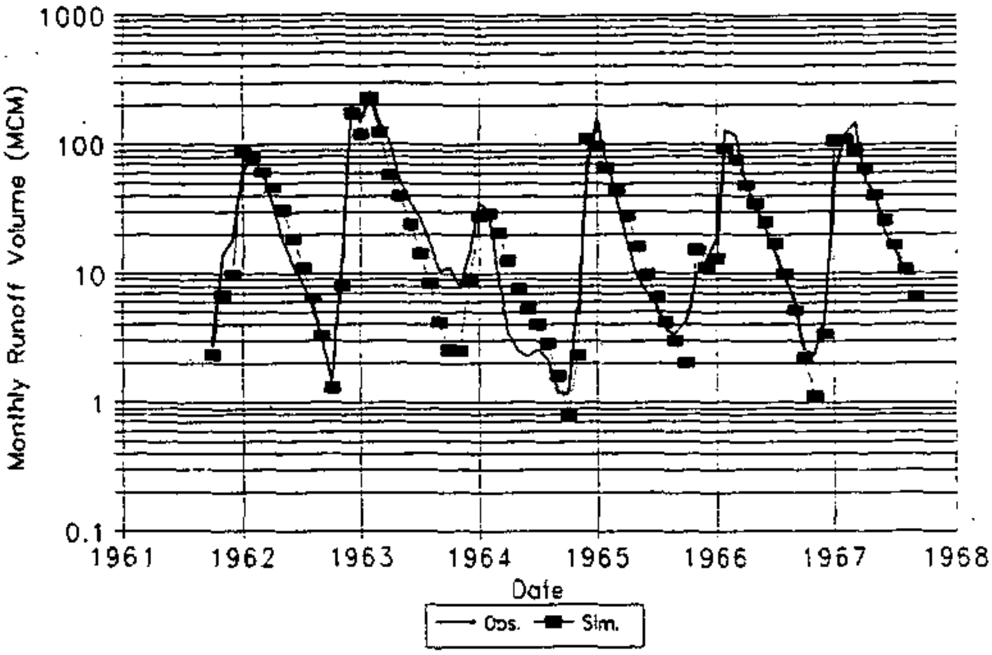

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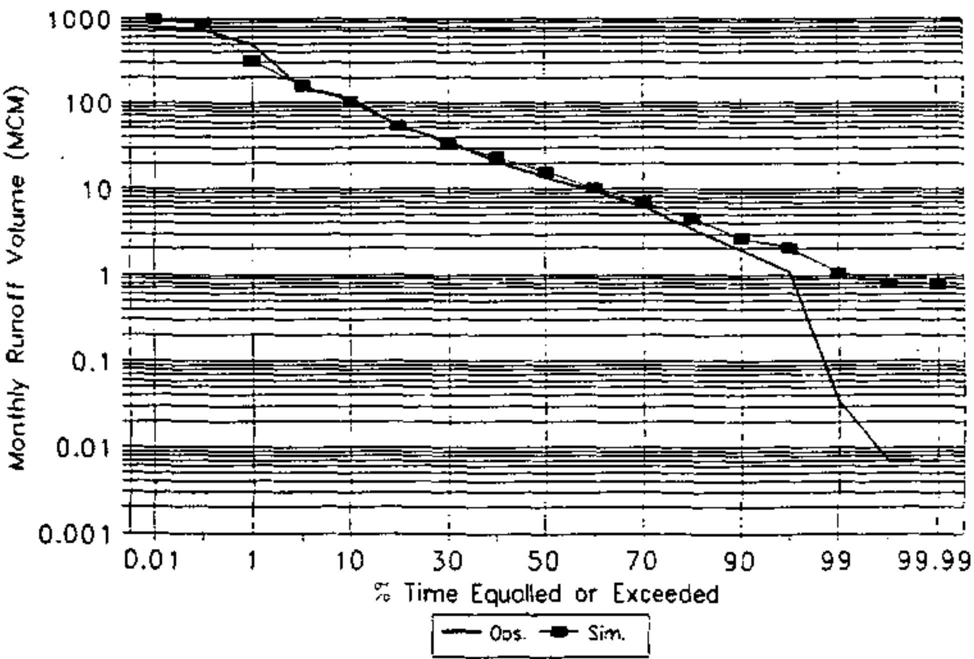
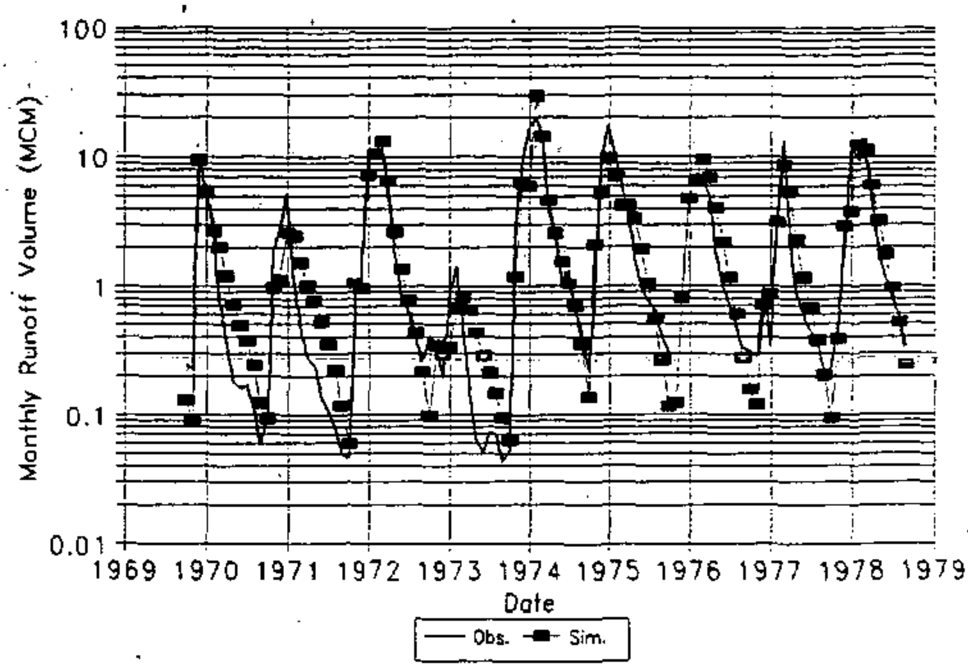


Figure A1.2 Catchment E19 (Macheke River): Observed and simulated A) Time series of monthly runoff volumes and B) Duration curves based on all data.

A



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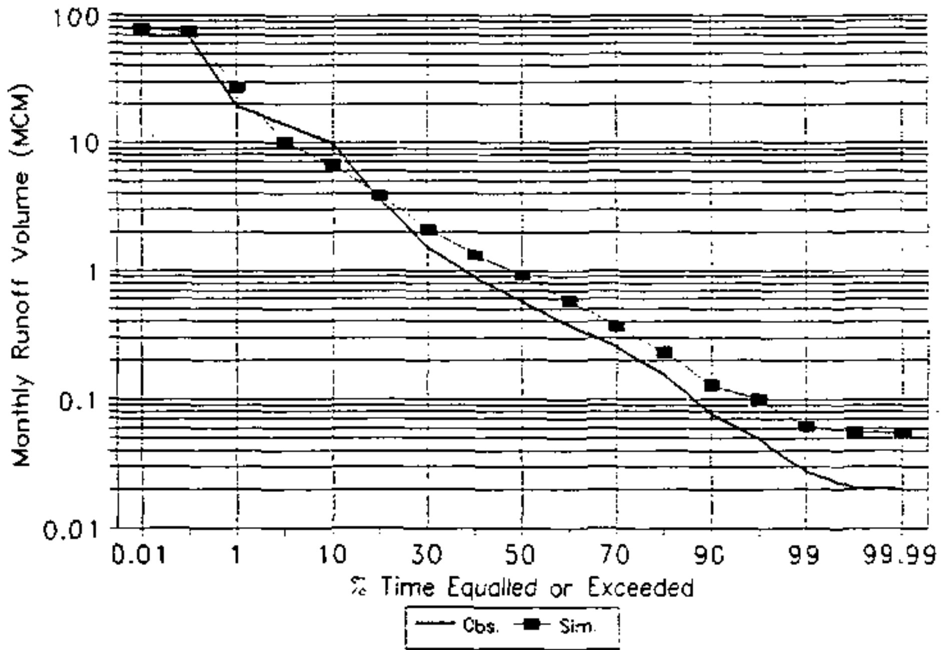
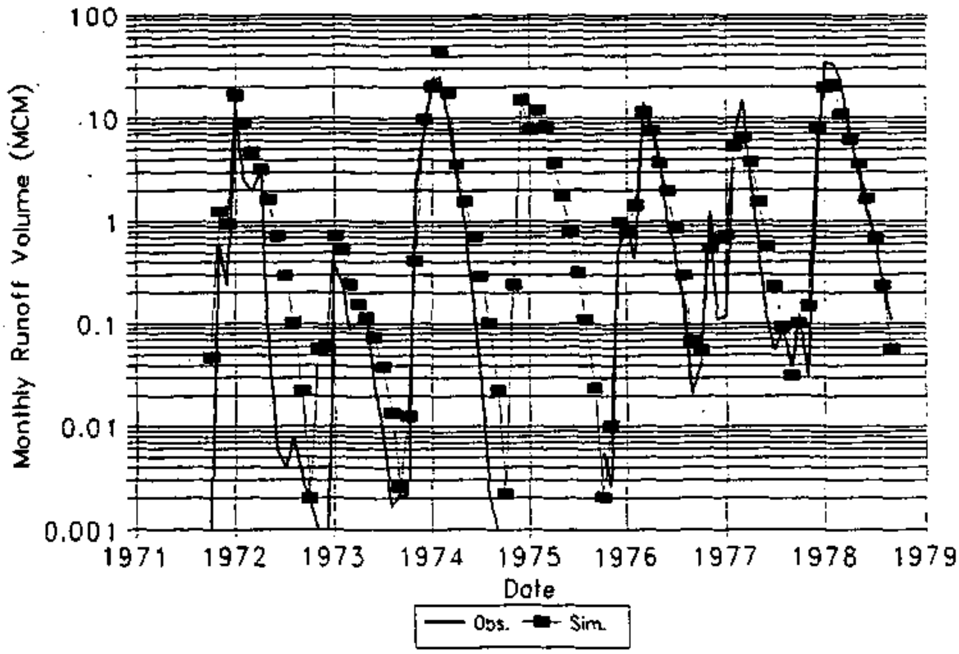


Figure A1.3 Catchment D46 (Mwarazi River) : Observed and simulated A) Time series of monthly runoff volumes and B) Duration curves based on all data.

A



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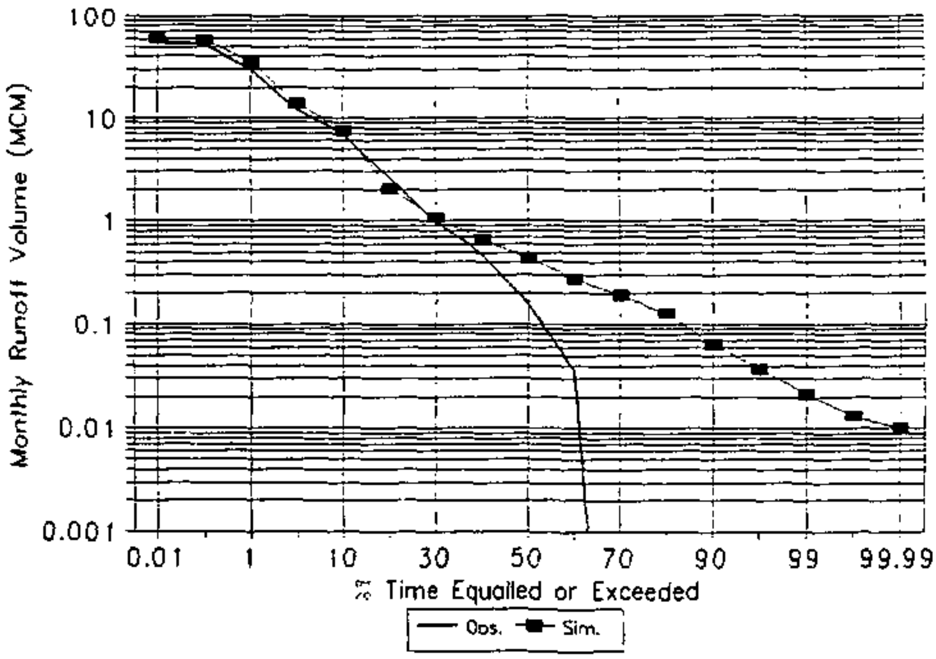

Figure A1.4 Catchment B77 (Shashani River): Observed and simulated A) Time series of monthly runoff volumes and B) Duration curves based on all data.

The calibration procedure involved using part of the observed time series, covering a range of wet and dry years, to identify clear signals about the processes that prevail within the catchments and to use these signals to guide the parameter modification procedure. One type of signal might be contained within the pattern of baseflows with respect to how peaked they are, how sustained they are over the dry season and how reliable they are over one or more years of low rainfall. Such information can be very useful to determine the best groundwater parameters to use, but can also be confused by ill-defined patterns of water abstraction. Most of the catchments are underlain by weathered granite material (the exception being C6, developed on sandstones and shales), below which the rock can be considered to be largely impermeable. The aquifers have therefore been assumed to be relatively thin and outflows to the river largely controlled by relatively localised recharge, conductivities and gradients.

Calibrating the soil parameters, including the infiltration equation, soil depth and texture related (field capacity and hydraulic conductivity) values, usually involves assessing the immediate and delayed runoff response to different types of rainfall inputs at different times during the season. However, this procedure relies upon reasonably accurate rainfall data with which to represent the spatial and temporal variation. Being a daily model, it is not possible to represent the fine details of the temporal variation and the model user has to accept that some fluctuations in the observed hydrographs will be impossible to simulate. It also has to be recognised that, in general terms, there are not enough raingauges available to define the spatial variation. The impact of this is expected to be more apparent where surface runoff processes prevail over more delayed sub-surface processes, which can play a role in smoothing the effects of spatial rainfall variability.

Table A1.3 Some key parameters of the VTI model for the Zimbabwe catchments.

Parameter / Catchment		B15	B29	D6	D46	E19	E153
Veg. cover fraction		0.46	0.46	0.56	0.58	0.56	0.51
Canopy capacity (mm)		0.53	0.53	0.78	0.86	0.78	0.67
Infiltration Curve	K	0.61	0.61	0.64	0.62	0.63	0.62
	C (mm h^{-1})	180.0	180.0	184.0	182.0	180.0	189.0
Total Soil Store (mm)		330.0	350.0	409.0	409.0	529.0 - 594.0	228.0
FC/Porosity		0.53	0.53	0.53	0.53	0.55	0.51
Soil K (mm h^{-1})		21.2	21.2	20.0	21.2	17.5	17.0
Texture dist. factor		0.9	0.9	0.85	0.85	0.85	0.90
St.Dev. of Moist. Dist.		0.125	0.13	0.14	0.12	0.15	0.17
G'Water K (mm h^{-1})		0.10	0.10	0.12	0.10	0.12	0.10

Table A1.3 lists some of the key parameters that have been established for the catchments used to assess the applicability of the VTI model in Zimbabwe. In all cases the groundwater gradient has been set at 0.001 less than the estimated effective planar slope parameter so that the aquifers are represented as relatively thin layers of weathered material with a storativity of about 0.015. The greatest variation is in the soil depth and standard deviation of the soil moisture content distribution parameters.

A1.7 Simulation Results (VTI Model).

Table A1.4 provides some statistics of the correspondence between observed and simulated daily discharges ($m^3 s^{-1}$), while table A1.5 lists similar values based on monthly flow volumes (Ml) and can be compared to the results generated using the Pitman model (table A1.2). The values given are for the complete time series available and no attempt has been made to differentiate between the calibration and verification periods. In general terms, the calibration period used was about 5 years and there was no consistent relationship between the fit statistics for the two periods, for some catchments the calibration period was simulated more successfully, while for others the verification period was better.

The main problem with the simulations of B15 and B29 occur during the relatively dry years when peak flows are of the order of 10 $m^3 s^{-1}$ and lower, there is little seasonal baseflow rise and a large part of the dry season experiences zero flows. Many of the short events that do occur within the observed record are either under-simulated or not simulated at all, while simulated events of varying magnitude do not correspond with observed increases in flow rates. At least part of the reason for this result must be attributed to poor definition of the rainfall input, which seems to have a greater impact when there is no smoothing influence of recharge and outflow to and from the soil and groundwater storages. The years where peak flows are greater than about 40 $m^3 s^{-1}$ and both soil and ground water baseflow appear to play a major role are better simulated, although even then the major peaks in the simulated and observed records do not always match (figures A1.5 A and B show examples of both). Overall, the long term baseflow response from groundwater has been simulated as too sustained (figure A1.6), which may be related to the conceptualisation of the aquifer properties, or to the influence of abstractions which are not included in the model.

The relevant topographic map suggests that there are a number of small impoundments within the D6 catchment and a nominal 15 * 10^6 $m^3 y^{-1}$ (about 5% of MAR) of storage and abstractions (distributed evenly over the year) have been included in the model. The results for most years are generally reasonable (note the high values for R^2 and CE using monthly totals in table A1.5), although the one-to-one fit based on daily data do not necessarily support this conclusion. Detailed comparisons of the two time series does not reveal any clear reason for the relatively poor statistics, except that in some cases, the observed hydrograph response appears to be very unusual, does not match the pattern of rainfall input and may be erroneous. This is one of the better endowed catchments in terms of available rainfall data and it is difficult to draw any conclusions for the frequent mis-match of observed and simulated events. The baseflow response is reasonably well simulated, although either the model has simulated too sustained a response, or abstractions are greater than specified within the model.

The simulations for catchment D46 generate very good results based on monthly volumes, but as with D6, the daily statistics are much poorer. One of the problems is that frequently the main peaks of a season are under-simulated, while the short-term baseflow response (simulated as soil water outflow in the model) is too great.

Table A1.4 VTI model simulation results based on daily data, Zimbabwe catchments.

Catchment	Model Period	Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
B15 - Obs.	1961 - 1983	0.85	3.64				-1.53	2.04			
- Sim.		0.82	2.67	-3.5	0.45	0.44	-0.79	1.43	48.4	0.55	0.42
B29 - Obs.	1961 - 1983	0.91	3.37				-1.18	2.16			
- Sim.		1.04	3.21	14.2	0.48	0.41	-0.31	1.40	73.7	0.50	0.34
D6 - Obs.	1969 - 1983	9.52	19.65				1.00	1.79			
- Sim.		10.47	24.82	10.0	0.57	0.32	1.06	1.70	6.0	0.69	0.68
D46 - Obs.	1969 - 1983	1.07	3.40				-1.41	1.67			
- Sim.		1.20	3.47	20.0	0.50	0.40	-1.19	1.64	15.6	0.79	0.77
E19 - Obs.	1969 - 1983	15.03	33.73				1.37	1.85			
- Sim.		15.89	38.87	5.7	0.77	0.70	1.52	1.58	10.9	0.65	0.64
E153 - Obs.	1979 - 1983	0.50	2.27				-1.70	2.18			
- Sim.		0.51	1.98	2.0	0.59	0.58	-0.96	1.45	43.5	0.34	0.22

Table A1.5 VTI model simulation results based on monthly totals, Zimbabwe catchments.

Catchment	Model period	Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
B15 - Obs.	1961 - 1983	2220	5187				6.21	2.36			
- Sim.		2168	4292	-2.3	0.75	0.75	7.02	1.41	13.0	0.62	0.47
B29 - Obs.	1961 - 1983	2277	5864				6.31	2.42			
- Sim.		2679	5485	17.6	0.86	0.85	7.44	1.29	17.9	0.64	0.35
D6 - Obs.	1969 - 1983	25355	41139				8.91	1.80			
- Sim.		27876	51238	9.9	0.89	0.80	9.01	1.64	1.1	0.81	0.80
D46 - Obs.	1969 - 1983	2886	6544				6.60	1.64			
_ Sim.		3220	6800	11.6	0.93	0.93	6.64	1.66	0.6	0.83	0.78
E19 - Obs.	1969 - 1983	40114	72395				9.41	1.86			
- Sim.		40970	82280	2.1	0.92	0.88	9.48	1.58	0.7	0.76	0.75
E153 - Obs.	1979 - 1983	1327	4488				5.91	2.51			
- Sim.		1329	3805	0.2	0.91	0.90	7.04	1.26	19.1	0.28	0.08

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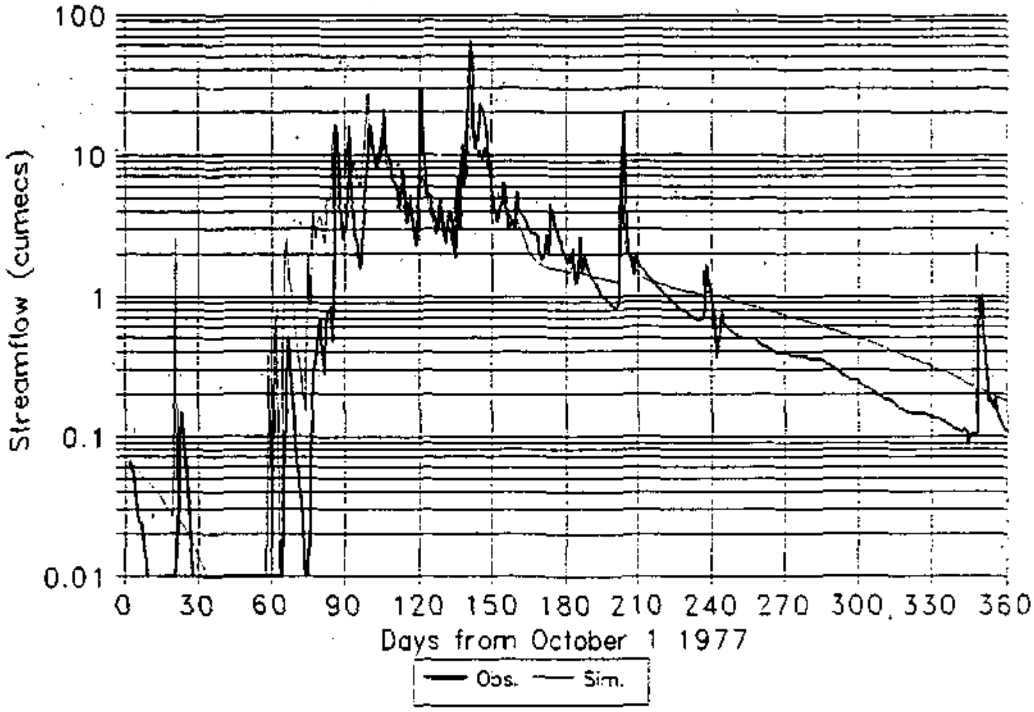

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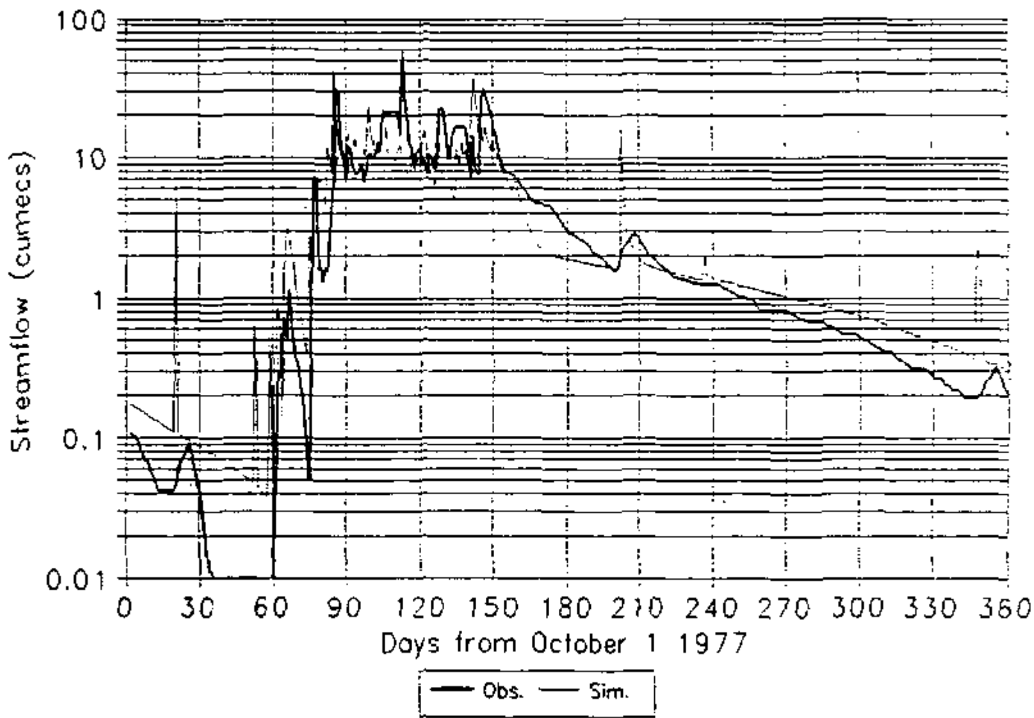

Figure A1.5 Catchments B15 (A - R. Lumani) and B29 (B - R. Mchabesi): Observed and simulated time series of daily runoff for the 1977 hydrological year.

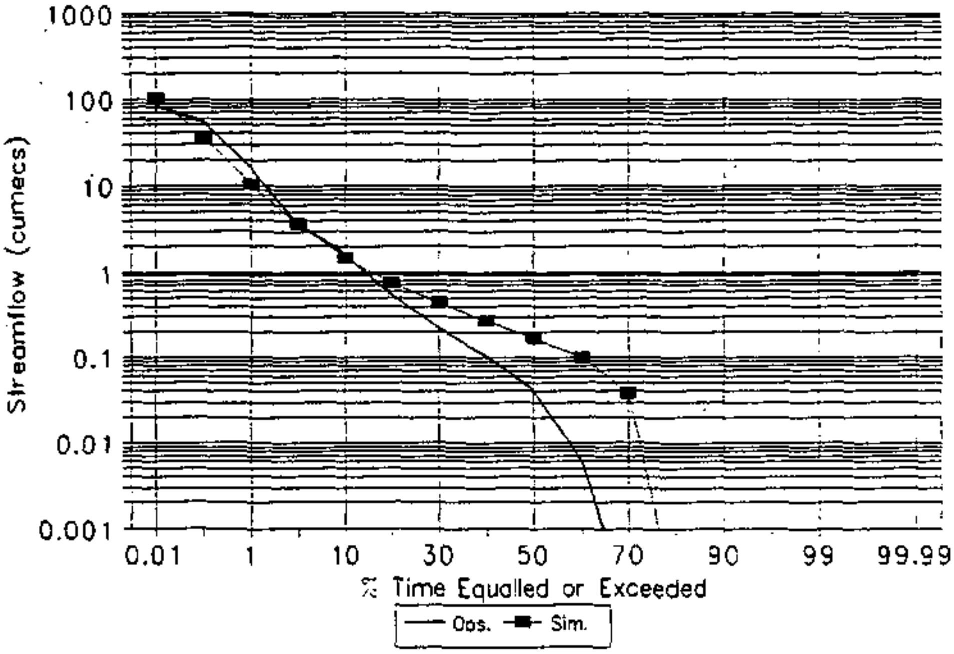

Figure A1.6 Catchment B15 (Lumani River): Observed and simulated duration curves based on all available data (1961 to 1983).

Further calibration of the model could possibly improve this aspect of the simulations, although there are also some instances where the peaks have been over-simulated and the baseflow response under-simulated. Figure A1.7A illustrates a dry year (1978) and indicates that most characteristics of the observed response have been simulated. Abstractions have been included for this catchment and have been set at 2.2 * 10^6 m^3 y^{-1} or about 6.5% of MAR. The storage from which these abstractions are derived has been set at a similar value and supplied by some 20% of the catchment area. Both figures A1.7 A and B suggest that, either the level of abstractions, or the supply area, may have been set too high.

The simulations for catchment E19, which has been established with six sub-areas, are certainly the best when the statistics based on daily data are considered. Abstractions have been set at some 47 * 10^6 m^3 y^{-1} (equal to about 10% MAR) derived from a maximum storage of 35 * 10^6 m^3 supplied by 20% of the catchment area. The example time series provided in figure A1.8A and the duration curve in figure A1.8B, suggest that the abstraction volume could have been higher. In general terms the patterns of correspondence of observed and simulated events, the short term recessions (derived from soil baseflow in the model) and some aspects of the longer term recessions (derived from groundwater baseflow in the model) all seem to be acceptable. As with the other catchments, there are specific events in some years which are either over- or under-simulated to varying degrees. Figure A1.1 indicates that the lower part of the catchment is well represented by raingauges, but that few exist within the boundary of the upper reaches of the northern part.

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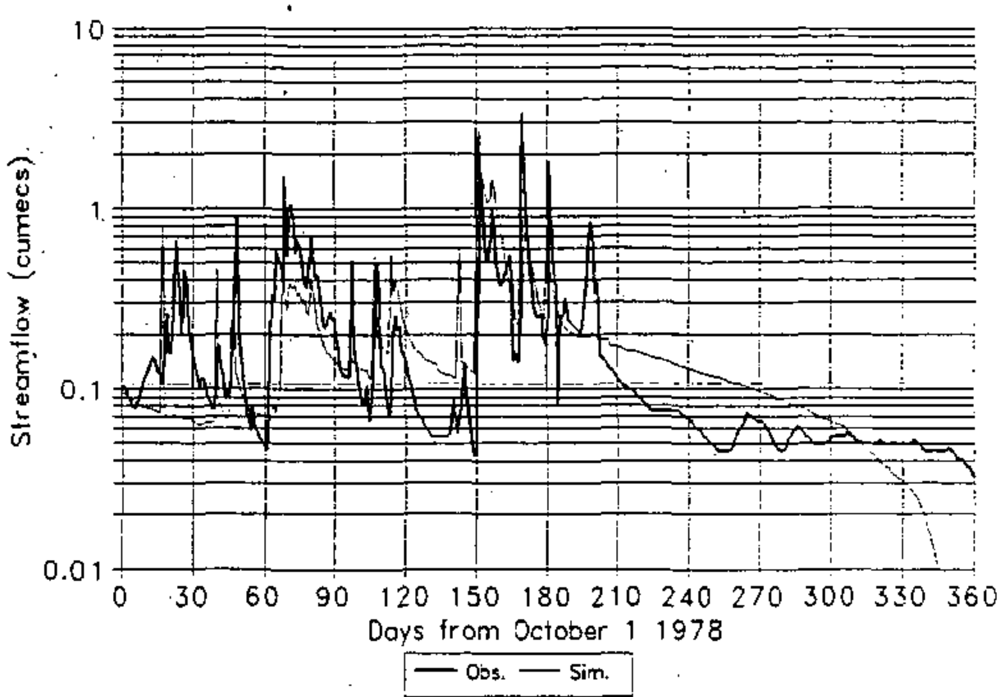

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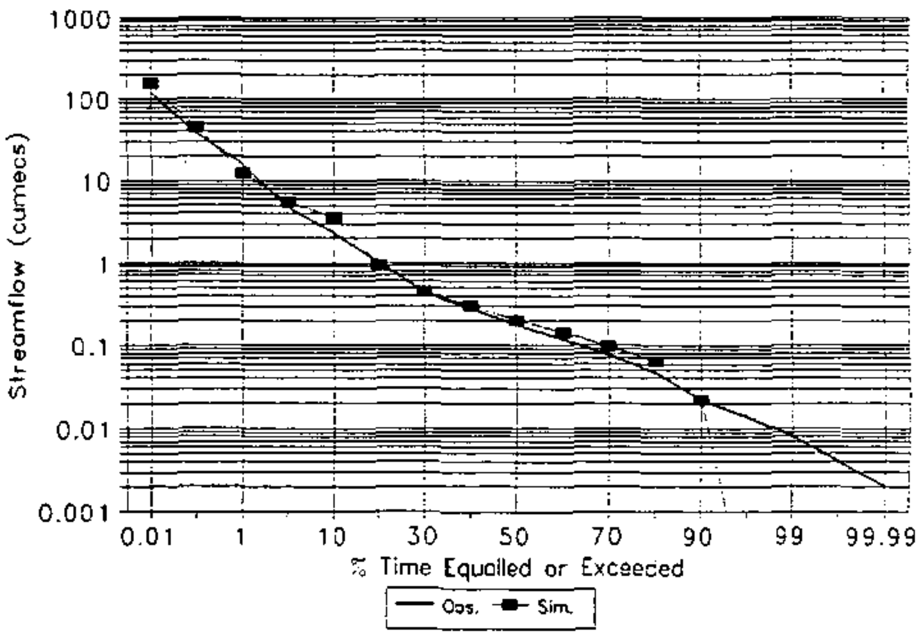

Figure A1.7 Catchment D46 (Mwarazi River): Observed and simulated A) Time series of daily discharges for hydrological year 1978 and B) Duration curves based on all available data for the period 1969 to 1983.

Unfortunately, there is a lot of missing data for catchment E153 and only two lengths of continuous data over 2 years in duration. The period simulated was October 1969 to September 1983 but observed data are available for only 1980 and 1981. There is therefore not really enough data to perform an effective calibration, nor to determine whether the parameters used (partly based on the other catchments results) are representative.

An attempt was also made to calibrate catchment C6, however, the observed response is very confusing when compared to the rainfall input. There are very big differences between the rainfalls at the three available raingauges, particularly during some of the larger events. It was therefore found to be very difficult to differentiate between potential problems caused by poor representation of the catchment rainfall input and those caused by inappropriate parameter values. Further information would be required about the mechanisms of flow generation before it would be worthwhile spending additional time attempting to calibrate the daily model on this catchment.

A1.8 General Conclusions.

Overall, the simulation results based on monthly flow volumes are slightly better for the VTI model than the Pitman model, but this has been achieved through far more calibration effort in the case of the VTI model. Catchment C6 indicates that this conclusion may not necessarily hold for all situations in Zimbabwe and that in some cases, the less complex monthly model may be the most appropriate model to use if a resolution of 1 month is adequate. Certainly, for most of the catchments (except A37 and A41), the Pitman model generates results that are more than adequate for many water resource planning purposes. Both models generate results that are somewhat deficient in terms of the estimation of low flows (indicated by statistics based on logarithmic values). However, given the lack of information on abstraction patterns, it is difficult to ascribe this result to any particular cause.

The VTI model parameters have been established without a great deal of information on the physical characteristics of the catchments used and it is expected that some improvement could be achieved if more were available. It is expected that, should such a model be used for practical purposes, additional resources would be applied to gathering more detailed physical catchment information than was used in this study. The implication is that the results presented in this report represent the minimum levels of success that can be achieved.

There is a reasonable degree of uniformity in many of the parameters of both models for catchments located within similar areas, suggesting that there is potential for a more complete regionalisation of parameter values (similar to the WR90 study in South Africa) to succeed. However, a greater number of catchments would have to be used and more detailed information on current and historical levels of abstraction and water use would be required.

Within some of the daily time series, there are hydrograph shapes that look distinctly odd and very unnatural. Some of these, particularly during the low flow periods, may be attributed to abstractions, but others certainly appear to be errors. It is therefore suggested that individual flow records be carefully screened and checked before use.

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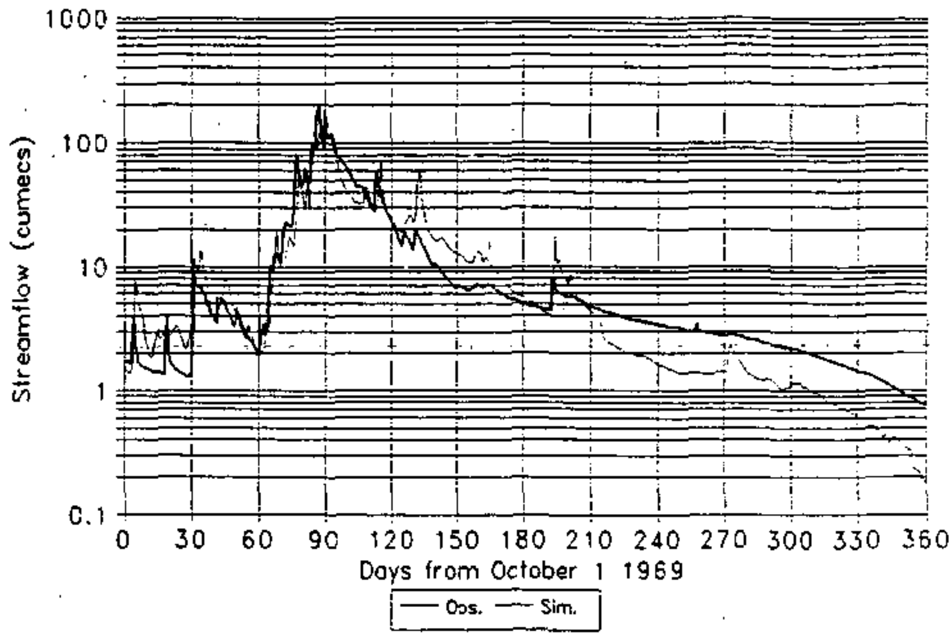

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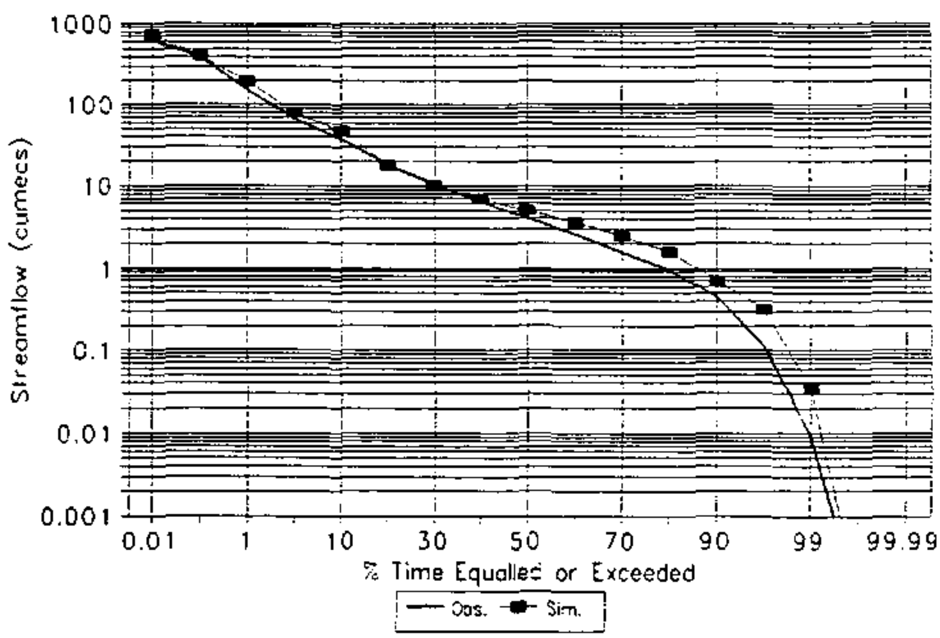


Figure A1.8 Catchment E19 (Macheke River): Observed and simulated A) Time series of daily discharges for hydrological year 1969 and B) Duration curves based on all available data for the period 1969 to 1983.

Appendix A2 MALAWI Catchments

A2.1 Availability of time series data.

Flow data.

Daily flow data were made available to the project team for some 40 gauging stations located throughout Malawi.. The format of the data were as ASCII files with a starting date header and 8 mean daily flow values per line. Unfortunately, this format makes it very difficult to check for gaps in the data, even though such gaps are not meant to exist. Many of the records begin in the early 1950s, while others only start much later in the 1980s. There are variable amounts of missing data. Some of the problems of streamflow gauging within Malawi are discussed in Drayton et al. (1980).

Rainfall data.

Monthly records for 23 raingauges were obtained from the Department of Meteorology on the basis of their proximity to 8 selected gauged catchments (Andrews and Bullock, 1994). Unfortunately, it became evident later that there were no flow data for two of these catchments and very little for a third. The availability of rainfall data has therefore restricted the modelling exercise to a sample of only 5 catchments. In addition to the time series of monthly rainfall, standard period (1961 to 1990) mean annual rainfall totals were obtained for all the raingauges in Malawi. These data have been useful for determining catchment average rainfall and for weighting the monthly time series. The Department of Meteorology were reluctant to release daily rainfall data (Andrews and Bullock, 1994) and therefore no daily model test were possible.

Evaporation data.

Long term average monthly potential evaporation data are available from climatological tables and some useful information is contained within the Institute of Hydrology (UK) study of actual evapotranspiration in Malawi (Mandeville and Batchelor, 1990).

A2.2 Availability of catchment description data.

Only very generalised information was available to the project team (e.g. Andrews and Stubbs, 1972), but more is thought to be available. As there were no daily data provided and it was not possible to test the daily model, the generalised information was considered adequate.

A2.3 Selection of catchments and brief descriptions.

The initial selection of 8 catchments (figure A2.1) was based on the availability of rainfall data. However, flow data were subsequently found to be unavailable for three of these catchments.

Southern Area.

2B8 Mulinguzi River at Zomba Plateau (18.1 km², located at 15°21'33''S 35°18'32''E). Daily flow data are available from November 1986 for about 4 years with some missing. Rainfall data are available from a single station close to the catchment outlet. Standard period rainfall data suggest that the mean annual rainfall varies from 1900 to 2000 mm.

14C2 Ruo River at M1 Roadbridge (193 km², located at 16°05'00''S 35°40'00''E). Daily flow data are available from August 1953 for 38 years with some missing and part of the period is certainly out of phase. Rainfall data are available for three raingauges, all situated within the lower parts of this mountain catchment. The mean annual rainfall varies from about 1700 to over 2200 mm.

Central area.

6C1 Dwangwa River at Kwengwele (2980 km², located at 12°52'51''S 33°27'09''E). No flow data were made available and therefore further information is irrelevant.

5D3 Mtiti River at Mtiti (233 km², located at 13°28'06''S 33°38'42''E). Daily flow data are available from November 1987 for less than one year, which is insufficient for model testing purposes.

4B3 Linthipe River at Linthipe (600 km², located at 14°10'44''S 37°07'28''E). Daily flow data are available from November 1975 for about 15 years with some missing. Rainfall data are available for a single station located in the centre of the catchment and the mean annual rainfall varies from 950 to over 1000 mm.

4B4 Diampwe River at Chilowa New Bridge (1460 km², located at 14°08'11''S 34°05'18''E). Daily flow data are available from June 1978 for about 5 years with some missing and most of it apparently out of phase (wet season to late in the year). The two available raingauges are both outside the catchment and the mean annual rainfall varies from 950 to 975 mm.

Northern Area.

7D3 Lunyangwa River at Zombwe (513 km², located at 10°20'11''S 35°50'47''E). No flow data were made available and therefore further information is irrelevant.

7H3 North Rumphi River at Chiweta (683 km², located at 10°41'00''S 34°11'00''E). Daily flow data are available from November 1980 for about 11 years. Rainfall data are available for four stations, but all of these are in the lower part of the catchment close to Lake Malawi. Mean annual rainfall varies from 1300 to 1500 mm over most of the area, but reaches as high as 1800 mm close to the outflow to the lake.

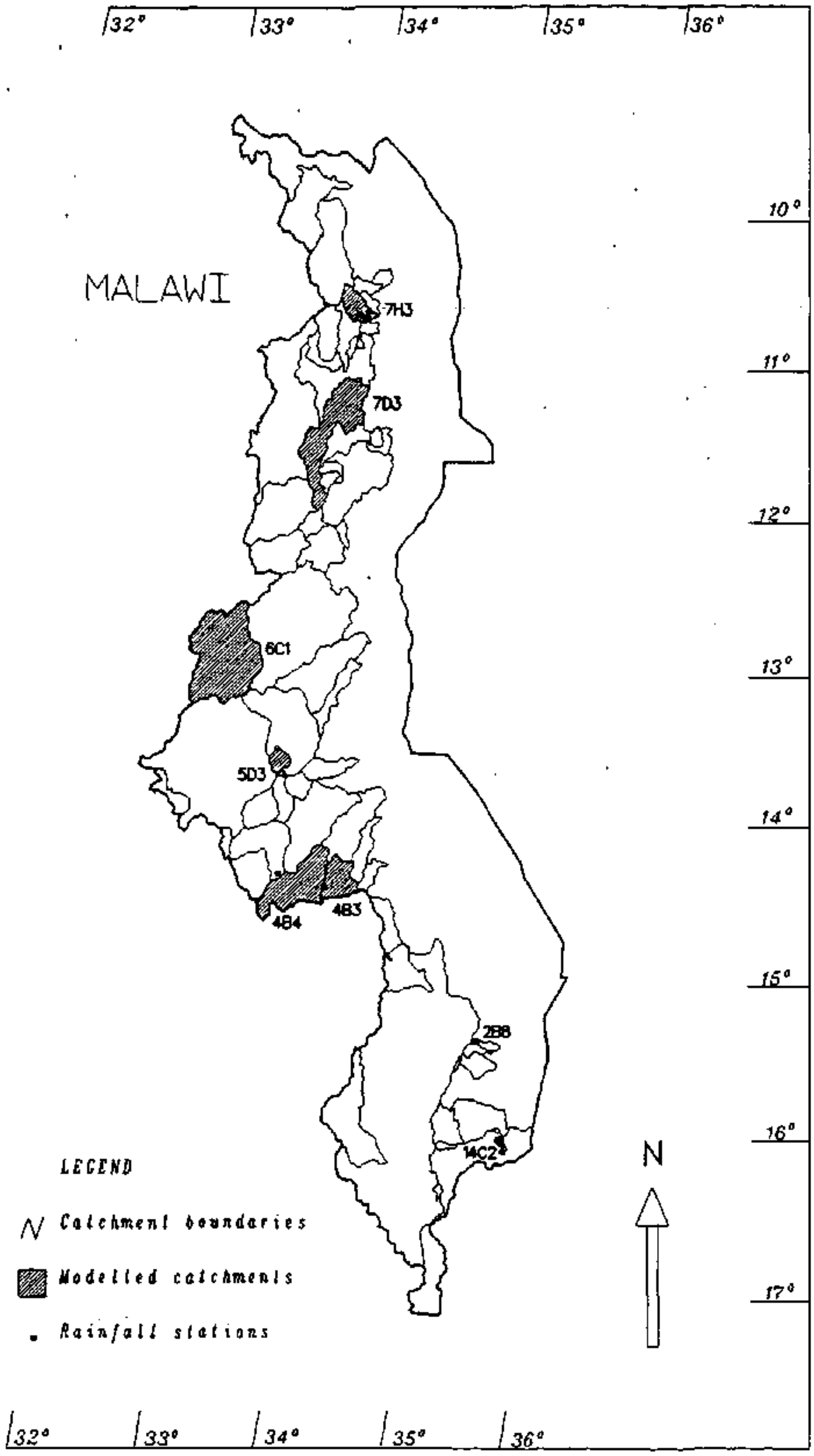


Figure A2.1 Gauged catchments in Malawi and those used in the FRIEND project.

A2.4 Calibration procedure (Pitman model).

The previous section indicates that only four catchments proved to be of any real value from a model testing point of view and because of the lack of rainfall data supplied, the tests on those four were unlikely to be very conclusive. It was therefore difficult to develop a satisfactory calibration procedure.

In most cases, isohyetal maps of mean annual rainfall were drawn up based on the standard period rainfall statistics available for all the Malawi raingauge stations. These were then used to interpolate sub-catchment mean annual rainfall depths, which were used to weight the gauge rainfall time series using a simple linear weight ratio. Unfortunately, where the number of raingauges is limited and all have missing data, the long term mean rainfall for that month is substituted (normal HYMAS procedure) and the correct flow response is impossible to simulate. While every effort has been made to avoid such periods, there are several catchments where this situation could not be avoided in order to get a reasonable length of time overlap between observed and simulated flows.

The catchments, length of simulation period, areas, mean annual rainfall and evaporation, as well as the main Pitman model parameter values are listed in table A2.1

Most of the catchments are underlain by weathered metamorphic rocks of the basement complex. In the high rainfall areas of Malawi it is likely that bedrock weathering can extend to over 20 m, giving rise to relatively high moisture storage (combined soil and groundwater) values and sustained baseflows. However, Kafundi and Laisi (1991) report that compacted clays frequently occur at the top of the weathered layer and these will certainly impede vertical drainage. It seems reasonable to suggest that, in general terms, the two runoff generation functions (catchment absorption and soil moisture drainage) of the Pitman model will be required to simulate the response; one for the immediate response due to heavy rainfall on soils with impeded vertical drainage (ZMAX and ZMIN), and one for the sustained response from a deep weathered bedrock storage (ST, FT and GW).

A2.5 Simulation results (Pitman model).

The results given in table A2.2 suggest that an acceptable calibration has been achieved for 2B8. However, only three years of observed flow data overlap with the available rainfall data and the result is somewhat inconclusive. It was found that the default rainfall distribution factor (1.28) was too high and that a value close to 1.0 gave improved results. This seems to be acceptable given that an average of over 20 days of rain normally occur, implying a more even distribution of rainfall than allowed for in the original model.

Table A2.1 List of catchments (local naming convention), model period, area, rainfall and Pitman model parameters for the Malawi catchments.

Catchment	Start year	End year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	POW	ST	FT	ZMIN	ZMAX	PI	R	TL
2B8	1964	1989	31	18	1950	1177	3.0	650	150	50	500	1.5	0.5	0.25
14C2	1961	1991	110	193	2200	1200	2.0 - 2.5	100 - 400	50 - 150	20 - 60	80 - 400	1.5	0.8 - 0.5	0.25
4B3	1961	1988	141	600	1000	1650	3.0	450	22	80	700	1.5	0.5	0.25
4B4	1961	1988	59	1460	970	1650	3.0	500	15	250	950	1.5	0.5	0.25
7H3	1961	1991	131	683	1400	1800	1.5	620	160	150	850	1.5	0.8	0.25

Table A2.2 Pitman model simulation results, Malawi catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
2B8	-Obs.	1822	1823				7.05	1.12			
	-Sim.	1753	1888	-3.7	0.84	0.82	6.92	0.99	-1.8	0.91	0.86
14C2	-Obs.	26920	23603				9.74	1.09			
	-Sim.	24289	20668	-9.8	0.71	0.69	9.65	1.02	-0.9	0.63	0.60
4B3	-Obs.	12766	18380				8.09	1.89			
	-Sim.	11181	16761	-12.4	0.35	0.24	8.21	1.73	1.5	0.70	0.69
4B4	-Obs.	21403	32470				8.75	1.87			
	-Sim.	22802	38054	6.5	0.01	-1.11	8.75	1.79	0.0	0.08	-0.40
7H3	-Obs.	39570	23535				10.42	0.57			
	-Sim.	39939	24317	0.9	0.79	0.77	10.39	0.66	-0.3	0.80	0.73

While the simulation for 14C2 extends over a period of 30 years, the first part of the flow record is out of step with the expected distribution of monthly streamflow values, suggesting a wet season during May to August. Only after 1980 can the record be used to compare with simulated flows. The catchment drains the Mulanje Forest Reserve and the slopes are very steep in the upper and central parts. The observed runoff depth of 1674 mm is very high, implying that the rainfall is far higher than that used for modelling (between 2400 mm in the upper areas and 1850 mm close to the outlet, or that the amount of storage is very limited and runoff ratios very high. The parameter values given in table A2.1 are the range used over three sub-areas, the lower end of the range used for the headwater sub-area and the high end for the downstream sub-area, where the slopes are lower and storage assumed to be greater. It was also found to be necessary to set about 15% of the upper catchment area to be impervious to generate sufficient response during low rainfalls. The evaporation-soil moisture relationship parameter (R) also required a value (0.8) different to the normal default (0.5) value used for most catchments in order to reduce the total amount of evaporation. Figure A2.2 illustrates the results for a 10 year period and it can be seen that the highest peaks are still not simulated adequately and some of the recessions into the dry season are too rapid. It should be further noted that the three available raingauges are all in the lower part of the catchment, while the upper mountain areas are not represented at all. A more accurate representation of the temporal and spatial patterns of rainfall will almost certainly have an effect on the parameter values. It is therefore necessary to conclude that the parameter values given in table A2.1 are only applicable in conjunction with the rainfall input used.

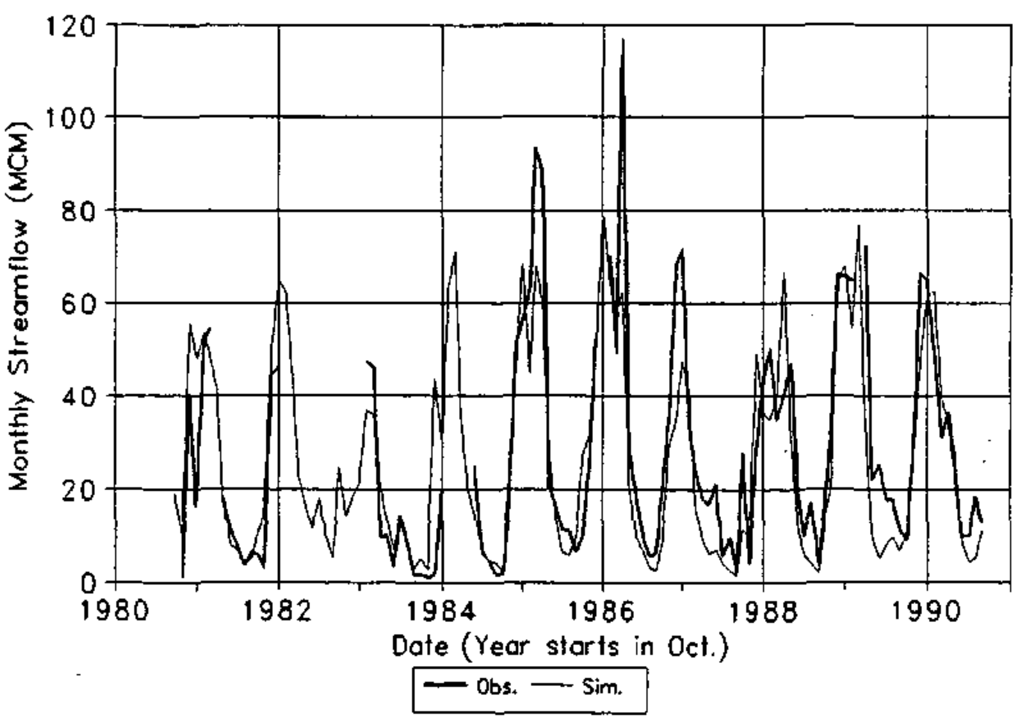


Figure A2.2 Time series of observed and monthly streamflow volume (MCM = $m^3 * 10^6$) for catchment 14C2 (Ruo River) over the period October 1980 to September 1990.

Both 4B3 and 4B4 are located in the central part of Malawi to the southeast of Lilongwe. Parts of the headwater areas are hilly with moderate slopes, while the lower reaches are characterised by broad valleys and dambos. Much of the available flow record for 4B4 is out of step and not usable for calibration purposes and little can be concluded from the modelling exercise. The results for 4B3 are mixed, with the overall reproduction of the flow regime quite acceptable (figure A2.3), but many individual months poorly simulated (statistics from table A2.2) and particularly the wet season months.

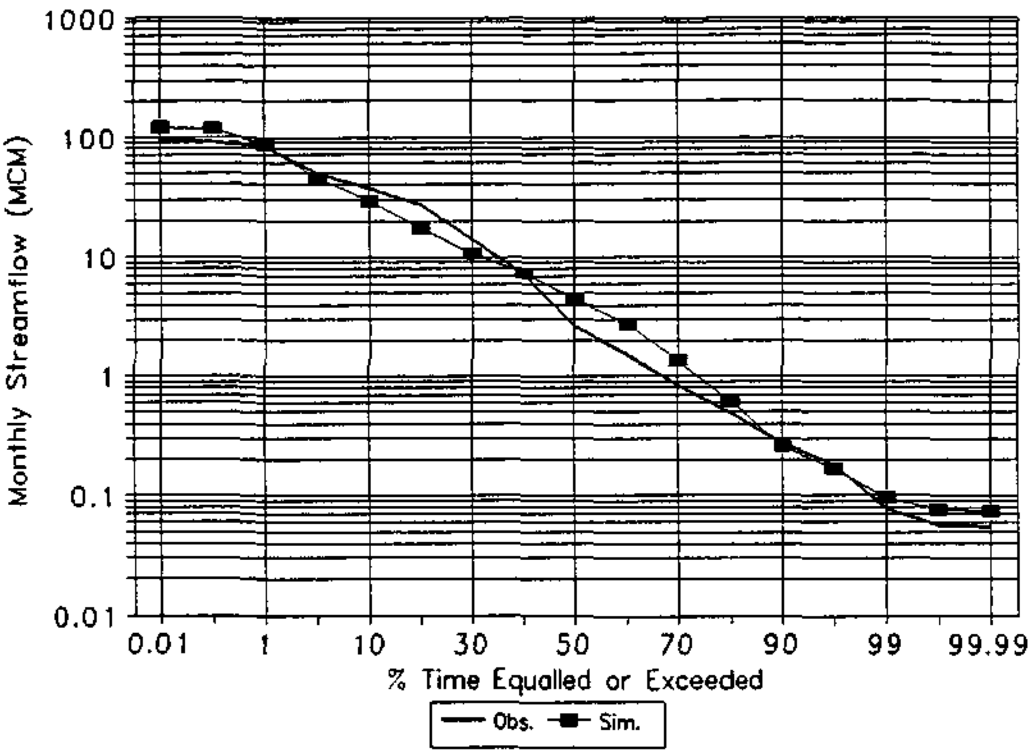


Figure A2.3 Monthly observed and simulated flow duration curves for catchment 4B3 (Linthipe River) based on data for October 1970 to September 1991.

Catchment 7H3 is a mountain catchment area draining the Nyika Plateau and has its outlet close to Lake Malawi to the south of Livingstonia. All the raingauges are located in the lower part of the catchment and the simulation exercise suffers from similar problems to 14C2. However, the situation appears to be different here and the parameters conform more closely to what might be expected, given the limited understanding of the subsurface characteristics of the catchment. It was found useful to set a value of 40 mm for parameter GW (groundwater response component of FT), with a groundwater delay parameter of 0.8. This improved the dry season baseflow response, which is quite high in this catchment (figure A2.4). The higher value for parameter R (0.8) than usual, implies less effective evapotranspiration as the main moisture store dries out, but this may also be a reflection of a mis-representation of rainfall input to the upper mountain areas. It could also be a reflection of the fact that the relatively high storage value includes groundwater storage that can not easily be depleted by evapotranspiration. Overall, the simulation was more than satisfactory and the calibration was one of the easiest and quickest to achieve.

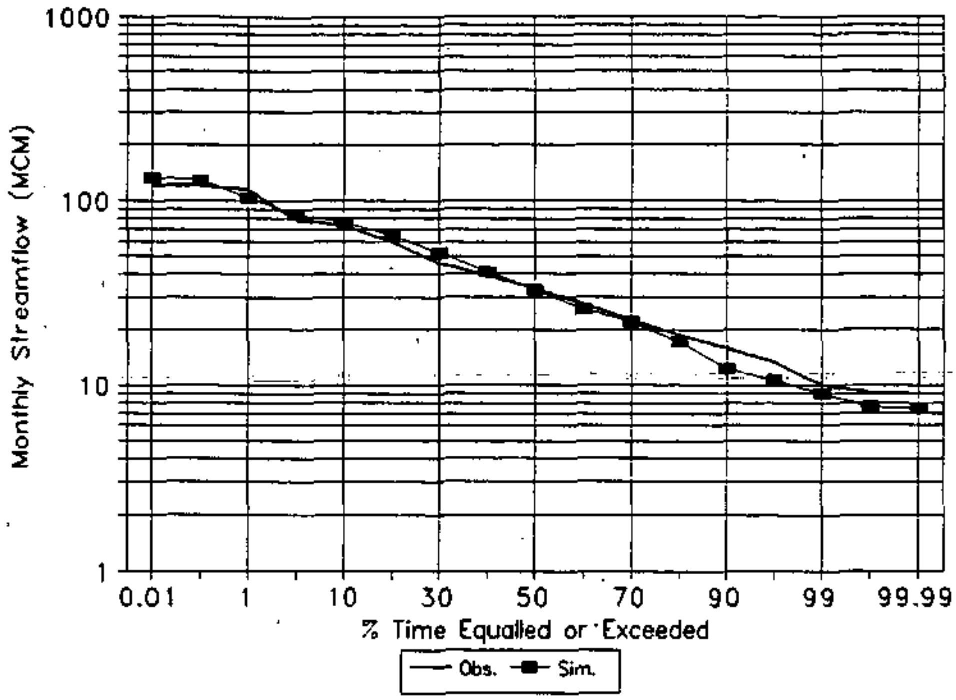


Figure A2.4 Monthly observed and simulated flow duration curves for catchment 7H3 (North Rumphi River) based on data for October 1980 to September 1991.

A2.6 Results of applying the 'Patching' model.

In the absence of daily rainfall data, an attempt was made to apply the daily flow data patching and extension approach of Hughes and Smakhtin (1996) to several groups of Malawi catchments. The groups used were catchments 3E1, 2 and 3 (South West Lakeshore); 2B8, 2B22 and 2C3 (Lake Chilwa basin) and 4D4, 4D6 and 4E1 (Lilongwe River basin). The approach relies upon being able to generate satisfactorily representative daily flow duration curves for each month of the year from the available observed flow data. The first problem encountered was being able to identify long enough continuous periods where the data recorded in proper time sequence. The author assumes that the problem lies with the data files supplied to the project (as a consequence of errors in the data extraction procedure or program) and not with the original data. However, the consequence is that for parts of the time series the high flow days occur during the dry season and these periods can clearly not be used in generating the duration curves. The second problem was that there are many periods of missing data, making it difficult either to find legitimate flow records at adjacent sites with which to 'patch' a destination site, or to find suitable lengths of record at the destination site to be able to make comparisons with the estimated flows. Figure A2.5 illustrates one of the more successful periods (part of the 1985 hydrological year) for catchment 4D6, where the simulated flows are derived from interpolation from 4D4 and 4E1 with equal weighting. The general pattern of flow is reasonably accurately reproduced, as are the low flows. However, individual peaks are not very well simulated, some being out of phase, some under-estimated and others over-estimated. These characteristics are common to the other catchments used in this exercise and result in relatively poor statistics based on un-transformed values. R^2 values are generally less than 0.5 and frequently less than 0.2, while CE values are often negative. The statistics based on log-transformed data are generally better, with R^2 values between 0.65 and 0.8 and CE values up to 0.15 lower. The % errors in the simulated mean daily flows (either un-transformed or log-transformed) are very variable. The general conclusion is that the technique is appropriate for low flows and the general seasonal pattern of flow, but is not generally suitable for individual events. Assuming that the timing of the observed flow data is accurate in the original records, the main restriction to the application of the method is the amount of missing data at key stations.

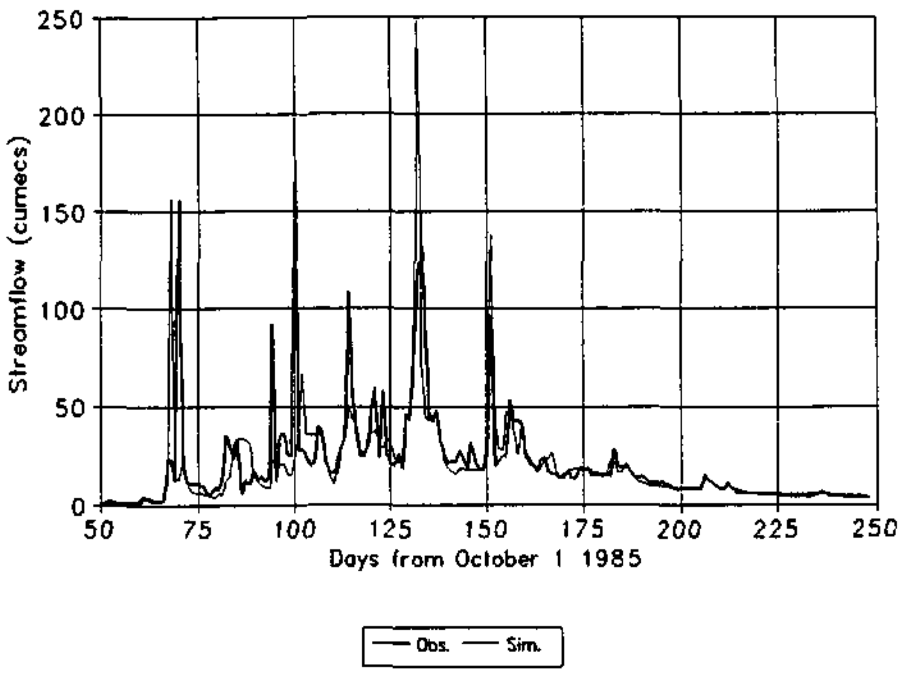


Figure A2.5 Daily observed and simulated (using the 'Patching' model) daily flows for part of the 1985 hydrological year for catchment 4D6 (Lilongwe River).

A2.7 General conclusions.

The main conclusion is related to the quality of the data that was made available to the project and the limitations that this placed on the modelling exercises. Many of the flow time series that could be used were quite short for the purposes of calibrating and assessing a monthly model because of the frequency of missing data, or data that were considered unreliable with respect to the date of observation (within the files available to the project). The major constraint has been the lack of sufficient raingauge records with which to define the spatial variations in rainfall input, even at a relatively coarse scale. It is not clear to what extent further rainfall time series are available, nor whether daily values could be made available in the future if required. Despite these relatively severe limitations, the Pitman model generated results that can be considered acceptable in most cases and which could be of value for water resource estimation purposes (mainly through the extension of gauged records). Unfortunately, an insufficient number of catchments were used for any conclusions to be reached about the regionalisation of parameter values within Malawi.

Appendix A3 SWAZILAND Catchments

A3.1 Availability of time-series data.

Flow data.

Daily streamflow data are available for a large number of rivers within Swaziland. Many of the gauging stations are on rivers which originate within South Africa, while others are on rivers which have catchments entirely within Swaziland. The simulation exercises for this project were largely confined to the latter. Some of the records begin in the early 1960s while others start later in the 1970s.

Rainfall data.

Daily rainfall data are available for some 80 stations within Swaziland, such that while there is a reasonable distribution of gauges for the country as a whole, the density within individual catchments is relatively low. Most of the rainfall records begin prior to the flow gauging records although some stations were only opened later. To support the time series of rainfall data, the database of median monthly rainfalls for 1' * 1' grids, available from the Computing Centre for Water Research at Natal University (Dent, et al., 1989), cover Swaziland and can be used to assist in defining the spatial variability of rainfall depths.

Evaporation data.

Daily pan evaporation data are available for nine stations, most of which have data for the 1980s, but few with records prior to that. These data can be used to establish representative monthly distributions of pan evaporation, but are not really of value as input time-series to the models.

The final selection yielded 3 catchments in the Mbuluzi basin, 1 station on the Ngwavuma River and 3 catchments in the Mhlatuzane basin. Data from 19 raingauge stations were used to define the rainfall input to the models. Gauging records for four sites on the Ngwempisi River (catchment shared with South Africa) were also selected for testing a very simple streamflow spatial interpolation algorithm ('Patching Model'), but these catchments were not used in rainfall-runoff model tests.

A3.2 Availability of catchment description data.

As Swaziland falls within the area covered by the Surface Water Resources of South Africa 1990 (WR90) publications, there are maps available (at a scale of 1:1 000 000) which provide information on landcover, geology, soils and vegetation. In addition maps on hydrogeology and groundwater resources at a scale of 1:250 000 and a 1:125 000 soils map were provided to the project team. The latter is supported by a publication on soils and land capability (Murdoch, 1970) which contains some more generalised information on climate, vegetation, geology and water resource usage. Topographic maps at 1:50 000 and 1:250 000 scales covering all of Swaziland were also used.

One of the problems with several sources of information about the same characteristic is that confusion arises due to different definitions and scales of mapping. For example, the WR90 soil map suggests that a large part of the lowveld region, lying along the eastern borders of Swaziland has moderate to deep sandy loams, which then pass into moderate to deep clay soils in the central part of the country. The northern highveld regions are mapped with moderate to deep sandy loams, while the southern parts with moderate to deep clayey loams. Comparisons with the more detailed 1:125 000 map are difficult as there are a greater number of mapping units and it is clear that soil variations are strongly linked to topography. The generalisations made in the WR90 publication are far from obvious from a study of the 1:125 000 map which indicates a great mixture of shallow and deeper soils with a wide variety of textures throughout the country. In general terms, it is quite difficult to define the hydrological character of the soils within the selected catchments, partly because of the apparent high spatial variation.

A3.3 Selection of catchments and brief descriptions.

11 gauged catchments were selected and their location is illustrated in figure A3.1.

Mbuluzi catchments. These are located in the northern part of Swaziland and consist of two gauges on the Black Mbuluzi (gauges 4 and 3, table A3.1) and one on the White Mbuluzi (gauge 10). The catchment of the upper Black Mbuluzi falls within the Highveld region while the lower catchment (gauged above Mnjoli Dam) and the White Mbuluzi predominantly drain the Middleveld region. The topography is generally quite steep and underlain by intrusive granites. While many of the soils of the Highveld region are described as shallow and stoney, it is possible that the weathered granites provide additional moisture storages and account for at least part of the baseflow contribution to streamflow. Four raingauges are available to define the catchment inputs for both the Black and White Mbuluzi catchments, however, the distribution of gauges is far from ideal with the central part of the Black Mbuluzi being under-represented and all the White Mbuluzi gauges situated outside the catchment.

Mhlatuzane catchments. These are situated in the south eastern part of Swaziland draining the Middleveld and Western Lowveld, the upper parts of the catchments have relatively steep topography, while the lower parts have gentler slopes typical of the Lowveld. Similarly, the upper catchment areas are underlain by granite intrusives, while parts of the lower catchments are underlain by Karoo sandstones and shales with dolerite intrusions. Two gauging sites are present on the Mhlatuzane (12 and 19, figure A3.1) and one on the Mhlatuze (13). The six raingauges that are available for this area are likely to reasonably represent inputs to the Mhlatuzane catchments, but not the more southern Mhlatuze.

Ngwavuma catchments. Flow data from a single gauging station are available for the Ngwavuma (8, table A3.1 and figure A3.1) and the catchment extends from the edges of the Highveld, through the Middleveld and into the Lowveld. Both the granites and the sandstones and shales are represented in the catchment and the topography is steep within the upper reaches changing to undulating in the lower parts of the catchment. Only three raingauges are available to define the catchment inputs and these are located on the upstream central and downstream boundaries.

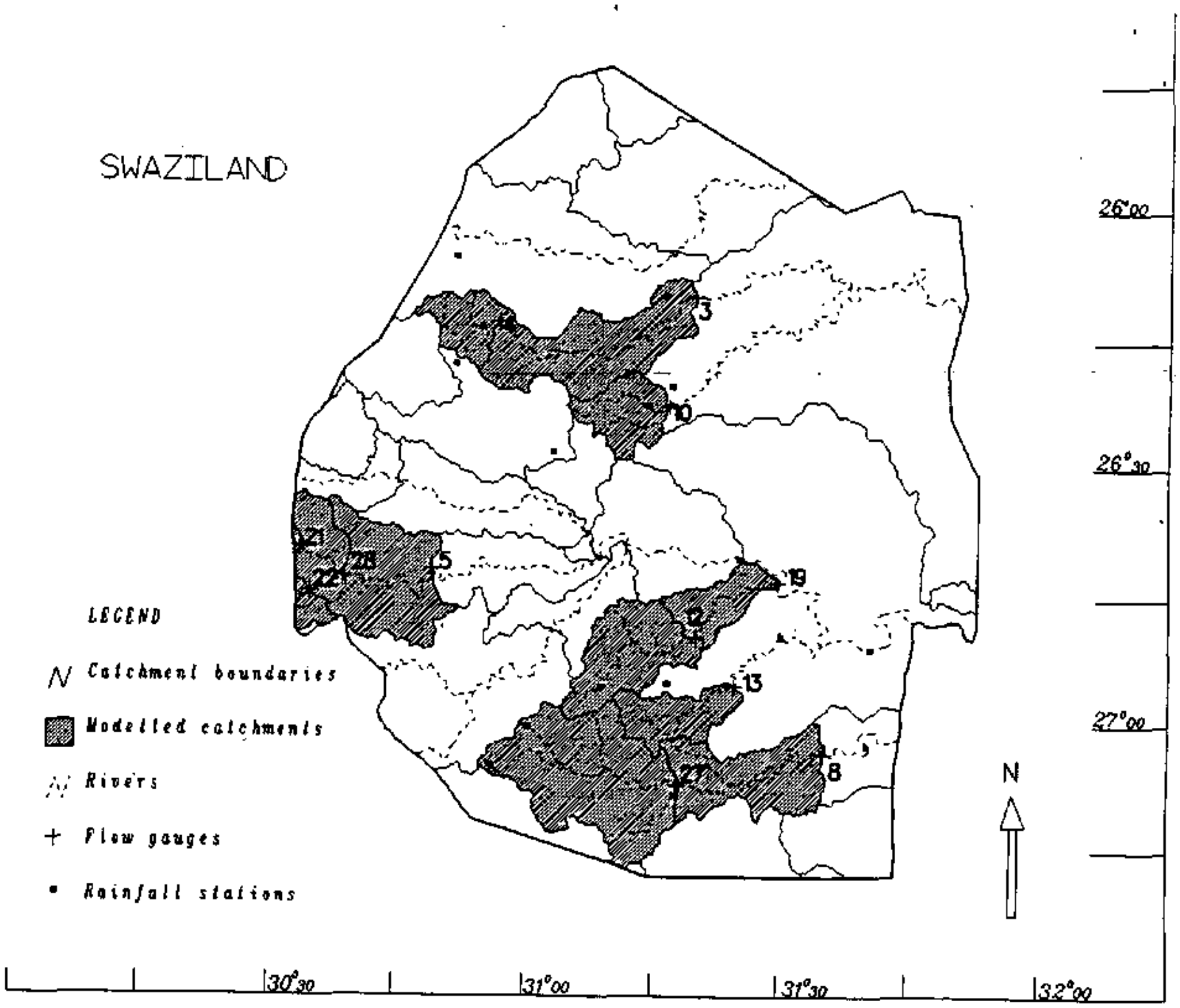


Figure A3.1 Gauged catchments in Swaziland and those used in the FRIEND project.

Ngwempisi catchments. These catchments have not been included in the rainfall-runoff model testing part of the programme, largely because the main parts of their drainage areas fall within South Africa. However, they do represent a cluster of four flow gauges within the same basin and as such provide a suitable data set with which to test a streamflow spatial interpolation model that is designed as a simple method of patching and/or extending time series of flow.

The vegetation cover is best described in association with the physiographic regions (High-, Middle- and Lowveld). The Highveld is characterised by short grassland with some areas of natural woodland in sheltered hollows and river valleys which were more extensive in the past, but have been cleared for grazing. The Middleveld is characterised by highly overgrazed grassland, while the Lowveld by tropical bush and savannah type vegetation. Overgrazing in the Lowveld has resulted in the invasion by thorny scrub.

A3.4 Calibration procedure (Pitman Model).

As this region is covered by both the earlier and current (WR90) versions of the Surface Water Resources of South Africa publications, regional values for the Pitman parameters are available to establish initial values prior to calibration. The new version (WR90) was not published until after the Swaziland catchments had been calibrated for the FRIEND project and therefore the initial simulations were based on the old regional values.

In general terms, the recommended regional values for parameter ST is 600mm for most of Swaziland, while values for FT vary between 45mm in the upper reaches of the Mbuluzi to 4mm over the majority of the Lowveld region. Similarly, there is little variation in the recommended values for the ZMIN and ZMAX parameters, with ZMIN set to zero throughout the country and ZMAX varying between 800mm for the western part of the country and 1050mm for the eastern part. The recommendations for POW follow those for ZMAX and a value of 2 is suggested for the western parts and 3 for the eastern.

Unfortunately, the parameter values suggested by the 1980 version bear little relationship to those proposed in the 1990s version. The new ST values range from 150 to 300mm, FT values from 2 to 60mm and only POW, ZMIN and ZMAX values conform reasonably well to the earlier recommendations. The basic structure of the model used for the two studies is supposed to be the same and it is difficult to understand why there is such a great variation in the two sets of recommended values. Section A3.5 below highlights the differences in the results obtained using the different parameter values with the version of the model used for this project (also identical in basic structure to the others).

A3.5 Simulation results (Pitman Model).

Table A3.1 lists the catchments, the periods of data (combined flow and rainfall) available for model testing, mean annual rainfall and pan evaporation depths and the calibrated values for the model parameters. Table A3.2 illustrates the model results based on the usual set of comparative (observed and simulated) statistics using normal and log transformed monthly flow volumes. As before, a period of some 10 years was commonly used for calibration and the remaining period reserved for validation.

Table A3.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Swaziland catchments.

Catchment	Start year	End year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	POW	ST	SL	FT	ZMIN	ZMAX	PI	R	TL
Black Mbuluzi (4)	1960	1983	259	166	1316	1400	2.0	620	0	45	0	800	1.5	0.5	0.25
Black Mbuluzi (3)	1960	1983	268	722	1064	1400	2.0	590	0	45	0	800	1.5	0.5	0.25
White Mbuluzi (10)	1964	1983	173	223	824	1400	2.0	500	0	12	0	600	1.5	0.5	0.25
Mhlatuzane (12)	1971	1986	120	365	993	1400	3.0	680	0	20	0	800	1.5	0.5	0.25
Mhlatuzane (19)	1971	1986	120	526	929	1400	3.0	690	0	15	0	1100	1.5	0.5	0.25
Mhlatuze (13)	1971	1986	155	215	864	1400	3.0	680	0	40	0	1000	1.5	0.5	0.25
Ngwavuma (8)	1965	1982	216	1305	744	1400	3.0	600	0	18 to 25	0	850	1.5	0.5	0.25
Ngwempisi (1)	1960	1985	143	1525	Not used for Pitman model testing, most of catchment within South Africa.										
Hlelo (22)	1960	1985	173	816	Not used for Pitman model testing, most of catchment within South Africa.										
Mponono (28)	1960	1985	57	267	Not used for Pitman model testing.										
Ngwempisi (5)	1960	1985	136	3320	Not used for Pitman model testing.										

Table A3.2 Pitman model simulation results, Swaziland catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Black Mbuluzi (4)	- Obs.	5738	4706				8.37	0.76			
	- Sim.	5897	5098	2.8	0.77	0.72	8.43	0.67	0.7	0.74	0.73
Black Mbuluzi (3)	- Obs.	18048	14209				9.57	0.65			
	- Sim.	17665	13833	-2.1	0.81	0.80	9.56	0.62	0.1	0.86	0.85
White Mbuluzi (10)	- Obs.	2004	2881				7.04	0.96			
	- Sim.	2102	2606	4.9	0.45	0.39	7.18	0.90	2.0	0.54	0.48
Mhlatuzane (12)	- Obs.	3965	4965				7.81	0.93			
	- Sim.	3787	5041	-4.4	0.77	0.75	7.83	0.82	0.2	0.70	0.70
Mhlatuzane (19)	- Obs.	4297	5298				7.92	0.90			
	- Sim.	4726	5952	10.0	0.78	0.72	8.05	0.83	1.6	0.73	0.70
Mhlatuze (13)	- Obs.	2191	2143				7.35	0.83			
	- Sim.	2077	1747	-5.2	0.51	0.50	7.39	0.68	0.5	0.61	0.60
Ngwavuma (8)	- Obs.	8018	8422				8.61	0.84			
	- Sim.	7815	7669	-2.5	0.46	0.40	8.62	0.81	0.1	0.59	0.56

The results for the Mbuluzi group of catchments are illustrated in figures A3.2 to A3.5. Table A3.1 suggests that the original (1980s) parameter value recommendations for the Black Mbuluzi were fairly close to those which have been derived through calibration and that both calibration period (figure A3.2) and validation period (figure A3.3) representations of observed flow characteristics are more than reasonable. The high and low flow parts of the duration curve for the upper site (figure A3.4) are somewhat over-simulated, but for the most part, the simulations can be considered acceptable. Table A3.2 and figure A3.5 demonstrate that the simulations for the White Mbuluzi were less successful and table A3.1 that the calibration parameter values are somewhat different to the suggested regional values. Part of the problem certainly lies with the relatively poor positioning of the available raingauges.

If the WR90 regional parameters are used with the version of the model applied in the FRIEND project and the rainfall input used, the statistics are far worse with errors in the mean monthly runoff of close to 20% and generally lower CE values. These parameters also tend to highly over-estimate low flow months.

The situation with the Mhlatuzane and Ngwavuma group of catchments is similar to the Mbuluzi, in that the catchments which have better rainfall coverage (12 and 19) appear to be those for which the model performs better (table A3.2). Most of the problems with the simulations for the Mhlatuze (13) and Ngwavuma (8) are related to mixed over- and under-simulation of the wettest months of the season, which is frequently an indication of inadequate rainfall definition. The calibration parameters are also somewhat different to those suggested by the earlier regional set with ST and FT values higher, although not as high as the Black Mbuluzi to the north. The best ZMAX values to use seem to lie between those recommended for the two areas of Swaziland (800 to 1050mm).

As with the Mbuluzi, the new version of the parameter value recommendations do not seem to be valid (given the model version and rainfall input), and in the case of the Mhlatuzane generate far too little dry season runoff due to low FT values. The low recommended ST value is frequently exceeded by the rainfall input which generates excessive soil moisture runoff during the wet months and, coupled with the under-estimated low flows, produces standard deviations of monthly flows which are close to 100% too high.

In general terms, the calibrated parameter values generate streamflow time-series which are representative compared to the available observed data. Even where table A3.2 indicates that the statistical correspondence is not very high, the duration curves of observed and simulated flows are reasonably close.

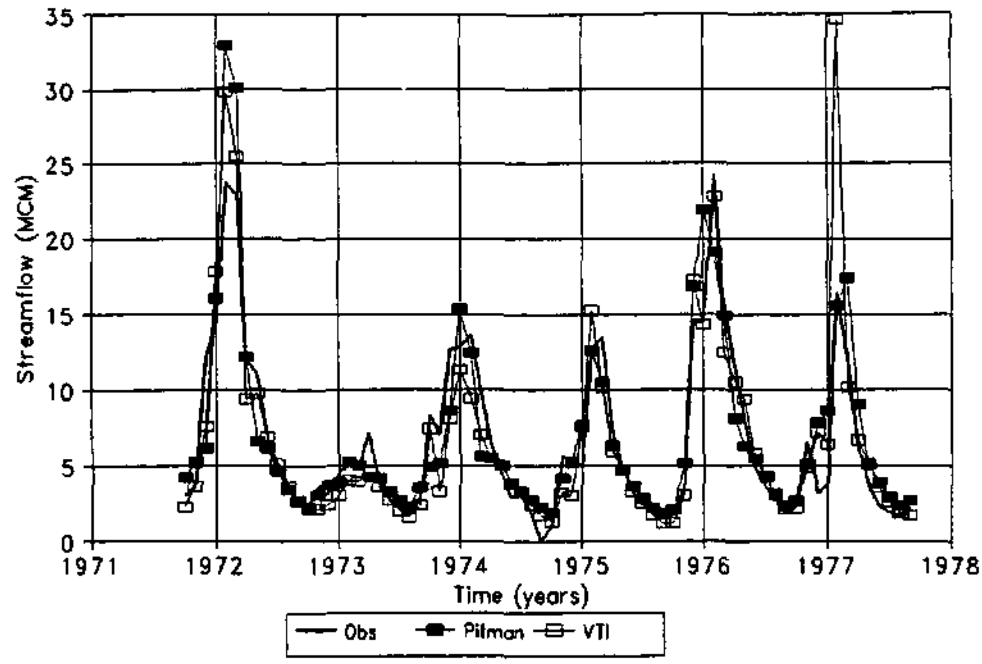


Figure A3.2 Upper Black Mbuluzi (catchment 4), observed and simulated (Pitman and VTI model) monthly flow time series for hydrological years 1971 to 1977.

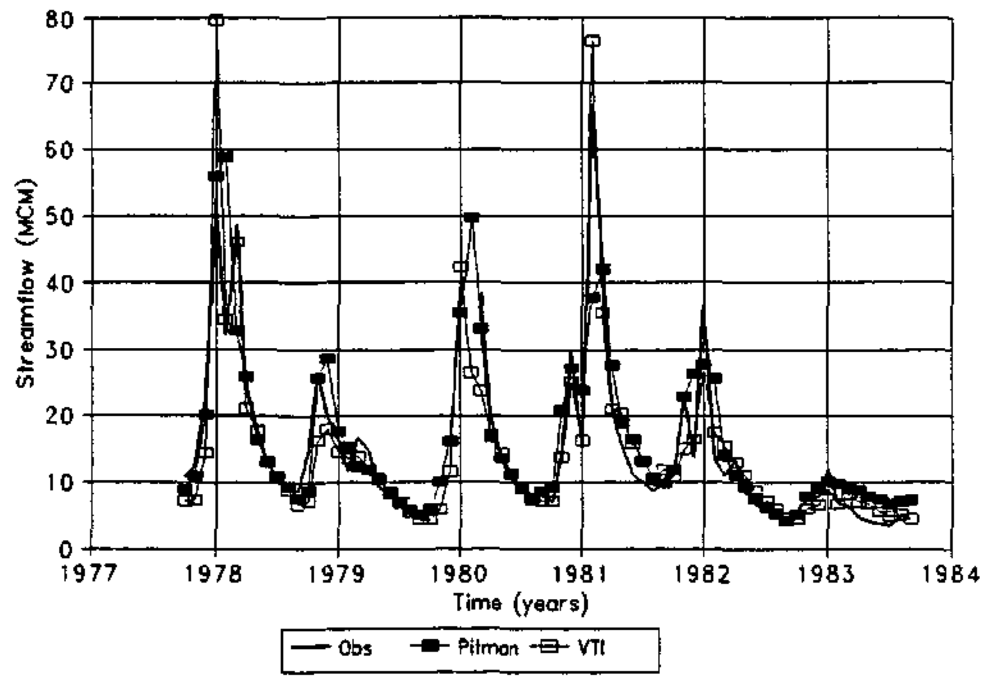


Figure A3.3 Lower Black Mbuluzi (catchment 4), observed and simulated (Pitman and VTI model) monthly flow time series for hydrological years 1977 to 1983.

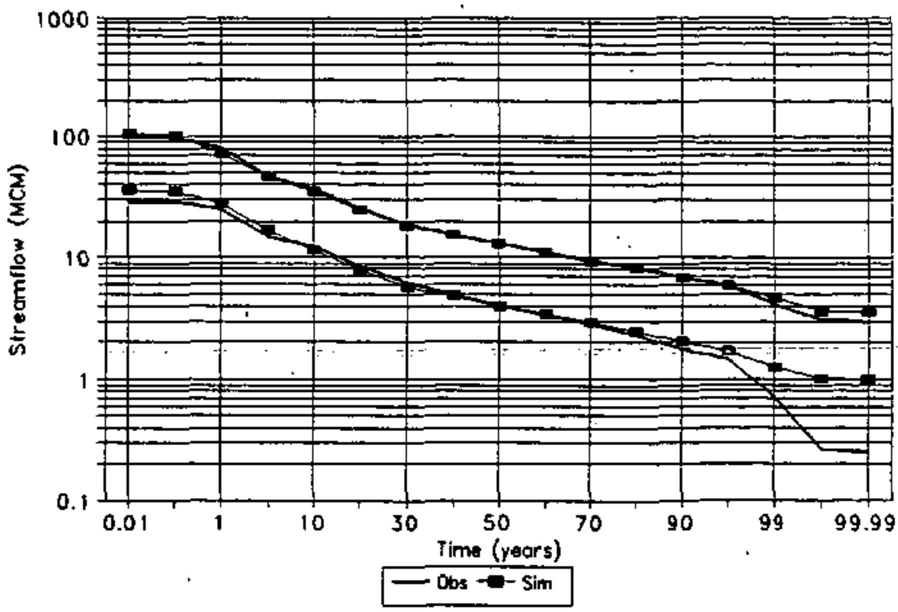


Figure A3.4 Black Mbuluzi (upper and lower sites) monthly duration curves for observed and simulated (Pitman model) data.

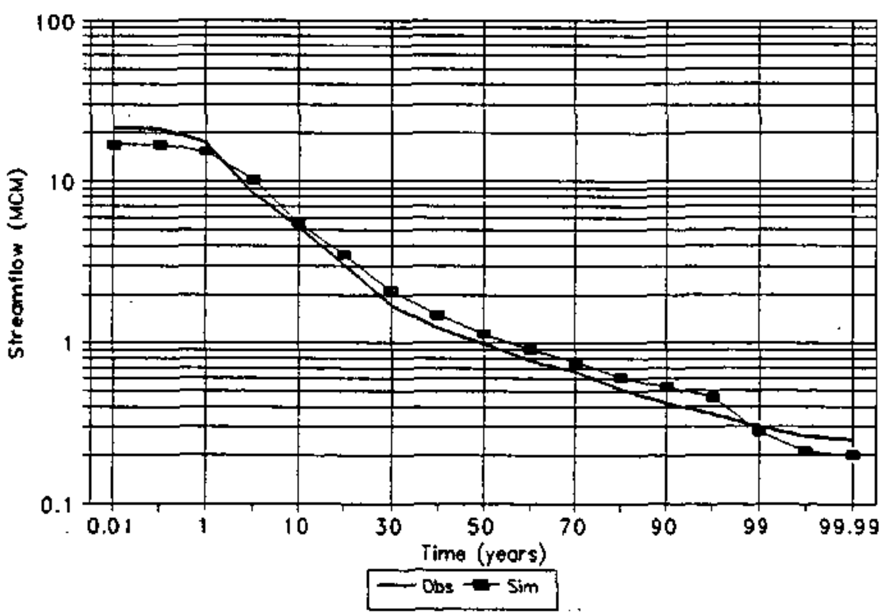


Figure A3.5 White Mbuluzi monthly duration curves for observed and simulated (Pitman model) data.

A3.6 Calibration Procedure (VTI Model).

The normal calibration procedure was followed (see section A1.6 for Zimbabwe), using all available sources of information to establish initial values for the physiographic variables. The soil and groundwater parameters are usually those that are most difficult to establish realistic starting values for and therefore those that are concentrated on during calibration.

Most of the catchments are underlain by weathered granites which is expected to give rise to shallow aquifers which supply a large proportion of the dry season baseflow. Large parts of the catchments have relatively steep slopes and therefore it was decided to simulate the groundwater baseflow as springs on the assumption that drainage from the aquifer occurs at discrete points at the base of slopes. In practice, the concept of groundwater intersection, with the aquifer geometry parameters set to emulate a water table close to the surface over most of the catchment, would have generated very similar results.

In general terms several years of the time series were used as key periods upon which to base the calibrations. These years were not necessarily sequential and were selected to represent the range of streamflow conditions prevailing throughout the whole period and included droughts as well as high flow periods. The remaining years formed the validation period. Table A3.3 lists some of the key parameter values that have been established after the calibration exercise.

Table A3.3 Some key parameters of the VTI model for the Swaziland catchments (the values given for those catchments with several sub-areas represent averages over the area below any upstream gauge. This applies to 3, 19 and 8).

Parameter / Catchment		4	3	10	12	19	13	8
Veg. cover fraction		0.57	0.50	0.40	0.53	0.50	0.50	0.50 - 0.42
Canopy capacity (mm)		0.82	0.64	0.42	0.71	0.64	0.64	0.64 - 0.45
Infiltration Curve	K	0.63	0.61	0.60	0.61	0.60	0.61	0.63 - 0.59
	C (mm h^{-1})	181.0	170.0	170.0	175.0	169.0	174.0	183.0 - 162.0
Total Soil Store (mm)		515.0	320.0	295.0	365.0	406.0	367.0	390.0 - 434.0
FC/Porosity		0.54	0.57	0.57	0.56	0.58	0.56	0.53 - 0.59
Soil K (mm h^{-1})		25.0	17.0	15.0	16.5	15.5	16.5	18.2 - 20.1
Texture dist. factor		0.85	0.85	0.80	0.85	0.85	0.85	0.85 - 0.75
St.Dev. of Moist. Dist.		0.13	0.14	0.12	0.13	0.13	0.13	0.13 - 0.12
G'Water K (mm h^{-1})		0.40	0.37	0.15	0.22	0.20	0.38	0.28 - 0.22

Table A3.4 VTI model simulation results based on daily data, Swaziland catchments.

Catchment		Model Period	Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Black Mbuluzi (4)	- Obs.	1970 - 1983	2.19	2.55				0.36	0.91			
	- Sim.		2.23	2.87	1.8	0.60	0.47	0.41	0.84	13.8	0.76	0.76
Black Mbuluzi (3)	- Obs.	1970 - 1983	7.47	8.57				1.69	0.74			
	- Sim.		7.46	8.44	-0.1	0.63	0.59	1.76	0.62	4.1	0.82	0.80
White Mbuluzi (10)	- Obs.	1964 - 1972	0.79	3.00				-1.05	1.01			
	- Sim.		0.86	2.20	8.9	0.14	0.02	-1.06	1.15	0.9	0.62	0.50
Mhlatuzane (12)	- Obs.	1971 - 1983	1.33	2.53				-0.29	0.96			
	- Sim.		1.31	2.42	-1.5	0.23	0.01	-0.25	0.93	16.0	0.56	0.51
Mhlatuzane (19)	- Obs.	1971 - 1983	1.41	3.07				-0.24	0.98			
	- Sim.		1.48	3.79	5.0	0.17	-0.51	-0.23	0.97	4.2	0.51	0.43
Mhlatuze (13)	- Obs.	1971 - 1983	0.83	1.44				-0.68	0.95			
	- Sim.		0.78	1.52	-6.0	0.36	0.15	-0.67	0.84	1.5	0.62	0.62
Ngwavuma (8)	- Obs.	1970 - 1982	3.56	7.51				0.73	0.92			
	- Sim.		3.44	7.36	-3.4	0.21	-0.06	0.78	0.79	6.8	0.54	0.52

Table A3.5 VTI model simulation results based on monthly totals, Swaziland catchments.

Catchment	Model period	Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Black Mbuluzi (4) - Obs.	1970 - 1983	5824	5184				8.32	0.85			
- Sim.		5930	5910	1.8	0.82	0.79	8.37	0.81	4.7	0.85	0.81
Black Mbuluzi (3) - Obs.	1970 - 1983	20650	5864				9.71	0.64			
- Sim.		20622	5485	-0.1	0.81	0.80	9.82	0.63	1.1	0.87	0.84
White Mbuluzi (10) - Obs.	1965 - 1972	2075	3076				7.04	0.98			
- Sim.		2262	3367	9.0	0.71	0.64	7.03	1.09	-0.1	0.75	0.69
Mhlatuzane (12) - Obs.	1971 - 1983	3494	3823				7.73	0.89			
- Sim.		3441	3542	-1.5	0.69	0.67	7.77	0.86	0.5	0.70	0.69
Mhlatuzane (19) - Obs.	1971 - 1983	3703	3867				7.83	0.86			
- Sim.		3888	5922	5.0	0.63	0.20	7.81	0.93	0.2	0.72	0.65
Mhlatuze (13) - Obs.	1971 - 1983	2195	2228				7.32	0.86			
- Sim.		2038	1998	7.0	0.53	0.50	7.31	0.78	0.1	0.75	0.75
Ngwavuma (8) - Obs.	1970 - 1982	8977	9475				8.73	0.83			
- Sim.		8593	9096	-4.3	0.51	0.45	8.71	0.79	-0.2	0.62	0.60

A3.7 Simulation Results (VTI Model).

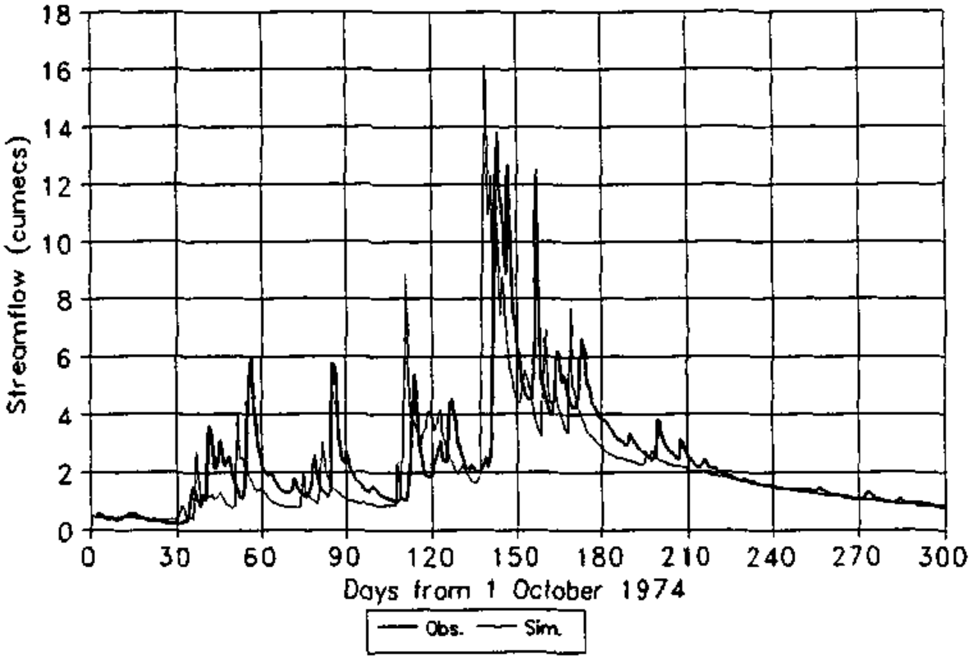
Table A3.4 summarises the results based on daily data, while table A3.5 lists the equivalent statistics for monthly totals and can be compared with the values given in table A3.2 for the Pitman model. No distinction has been made in the tables between the calibration and validation periods and, in general terms, no differences were found with well and poorly simulated periods occurring in both.

Figures A3.6 and A3.7 illustrate the very good results achieved for the two Black Mbuluzi catchments. Most aspects of the flow regime are acceptably modelled including peak flows, event recessions and seasonal baseflow. The 1974 year highlights a possible observed data error at the upper gauged site in that the values appear to be some 5 days out of phase (fig. A3.6 A). In figure A3.6 the observed flow at site 3 (downstream gauge) and the simulated flows at both sites are in phase with each other, while those for site 4 are not. The problem only appears to occur during this year and has been corrected later (fig. A3.7 A). 1974 was part of the calibration period while 1980 was one of the validation years. Tables A3.2 and A3.5 illustrate that the monthly values generated by the VTI model are marginally superior to those given by the Pitman model, but that either can generate suitably representative time series.

Table A3.4 suggests that the simulation for the White Mbuluzi was not very successful and this is in keeping with the result found for the Pitman model (table A3.2). The reason seems to be at least partly related to the rainfall input. Four gauges are available, but all are outside the boundary of the catchment and, on a daily basis, the recorded depths are very different. It is therefore difficult to define the real catchment input and this is reflected in the results. However, table A3.5 indicates that the monthly statistics generated from the VTI model simulations are much better than those for the Pitman model and figure A3.8 illustrates that the character of the flow regime has been reasonably well simulated, even if individual days have not.

The results for the three gauges within the Mhlatuzane group and the single Ngwavuma gauge are similar to the White Mbuluzi (tables A3.4 and A3.5). While the general character of the flow regime, and particularly the low flows, has been reasonably well simulated, the individual daily events have not. In most cases this has resulted in overall worse simulations than the Pitman model when the statistics based on monthly flow volumes are compared. This illustrates the difficulties of calibrating the parameters that control the major event responses when little real confidence can be expressed in the representativeness of the rainfall input. Figure A3.9 illustrates a typical simulation result for the Ngwavuma River where some events (around day 140) have been well simulated, but others (about day 90, 120, 150 and 175) have not. This catchment was divided up into three sub-areas covering the three major physiographic zones represented and the parameters were initialised to be representative of the conditions in these zones (based on some of the calibrations of the other catchments). However, the complex patterns of daily rainfall variations between the three available raingauges, makes it very difficult to determine the most appropriate parameter values to use.

A



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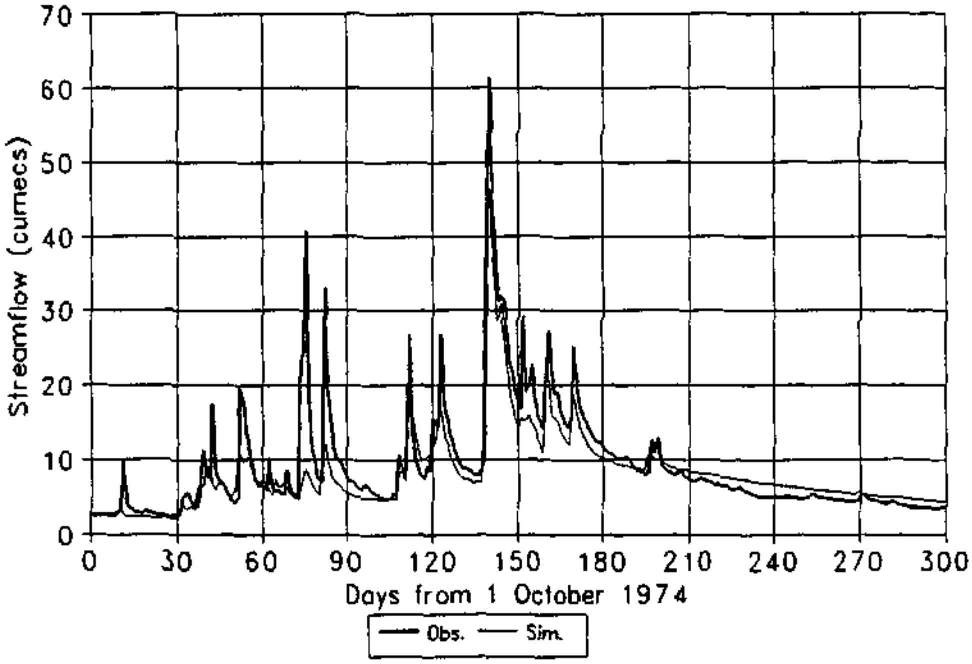


Figure A3.6 Daily streamflow time series for the Black Mbuluzi for the 1974 hydrological year. A: Site 4 upstream, B: Site 3 downstream.

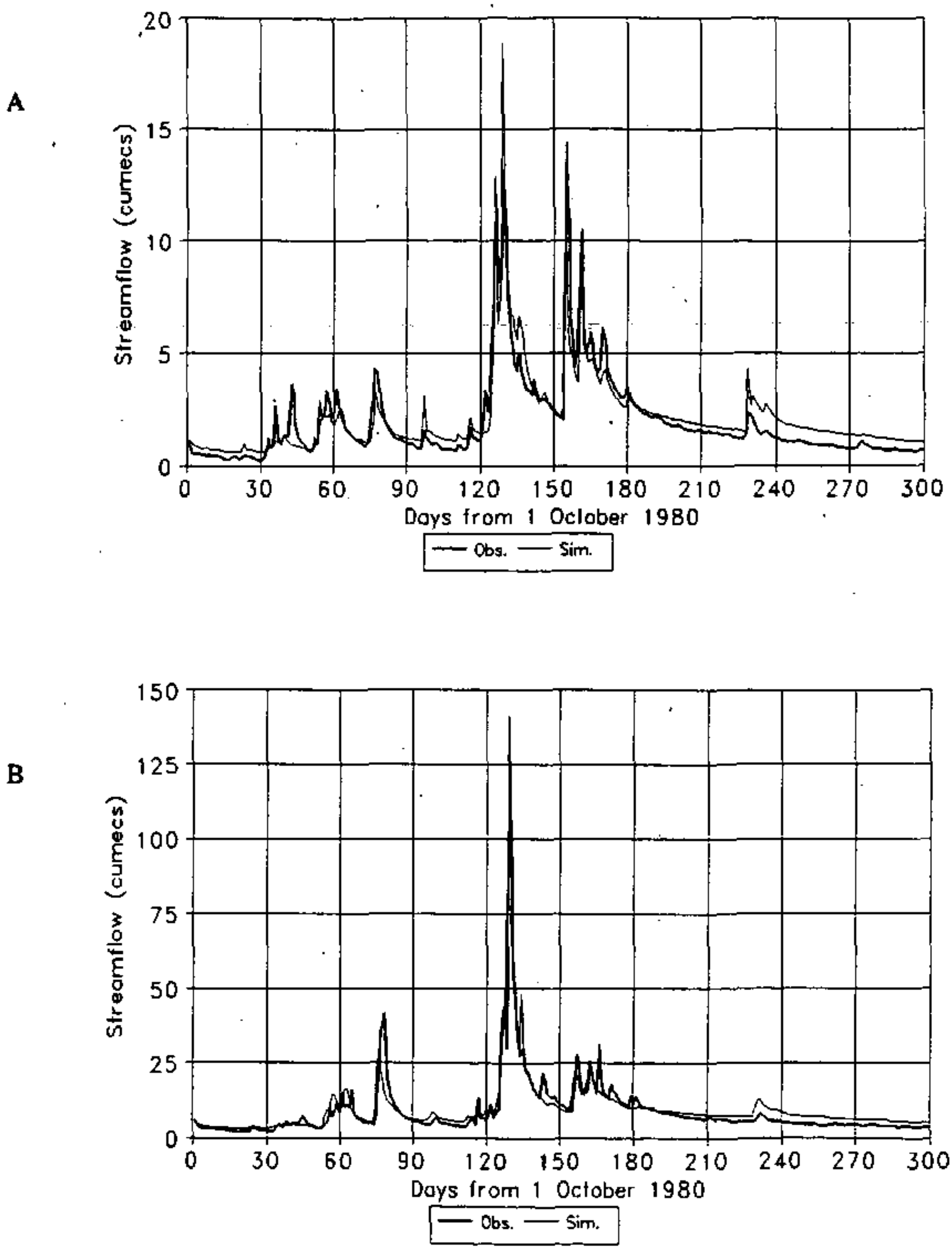


Figure A3.7 Daily streamflow time series for the Black Mbuluzi for the 1980 hydrological year. A: Site 4 upstream, B: Site 3 downstream.

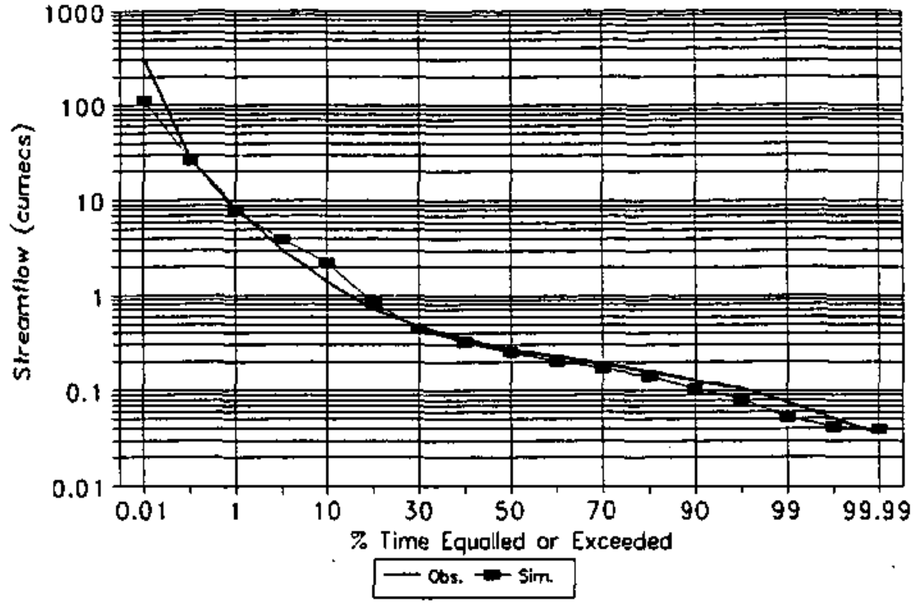


Figure A3.8 Observed and simulated duration curves based on daily flows for hydrological years 1965 to 1971 for the White Mbuluzi (site 10).

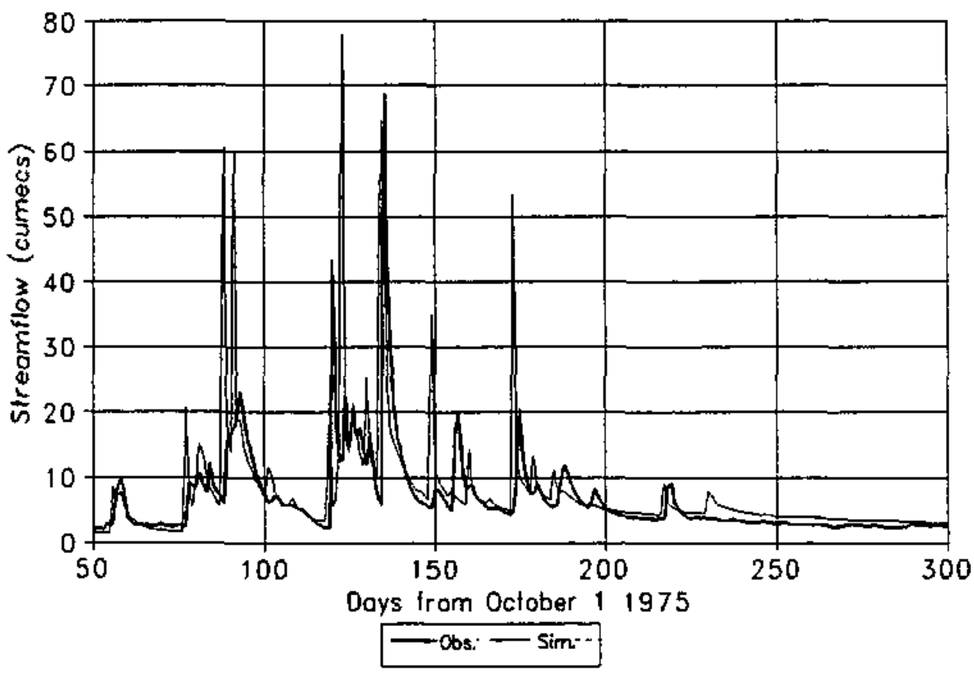


Figure A3.9 Observed and simulated daily time series for part of hydrological year 1975 for the Ngwavuma River (site 8).

In terms of the variability of the calibrated parameter values across the range of catchments tested, many are very similar and regional values could be used effectively. The main variations are in the total soil store and the groundwater hydraulic conductivities. Unfortunately, there is not enough information about the soils and aquifer characteristics to be able to assess the physical justification for the variation in these values.

A3.8 Results of applying the 'Patching' Model.

The grouping of the Swaziland gauged catchments within similar physiographic and climate zones allows the 'Patching' model (Hughes and Smakhtin, 1996) to be tested. Essentially, this model is a daily flow interpolation approach based on the use of calender month duration curves to interpolate daily flows from one site to another. Table A3.6 lists the R^2 and coefficient of efficiency statistics of correspondence for both un-transformed and log-transformed daily flows for the same time series periods used for the VTI model. The simulated values are based on patching the complete time series using one or more adjacent gauges and it is clear that results at least as good as the VTI model can be achieved with this simple approach. However, some of the relatively poor values for the un-transformed CE indicate that there are substantial spatial variations in runoff response within these regions of Swaziland and much of this variation appears to be due to spatial variation in daily rainfall.

Table A3.6 'Patching' model simulation results for the Swaziland catchments.

Catchment	Un-transformed		Ln transformed	
	R^2	CE	R^2	CE
Upper Black Mbuluzi (4)	0.72	0.68	0.81	0.76
Lower Black Mbuluzi (3)	0.65	0.60	0.79	0.78
White Mbuluzi (10)	0.33	0.33	0.63	0.60
Upper Mhlatuzane (12)	0.40	0.15	0.85	0.78
Lower Mhlatuzane (19)	0.56	0.36	0.82	0.73
Mhlatuze (13)	0.46	0.40	0.83	0.81
Ngwavuma (8)	0.40	0.38	0.75	0.75
Ngwempisi (21)	0.75	0.72	0.84	0.82
Hlelo (22)	0.62	0.51	0.81	0.79
Mpoono (28)	0.41	0.39	0.45	0.43
Ngwempisi (5)	0.87	0.85	0.90	0.89

One of the worst overall simulations is for the small Mpoono River tributary of the Ngwempisi River. The other gauges used to 'patch' flows at this site are all situated at the outlets of catchments that are partly within South Africa where there is a great deal more artificial control of the flow regime through abstractions. This result therefore illustrates that a modified flow regime cannot satisfactorily be used to 'patch' the flow regime of a more natural river.

A3.9 General Conclusions.

The overall conclusion is that the two models are applicable to simulating the flow regimes of Swaziland rivers. Regional values for the Pitman model parameters can be defined such that acceptable first estimates of the natural flow conditions in even un-gauged catchments should be possible in most cases. This conclusion, however should be tempered by two factors. The first is that care should be taken when defining the rainfall input and the second that appropriate regional values should be used. It is still not clear why the 1980s and 1990s versions of the Water Resources of South Africa publication offer such different recommendations for the main parameter values of the model. This question should be answered before the combination of a specific version of the model, set of regional values and rainfall input are used.

One of the main limitations to the generation of daily flow time-series appears to be an adequate definition of the rainfall input and particularly its spatial variation. The fact that the simulated daily duration curves are reasonable representations of the observed curves suggests that the VTI model is at least generating time series with the correct characteristics.

Appendix A4 BOTSWANA Catchments.

A4.1 Availability of time series data.

Flow data.

Daily flow data are available for a number of catchments, mostly concentrated around the southern and eastern borders of the country and flowing toward the Limpopo River. There are also stations situated within the endoreic drainage systems of the Okavango Delta area and the Makgadikadi Pans. The earliest date of recordings is 1969/70, while some of the stations only have records from the mid 1980s. The data were made available from the Department of Water Affairs, via the Institute of Hydrology, UK in CLICOM (World Meteorological Organisation) daily and monthly formats. The Botswana National Water Master Study (SMEC, 1991 - Volume 6) discusses issues related to data accuracy and to the accuracy of the rating tables currently in use.

Rainfall data.

The department of Meteorological Services operate over 240 rainfall measuring sites and at 11 of these, other meteorological variables are also observed, including Class A pan evaporation values. Some of these are autographic gauges (short records), while most are based on daily observations. These data are also stored using the CLICOM (WMO) system, and daily and monthly data were supplied to this project. Additional monthly data are tabulated within SMEC (1991). Many of stations have records extending back to the 1920's, while others were opened much later. SMEC (1991) provides more detail about the gauging network, some details of regional rainfall analysis and monthly rainfall totals for a range of stations.

Evaporation data .

SMEC (1987) provides open water evaporation estimates for a range of station (10) within Botswana as time series of monthly values with highly variable lengths. The data appear to be sufficient to define regional estimates of mean monthly potential evaporation.

A4.2 Availability of catchment description data.

Vegetation (1:2 000 000), soils and land system maps (1:1 000 000) were made available from the Land Use Division of the Ministry of Agriculture, Botswana and are generally suitable for the requirements of the project. In addition, copies of the 1:250 000 topographic maps were available for the purposes of defining drainage patterns, catchment boundaries and the locations of raingauge stations.

A4.3 Selection of catchment and brief descriptions

Five catchments or groups of catchments have been selected for use.

Shashe System.

These catchments are located in the east central area of Botswana, close to the border with Zimbabwe and drain into the Limpopo River. Gauging stations are located at Tati Weir (4511 - 570 km^2) on the Tati River and Ntse Weir (4411 - 800 km^2) on the Ntse River, two of the major north bank tributaries of the Shashe River flowing through Francistown. Further stations are available at Mooke Weir (4361 - 2460 km^2), above Shashe Dam, at the dam itself (4351 - 3650 km^2) and further downstream at Lower Shashe (4321 - 7810 km^2). No records for the latter two sites were made available to the project, which unfortunately precluded an attempt to simulate the impacts of Shashe Dam. However, no information was supplied about the operation of abstractions from Shashe Dam, so it would have been difficult to attempt such simulations anyway. The topography is gently undulating with occasional hill ranges and underlain by granitic gneiss or meta-basic rocks. The vegetation cover is savanna bush and trees, while the soils are predominantly loamy sands to coarse sandy loams with 10 to 20 % clay contents and approximately 800 mm in depth. In some areas of the upper catchments the soils are sandy clay loams and sandy clays and can be up to 2 m deep. Thirteen raingauges are available within the area and most have good, fairly complete, records over the streamflow gauging period of 1970 to 1990.

Nata system.

This system consists of the rivers flowing into the Sua Pan (part of the Makgadikgadi Pans) in the east central area of Botswana (figure A4.1), where there are three gauged catchments. The Nata River (gauge 5311 - 21 216 km^2) flows into the northern end of pan and has much of its catchment area within Zimbabwe. The Mosetse River (gauged at 5211 - 1026 km^2) flows into the eastern part of the pan, while the Mosupe River (gauged at 5111 - 819 km^2) flows into the south eastern part of the pan. The topography of all the catchments is mainly very flat and the vegetation consists of sparse to moderately dense bush. The soils seem to be quite variable and there is no information available about depths and hydraulic characteristics. Parts of the more southern catchments are underlain by granitic gneiss and parts by sandstones, while areas bordering the pan and most of the Nata basin are underlain by Kalahari alluvial deposits. Monthly rainfall data are available for a total of nine sites within the region (two from Zimbabwe) and daily data for four of the Botswana sites.

Mhalapswe system.

A northern tributary of the Limpopo River situated further downstream than the Metsemotlhaba River and gauged near Mahalapye (3221 - 754 km^2). The topography is characterised as a dissected undulating plain with associated pediments and the underlying rocks are granitic gneiss. Vegetation is a mixture of bush and tree savanna, while soils are mainly sandy clay loams to sandy clays of variable depth (0.3 to > 2 m). Around the major channels are also floodplain deposits consisting of layered sands, loams and clays which can be up to 5 m deep (Langsholt and Gottschalk, 1988). Data for four raingauge stations were made available and all of these are located either on the catchment boundary, or remote from the catchment, although it is apparent that other, more detailed, rainfall data are available.

Metsemotlhaba system.

Situated close to Gaborone in the south of Botswana two gauges are available on the Metsemotlhaba River, one at Thamaga (2421 - 1230 km^2) and one downstream at Morwa (2411 - 3570 km^2). The topography is almost flat to gently undulating and underlain by granites. Vegetation cover consists of shrub savanna and the soils are predominantly loamy sands or coarse sandy loams over 1 m deep. Data from 13 rainfall gauging stations are available, with records starting in some cases earlier than the available flow data and in others, later. The spatial distribution of these gauges is more than adequate for modelling purposes.

Motloutse System.

These catchments are situated south of the Shashe River and enter the Limpopo River just upstream of the Shashe. Data for a single gauging station is available (4121 - 7930 km^2). Although other stations do exist within this area, very little flow data are available and certainly not enough for modelling purposes. The majority of the catchment is a gently undulating plain underlain by granitic gneiss or in part by sandstones, while the upstream areas of the main catchment are flatter and underlain by superficial aeolian sands on basalt and sedimentary rocks. Vegetation cover consists of open tree savanna, while soils are similar to those found in the Mhalapswe catchment. The only raingauge information available is at Serowe (outside the catchment to the south), Tonota (outside to the north) and Selibi-Pihikwe (close to the outlet).

A4.4 Calibration procedure (Pitman Model).

Although SEMEC (1991) provide parameter values for most of the catchments used in this study, it was not possible to regenerate the results that are reported and it has been revealed that a modified version of the Pitman model was used. What is not clear is the nature of the modifications. Despite this, the parameter values given were used as starting values in the present studies calibration procedure. These values are also close to those suggested by the WR90 (1994) report for South African catchments on the other side of the Limpopo River.

The initial simulations indicated that the modifications made to the Pitman model by the author (Hughes, 1995) improved the results and therefore table A4.1 has a slightly different format to the tables used for most of the other countries. The runoff from soil moisture function is not used (POW and FT = 0), but the Rainfall Distribution Factor has been set to a smaller value (more even distribution of rain over the month) than the default value of 1.28 (as in the original version of the model). Similarly, an asymmetric catchment absorption distribution has been used and ZAVE has been set to a value that is less than half the difference between ZMIN and ZMAX.

Table A4.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Botswana catchments.

Catchment	Start year	End year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	RDF	ST	SL	ZMIN	ZAVE	ZMAX	PI	R	TL
4411	1970	1991	226	800	469	1 600	1.0	200	0	40	110	1250	1.5	0.5	0.25
4511	1970	1991	228	570	449	1 600	1.0	120	0	40	110	900	1.5	0.5	0.25
4361	1970	1991	227	2460	466	1 600	1.0	400	0	30	110	1250	1.5	0.5	0.25
5311	1970	1987	192	21 216	456	1 700	1.0	180 to 500	0	80 to 150	80 to 150	800 to 1 000	1.5	0.5	0.25
5211	1970	1987	214	1 026	482	1 700	1.0	250	0	50	180	900	1.5	0.5	0.25
5111	1970	1987	192	819	414	1 700	1.0	250	0	45	350	900	1.5	0.5	0.25
3221	1970	1991	224	754	476	1 600	1.0	280 to 500	0	40 to 100	550 to 1 800	2 000	1.5	0.5	0.25
2421	1970	1991	90	1 320	445	1 555	1.0	350	0	35	240	650	1.5	0.5	0.25
2411	1970	1991	135	3 570	480	1 555	1.0	350	0	40 t0 75	450 to 500	1 000	1.5	0.5	0.25
4121	1970	1991	225	7 930	440	1 660	1.0	300	0	35 to 100	100 to 400	1 100	1.5	0.5	0.25

Table A4.2 Pitman model simulation results, Botswana catchments.

Catchment	Mean (Ml)	SD (Ml)	Mean % Error	R2	CE	Mean ln	SD ln	Mean ln % Error	R2 ln	CE ln
4411 - Obs.	2 592	8 156				7.74	1.84			
- Sim.	2 421	11 067	-6.5	0.77	0.55	7.15	1.85	-7.6	0.44	0.21
4511 - Obs.	2 642	9 599				7.74	1.63			
- Sim.	2 646	10 116	0.2	0.73	0.70	7.33	1.93	-5.2	0.39	0.01
4361 - Obs.	5 242	15 893				8.08	2.27			
- Sim.	5 252	21 440	0.2	0.74	0.50	7.82	2.29	-3.2	0.29	0.06
5311 - Obs.	9 326	43 737				8.81	2.18			
- Sim.	10 462	40 743	11.8	0.43	0.35	8.09	3.19	-8.2	0.24	-0.82
5211 - Obs.	1 821	6 927				6.90	2.42			
- Sim.	1 732	6 437	-4.9	0.67	0.66	6.97	2.40	1.0	0.18	-0.13
5111 - Obs.	511	1 783				6.13	1.99			
- Sim.	538	1 867	5.3	0.43	0.27	4.85	3.46	-20.9	0.10	-2.32
3221 - Obs.	74	208				3.94	2.23			
- Sim.	67	246	-8.7	0.50	0.27	3.51	2.34	-10.9	0.15	-0.33
2421 - Obs.	1 010	2 794				5.97				
- Sim.	1 039	2 906	2.9	0.63	0.57	5.80	2.50	-2.80	0.49	0.38
2411 - Obs.	9 457	30 969				6.6	2.50			
- Sim.	1 230	3 759	5.3	0.39	0.27	6.71	2.03	1.7	0.10	-0.15
4121 - Obs.	9 457	30 969				8.39	2.10			
- Sim.	9 193	30 282	-2.8	0.57	0.51	7.57	3.07	-9.7	0.23	-0.87

A4.5 Simulation Results (Pitman Model).

The results of the Pitman model simulations are presented in Table A4.2 and one of the most noticeable features is the relatively poor simulation of low flows, as evidenced by the statistics based on log transformed data.

Shashe system.

Figures A4.1 to A4.3 illustrate the observed and simulated flow duration curves for the two tributaries of the Tati River and for the main Shashe River above Shashe Dam. The values plotted for exceedence values below about 0.4 % are interpolated and should be treated with caution. All three show similar characteristics in that the duration curves above about 30 % exceedence are over extended, implying that the model has simulated flow during more months than it actually occurs. Although this represents a minor proportion of the total flow volume, attempts to correct the problem were not successful and also resulted in a decrease inflows occurring between 10 and 30% of the time. The reason for this problem with the simulation is thought to be related to the lack of a channel transmission loss function in the model. Some small flows are generated by the catchment absorption function which, in reality, probably do not survive downstream. *Increasing the threshold for runoff generation* (increasing ZMIN), solves this problem but also reduces the flow volumes in other months. As can be seen from the good agreement between observed and simulated flows over the 1 to 30 % exceedence range, such a reduction cannot be justified. The rainfall distribution factor was decreased below its default value of 1.28 to ensure a more even distribution of rainfall input over the four model iterations each month. Without this flexibility in the operation of this function, the peak flows tend to be over-simulated (Hughes, 1995).

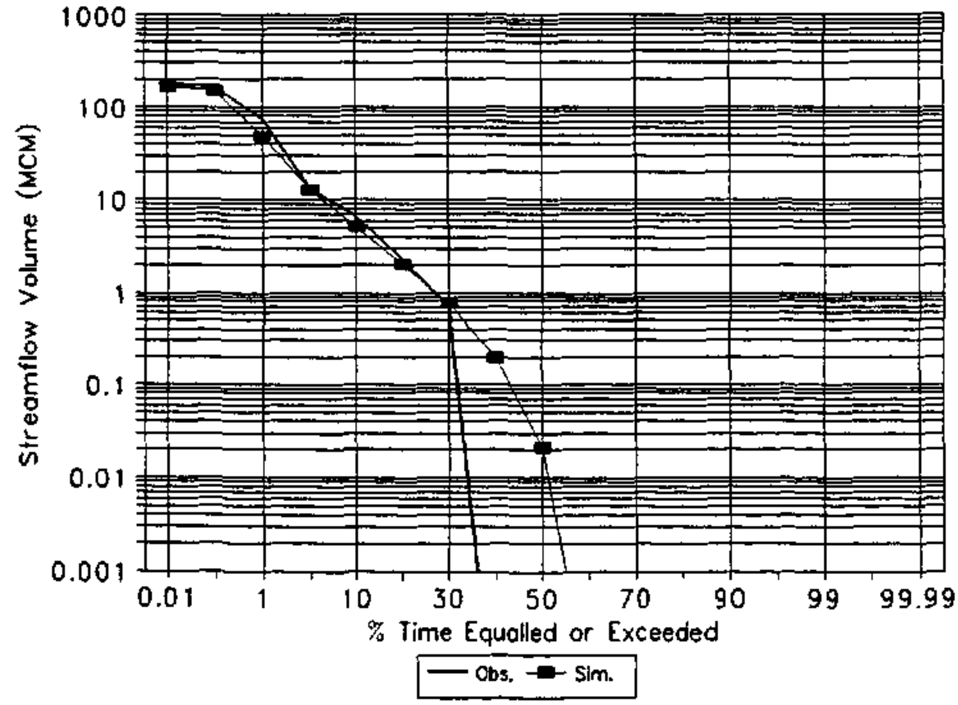


Figure A4.1 Catchment 4511 (Tati River): Observed and simulated flow duration curves based on all available data, 1970 to 1991.

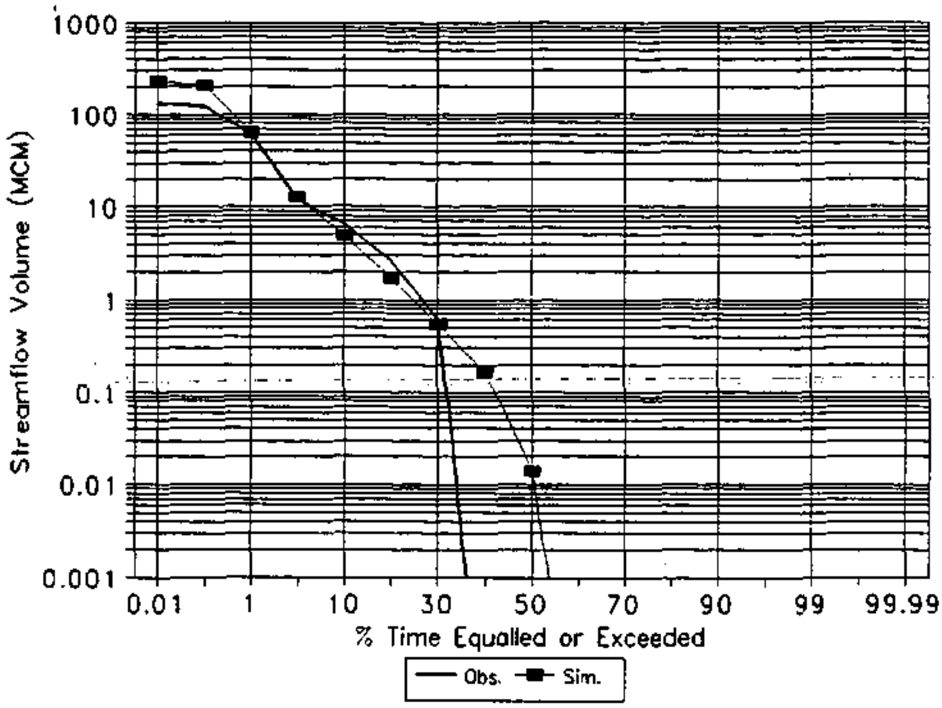


Figure A4.2 Catchment 4411 (Ntse River): Observed and simulated flow duration curves based on all available data, 1970 to 1990.

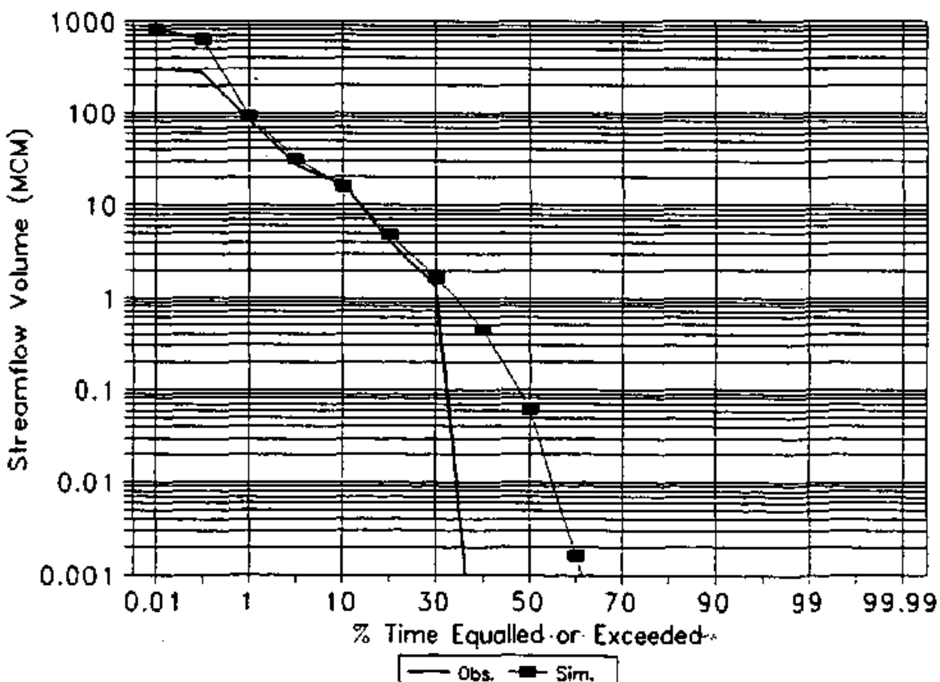


Figure A4.3 Catchment 4511 (Shashe River): Observed and simulated flow duration curves based on all available data, 1970 to 1991.

Nata system.

The first notable feature found when calibrating the large Nata catchment (which was divided up into three upstream sub-areas of 5 000 to 9 000 km² is that the parameters have to be set to very different values for upstream and downstream sub-areas. This is largely a result of channel transmission losses and the fact that runoff generated upstream frequently will not survive as channel flow to the catchment outlet. A range of parameter values are given in Table A4.1 and the smaller values are applicable to the downstream sub-area, while the larger ones to the upstream areas. The effect is to increase the storage and decrease the threshold at which runoff is generated from upstream areas in the model - not really a true reflection of what is considered to occur. This was the only way in which a reasonable simulation result could be achieved and table A4.2 indicates that, even so, the results are not very good, particularly with respect to medium to low flows (statistics based on log-transformed data). Figure A4.4 illustrates the pattern of modelled versus simulated response for a 7 year period.

The two other gauged catchments flowing into Sua Pan are much smaller and while the effects of transmission losses are still thought to be present, the scale of the effect is much less and the parameter values are closer to those established for the Shashe system. Figure A4.5 illustrates the results for the Mosetse River (5211) for the same 7 year period used in figure A4.4. The simulated duration curves for all three rivers have similar characteristics as those from the Shashe rivers in that they over-estimate the length of time that flow occurs, but are otherwise reasonable reflections of the observed curves.

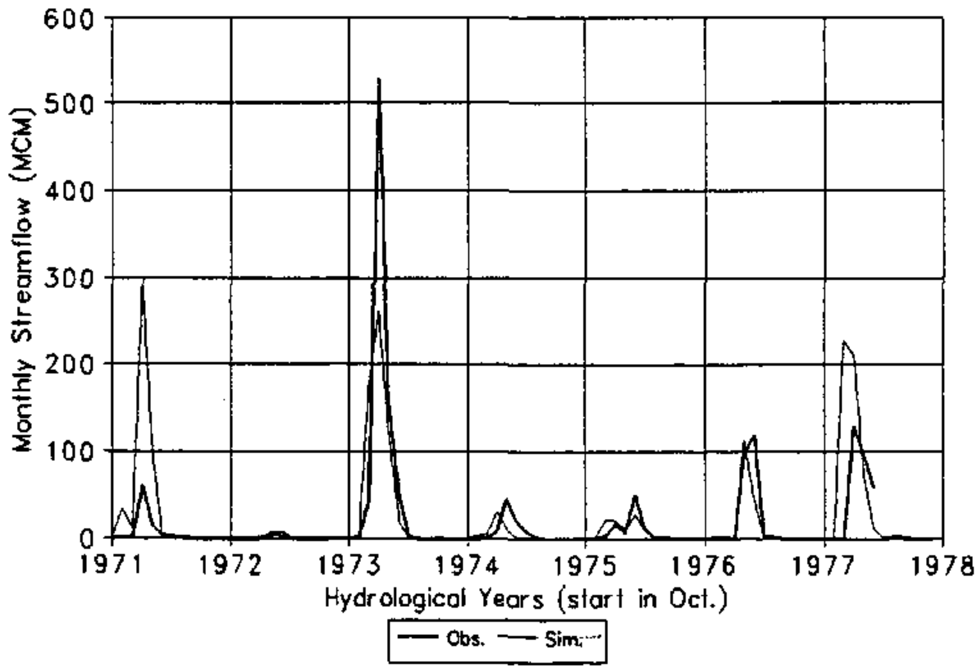


Figure A4.4 Catchment 5311 (Nata River): Observed and simulated time series for the period October 1971 to September 1978.

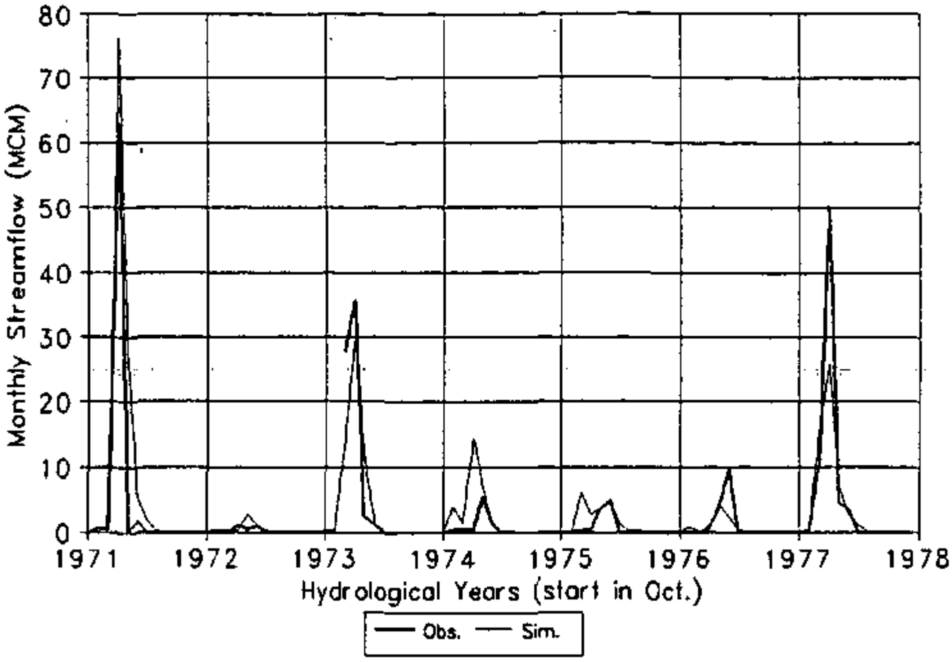


Figure A4.5 Catchment 5211 (Mosetse River): Observed and simulated time series for the period October 1971 to September 1978.

Mhalapshwe system.

This catchment proved to be extremely difficult to calibrate and it was impossible to generate flows in some months without generating excessive flows in other months. The very low value for the mean annual runoff (888 Ml or 1.2 mm) and the evidence for extreme transmission losses presented by Langsholt and Gottshalk (1988) suggest that a large proportion of the rainfall either contributes to direct recharge on the catchment surface, or as indirect recharge to groundwater storage in the unconsolidated valley bottom sediments. The Pitman model is not designed to simulate these processes and it is hardly surprising that the results are poor.

Metsemotlhaba system.

This system consists of two gauged catchments, one (2421 - 1 320 km²) within the other (2411 - 3 570 km²) and therefore serves as a good example to illustrate the effects of transmission losses on the runoff regime and the parameter values of the model. The entry for 2421 within Table A4.1 lists the parameters used to obtain the statistics given in the equivalent entry in table A4.2. Figure A4.6 (line Sim. 1) illustrates the results for a 6 year period. The values of the parameters for 2411 given in Table A4.1 are the range over the 10 sub-areas used, where the higher values apply to the upper 7 sub-areas (including the four that comprise catchment 2421) and the lower values (greater runoff generation) to the lowest three sub-areas. The simulated flow at sub-area 4 (the outlet of 2421), with these parameter values, is illustrated in figure A4.6 as line Sim. 2. If the parameter values used to obtain the best fit at 2421 are used at the larger scale, the result would be excessive runoff at the outlet of 2411. The ratio of mean annual runoff (MAR) to mean annual rainfall for 2421 is approximately 2% (MAR = 9.2 mm), while the equivalent ratio for 2411 is only 0.8% (MAR = 3.9 mm).

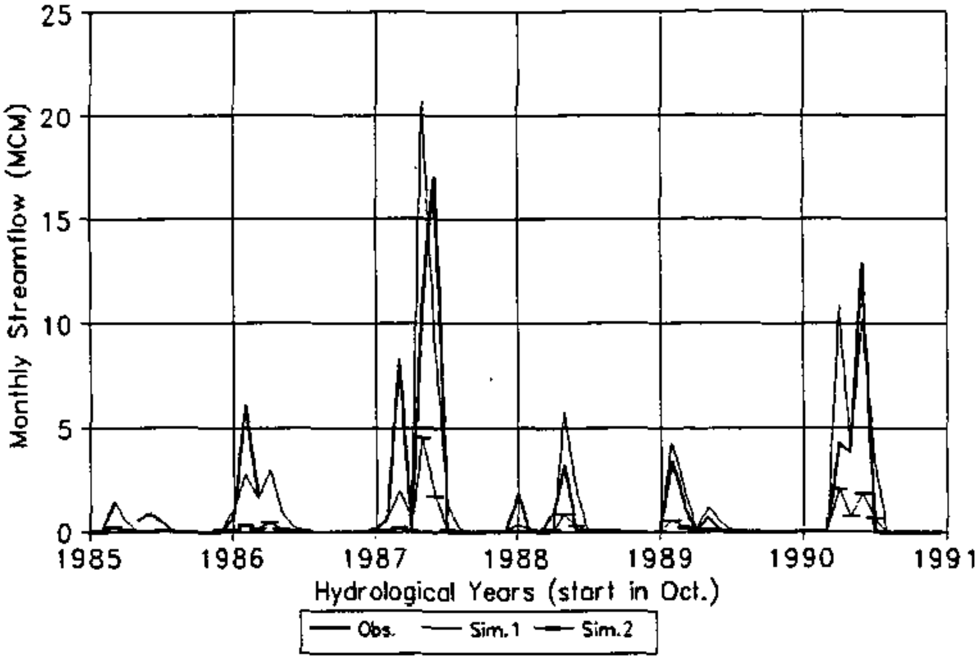


Figure A4.6 Catchment 2421: Observed and simulated time series for the period October 1985 to September 1991. Sim.1 represents the simulated flows using parameter values applicable to this catchment alone, while Sim. 2 represents simulated flows using parameters applicable to the contribution from this catchment to the larger area gauged at 2411.

Motloutse system.

The catchment has been divided into four sub-areas, two representing the upper part of the Motloutse River, one representing the Letlhakane Rive and one the area close to the outlet and including some smaller tributaries. Initially a set of parameters similar to those developed for the other Botswana catchments were transferred for this area; i.e. similar ZMAX (1 000) and ST (300) values for all sub-areas, low ZMIN (50) and ZAVE (120) values for the two lower sub-areas and high ZMIN (100) and ZAVE (500) values for the upper sub-areas and other parameters as they appear in table A4.1. The results were not very different to those given in Table A4.2 which were derived after some limited calibration. The characteristics of the simulated flow regime (compared to the observed) are very similar to the other Botswana examples with some peak flow months simulated well and others both over- and under-simulated, coupled with a duration curve that reflects more prolonged flow than actually exists.

A4.6 Calibration procedure (VTI Model).

The normal calibration procedure for the VTI model has been used for the Botswana catchments. This involves quantifying the physiographic variables given the available information about soils, vegetation, topography and geology and using these to provide initial estimates of the model parameters. There was generally found to be adequate information available to provide guidelines for quantifying most of the variables, although as is common throughout the whole region, not enough details about soil characteristics are known. Once the initial parameter values are established, the procedure followed was to select key months or years in the calibration period, try to identify the characteristics of the observed response and modify the parameter values to reflect these. As already stated in the main report, this is a very difficult task in semi-arid areas where there are few simple signals to use to identify the response characteristics and they may be confused by inadequate detail in the input rainfall data. A period of between 5 and 10 years was used for calibration purposes and a similar length period used to validate the calibrated parameter set.

The VTI model was applied to three areas; the two ungauged catchments of the Tati River in the Shashe system, the Mosetse River in the Natá system and the two gauged catchments forming the Metsemothlaba system. The latter were included to discover if the VTI model could simulate the transmission losses that are thought to occur between the upper and lower gauging stations.

A4.7 Simulation Results (VTI Model).

Tati catchments.

The period October 1973 to September 1980 was used for calibration, while October 1980 to September 1991 was used for validation. Data from only 6 of the original 13 raingauges were available at the daily resolution and these stations are less than ideally located relative to the two Tati catchments (4411 and 4511). The main adjustments to the parameters after initial quantification from the physiographic variables were to the soil depth and infiltration rate values. There is very little information about soil depth and this parameter value had to be calibrated to achieve a satisfactory simulated response. It was found that the soil depth for the Tati (4511) had to be set substantially lower than for the Ntse (4411) and this is consistent with the calibrated values of the ST in the Pitman model. The initial estimates of the infiltration curve parameters were found to allow too much infiltration and had to be lowered. The calibration and validation period results for daily data are given in table A4.3, while duration curves for the two catchments and the two periods are given in figures A4.7 and A4.8.

Table A4.3 indicates that the calibration simulations are surprisingly good given the resolution (temporal and spatial) of the input rainfall data. This period was relatively wetter than the validation period, having an average of almost 600 mm y^{-1} of rainfall compared to 400 mm y^{-1}. The observed response during the calibration period suggests some short term baseflow which has been successfully simulated. The indications are that soil water storage plays a much greater role in dictating runoff response during this period, than during the drier validation period, when the response is made up of many individual short duration events which are more difficult to simulate.

Table A4.3 VTI model simulation results (daily data), Botswana catchments.

Catchment	Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Errors	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
4511 (Calib) - Obs.	1.40	5.13				0.63	1.72			
- Sim.	1.44	5.41	2.8	0.40	0.23	0.90	1.52	42.8	0.20	-0.01
4411 (Calib) - Obs.	1.04	4.78				0.49	1.69			
- Sim.	1.04	4.55	0.0	0.49	0.43	0.60	1.59	22.4	0.31	0.15
4511 (Valid) - Obs.	0.75	4.24				0.87	1.81			
- Sim.	0.73	5.22	-2.7	0.15	-0.27	0.82	1.88	3.9	0.15	-0.28
4411 (Valid) - Obs.	0.79	4.58				0.42	2.04			
- Sim.	0.79	6.75	0.0	0.46	-0.18	0.65	1.75	35.4	0.26	0.13
5211 (Calib) - Obs.	1.21	8.18				0.37	2.51			
- Sim.	1.17	7.03	-3.3	0.46	0.42	-0.55	2.32	248.7	0.31	0.22
5211 (Total) - Obs.	0.69	5.35				0.11	2.65			
- Sim.	0.92	6.95	33.3	0.16	-0.64	0.22	2.45	100.0	0.11	-0.42

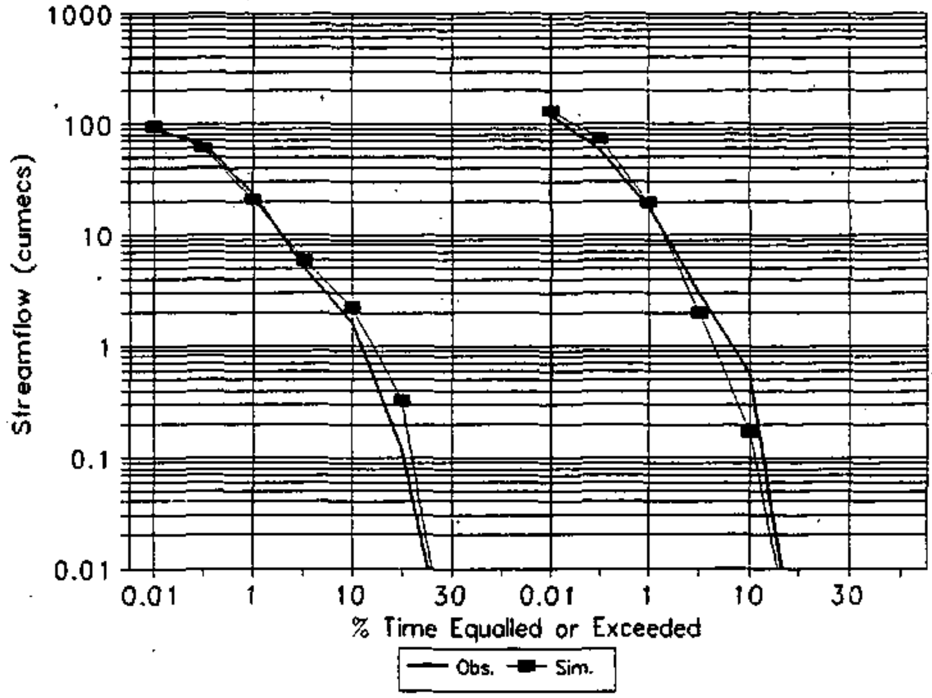


Figure A4.7 Catchment 4511 (Shashe River): Daily flow duration curves for the calibration (left side: 1973 to 1979) and validation (right side: 1980 to 1990) periods.

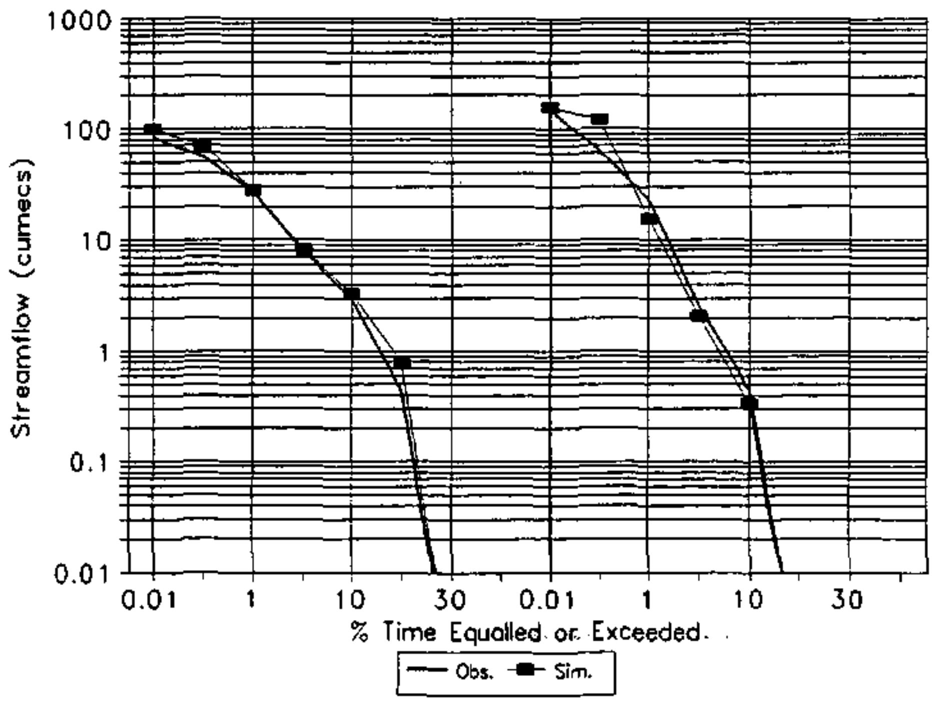


Figure A4.8 Catchment 4411 (Ntse River): Daily flow duration curves for the calibration (left side: 1973 to 1979) and validation (right side: 1980 to 1990) periods.

It is not really surprising that the validation period events are more difficult to simulate when it is understood that they will be made up primarily of intensity excess runoff, which will be very spatially variable and dependent upon localised rainfall intensities and soil surface conditions. The temporal and spatial resolution of the input rainfall data are not high enough to provide the model with sufficient detail and therefore it can hardly be expected to give accurate results. Similarly, the temporal resolution of the flow data (mean daily flows) is not high enough to present an accurate picture of the actual peak flows that occurred, despite providing the correct volumes of runoff. It is therefore somewhat encouraging that the model has managed to simulate the volume of runoff, as well as the overall range of flows that occur during the validation period, despite not being able to simulate individual days events very well.

The simulation results based on monthly volumes (aggregated daily values) given by the VTI model are similar to those given by the calibrated Pitman model.

Mosetse River (Nata system).

This catchment was simulated by Hughes (1995) as part of a study to investigate the use of monthly models in semi-arid areas and during which the main modifications were made to the Pitman model. The VTI model was assessed on the Mosetse catchment (5211) to provide a comparison with the use of a daily model. Table A4.3 summarises the results and indicates that the calibration period (October 1970 to September 1975) results were far better, in all respects, than the validation period (up to September 1987). Comparison with the Pitman model, using daily flows aggregated to monthly volumes, indicated that the calibration period VTI model results showed an improvement, but not the validation period results.

Metsemothlaba system.

The main problem with the Pitman model simulations for these catchments were that the parameters for the upper gauged catchment (2411) had to be modified, after calibration against observed flows at that site, to be suitable for generating the contribution to flow gauged at the lower catchment (2421). It was hoped that this could be avoided using the daily model that explicitly simulates transmission losses. Daily data were only available for 6 of the original 13 raingauges and their spatial distribution over the catchment is very unsuitable. The upstream catchment was simulated first and a representative set of parameter values derived. The most important (i.e. those that the results were most sensitive to) parameters were found to be the infiltration curve characteristics and the routing parameters (including the transmission loss zone description values). It was found to be almost impossible to achieve a reasonable calibration as quite high observed flows occurred at times of no input rainfall and no observed flows occurred during times when the input rainfall data suggested intense storms. Although the long term mean and duration curve shape (except for the highest peak flows) could be reasonably reproduced, the calibration is somewhat meaningless in the light of the poor reproduction of individual events. Applying similar parameter values to the whole area down to 2421 gave similar results, but it is impossible to assess the value of the transmission loss function, when the upstream observed and simulated events do not match. The calibration process was therefore abandoned and the conclusion reached that the available rainfall data is totally unable to represent the real input.

A4.8 General Conclusions.

One of the main problems with the application of both models is the relative inadequacy of the rainfall data which is available to define the spatial variation in catchment rainfall.. The effect of this is usually more marked in attempting to apply the daily model for two reasons. Firstly, there were less stations for which daily data were available and secondly, the monthly model does have the advantage of smoothing the variations within individual months. To a certain extent, the latter also represents one of the disadvantages of monthly models, when applied to semi-arid and arid areas. If the intra-month variations in rainfall are highly variable they will not always match the way in which the variation is accounted for in the model. It the observed rainfall is more concentrated than the model suggests there is the potential to under-simulate runoff and vice-versa. This is stating the problem very simply when in fact the issue is far more complex and discussed in detail in Hughes (1995).

One of the main problems with the Pitman model results is the tendency for the model to simulate flows for longer periods than observed flow actually occurs, therefore generating extended duration curves. The SMEC (1991) report noted the same deficiency. A further problem in nested catchment situations is that transmission losses are not accounted for in the model and flow volumes, once generated upstream, must survive to a lower site unless the artificial abstraction parameters are used within the model. If internal flows are of no interest in a catchment, the parameter values of the model can be adjusted to account for the losses and the eventual downstream contribution of a particular sub-area. This is an important observation about the use of this type of model in a semi-distributed (or sub-are) type of format. The problem does not really arise if the model is used in a lumped form with a single sub-area.

There does seem to be some potential for regionalisation of the Pitman parameter values (as also indicated by SMEC, 1991), although whether the sample of catchments used in both this study and SMEC (1991) is large enough is questionable. Ultimately, the estimation of parameters for ungauged catchments will have to take into account the regional variations in parameters indicated in table A4.1, the way in which the catchment is sub-divided into subareas, as well as the number and positioning of the available raingauges.

It would seem that the daily model has some potential to simulate flows in this type of semi-arid region, in that the correct type of response can be generated with parameter values that are realistic in terms of their physical meaning and the known characteristics of the catchment. However, given a lack of detail in the input rainfall, the model is difficult to calibrate and the results difficult to interpret. The results obtained by SMEC (1991) with a somewhat simpler daily model (Monash model) certainly seem to support the use of a daily time-step for simulation, although without access to the simulated daily values it is difficult for this author to properly evaluate the model results.

Appendix A5 MOÇAMBIQUE Catchments

A5.1 Availability of time-series data.

Flow data.

Daily flow data are available for 16 catchments, however, many of these are located on large rivers which have the majority of their areas located outside Moçambique. The choice, for the purposes of the FRIEND project, was limited to those which have most of their catchments located within the country. A total of five gauging stations were considered suitable; two on the Pungo River and one on the Buzi River, both flowing toward the coast at Beira; one on the Licuare River flowing to the coast at Quelimane; one on the Messalo River in the northern part of Moçambique, inland of Porto Amelia. The earliest date of recordings is during the mid 1950's and some of the records extend to almost the present day. While there are many periods of missing data, particularly during the late 1980's, there are sufficient periods of continuous data to allow the modelling exercises to be carried out. No information was available to the project team about the accuracy of the records, nor the methods of observation (i.e. daily or automatic recording, range of stage-discharge relationships, etc.).

Rainfall data.

The full list of raingauges operated now, or in the past, within Moçambique includes 1 259 stations. Daily data were made available to the project team for a total of 340 stations and these were selected on the basis of the original choice of catchments to include in the FRIEND database. Unfortunately, the choice of catchments has subsequently changed and the raingauge information was not selected with the five flow gauging stations referred to in the previous paragraph specifically in mind. However, this only seems to have affected part of the Buzi catchment and all the others are reasonably well represented by rainfall information. A more detailed examination of the location of the available stations suggests that there are concentrations of gauges around some centres (probably where higher levels of economic activity exist, or were present in the past), but a relatively sparse network elsewhere. This is a fairly typical pattern for many parts of southern Africa. The rainfall data span a similar record period as the flow data, but also suffer from periods of missing data.

Evaporation data.

Mean monthly Penman estimates of potential evapotranspiration are available from an FAO report compiled in 1981. Values are provided for 32 key stations covering most of the country and appear to be sufficient to define estimates of a mean monthly potential evaporation for the catchments used.

A5.2 Availability of catchment description data.

Very little information is available and the project team had to rely upon topographic maps with little detail (1:1 000 000) and a very generalised geological map (1:2 000 000). As it was impossible to assess the initial parameter values of either model a *priori*, the modelling exercises had to be carried out using pure calibration. Even physiographic parameters, such as channel and catchment slope were difficult to estimate and their values had to be guessed.

A5.3 Selection of catchments and brief descriptions.

Five catchments have been selected for use and the details of their size, period used for modelling, mean annual rainfall and potential evaporation are given in Table 5.1.

Pungoe River.

The Pungoe River rises on the eastern slopes of the Zimbabwe north-eastern highlands (Inyanga Range) and drains southeast across the full width of Moçambique to reach the coast at Beira. The river is gauged at two points; one in the upstream area (gauge 65 at 3 100 km^2) and one further downstream close to the low lying coastal wetland areas (gauge 66 at 15 046 km^2). The central part of the catchment is very poorly represented by the available rainfall data and the smaller upstream catchment has no raingauges within its boundary. Most of the rainfall stations lie along he main catchments southern border, are clustered around the catchment outlet, or are located in the northern parts of the catchment. The catchment is underlain by weathered granites and while the headwaters are likely to be steep, the majority of the catchments topography is thought to be characterised by rolling hills.

Buzi River

The Buzi River is situated to the south of the Pungoe and rises in the same mountain system (Umtali-Chimanimani-Chipinga) that forms the border between Zimbabwe and Moçambique and flows to the coast at Beira. The gauging stations (gauge 188 at 26 314 km^2) is located in the lower reaches just above the coastal wetland areas, in similar relative position to the lower Pungoe station. The catchment is made up of three main tributary areas; the Revue River lying to the north, bordering the Pungoe and draining the upland area around Umtali; the Lusito River in the centre and draining the uplands around Chimanimani and Chipinga; and the Buzi draining some of the southern Chipinga uplands, but also lower relief areas closer to the coast. The northern area is well represented by the available raingauges, the middle area less well and the upper Buzi not at all. It has therefore been necessary to assume that some of the more upland stations in the central tributary can also be used to represent rainfall to the south. This will inevitably have some influence on the simulation results. The northern and central tributary areas are underlain by similar geology to the Pungoe catchment, whereas the southern areas is underlain by both basalts, interbedded quartzites and shales and conglomerates.

Licuare River.

The Licuare catchment (gauge 104 at 3 975 km^2) drains moderately sloping inland hills to the northeast of the Zambezi River and reaches the coast at Queliman. The gauging station is once again located somewhat inland of the low-lying coastal area and the majority of the catchment is underlain by weathered granite. While the available raingauges are not ideally situated, they do at least represent variations that occur between the coast and further inland.

Messalo River.

The Messalo River is situated in the northern part of Moçambique and is gauged at a point west of Porto Amelia (gauge 147 at 10 000 km ^{2}). The catchment shape is elongated with relatively short tributary channels feeding the main channel. Rainfall data are available at stations distributed along the length of the catchment, but not always within its boundary. The catchment is underlain by weathered granites.

A5.4 Calibration procedure (Pitman Model).

Without previous experience of applying the Pitman model to Moçambique catchments and without much information about the characteristics of the catchments, it was difficult to develop a procedure for initial evaluation or parameter values. However, the relatively high rainfall and the age of the underlying rocks suggest quite deep weathering and therefore relatively high maximum water storage values. Appendix A2 indicates that within Malawian catchments compacted clays frequently occur at the top of weathered layers and that both runoff functions (catchment adsorption and soil moisture drainage) of the Pitman model may be required to simulate the observed response.

A5.5 Simulation Results (Pitman Model).

Pungoe River

Table A5.2 and Figures A5.1 and A5.2 indicate that the simulations for the two Pungoe catchments have been reasonably successful, given the limitations of the input rainfall data. The major criticisms are the under-estimation of the low-flows during some years for catchment 65 (the upstream area) and the over-estimation of the wet season flows in the last two years for catchment 66. The former are a result of a compromise calibration to ensure that flows in the dry season of other years and flows in the wet season of 1968 are not over-simulated. The latter may be a result of inadequate high-flow gauging at the lower gauging station, although no information is available about the characteristics of the gauging site. It is clear that, at least in some years, a large part of the runoff at the lower site is generated from the 17 % of the total catchment area that lies above gauge 65. This may be a consequence of steeper slopes, shallower soils and less dense vegetation in the upland areas close to the border between Moçambique and Zimbabwe.

Buzi River.

The results of calibrating the Pitman model on the Pungoe have been used to assist with establishing sub-area differences in parameter values for the five sub-areas of the Buzi catchment. Three of the sub-areas are in headwater positions and include parts of the border upland areas, while remaining two are in downstream positions. The parameters of the upper sub-areas have been set at values intermediate between the two Pungoe catchments, while those for the lower sub-areas have been set similar to the lower Pungoe. The results in Table A5.2 indicate that these parameters value configurations can be considered to be appropriate and that the simulations are acceptable. Improvements could possibly be made had more representative rainfall data been available for the southern part of the catchment.

Table A5.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Moçambique catchments.

Catchment	Start Year	End Year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	POW	ST	SL	FT	ZMIN	ZAVE	ZMAX	PI	R
65	1962	1975	156	3 100	1 245	1 230	2.8	540	0	120	150	700	1.250	1.5	0.5
66	1962	1975	139	15 046	1 080	1 300	3.5	1 200	0	10	300	800	1 300	1.5	0.2
188	1957	1975	142	226 314	1 067	1 300	3.0 to 3.5	750 to 1 200	0	70 to 10	250 to 300	750 to 800	1 250 to 1 300	1.5	0.4 to 0.2
104	1966	1981	127	3 975	1 098	1 350	3.4	1 000	600	30 to 10	130 to 200	400 to 600	1 000	1.5	0.2
147	1963	1984	159	10 000	932	1 480	4.0	700	190	35	150	560	1 000	1.5	0.2

Notes: For catchment 66 and the listed parameter values reflect the model setup for the incremental area below catchment 65.
For catchments 188 and 104 the start of the listed range of parameter values are for the upstream areas, while the end values refer to the lower sub-areas.
The Rainfall Distribution Factor is always kept at the default value of 1.28.
A value of 0.25 has been used for parameter TL throughout.

Table A5.2 Pitman model simulation results, Moçambique catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
65	- Obs.	120 119	121 870				11.30	0.86			
	- Sim.	114 873	108 280	-4.4	0.77	0.77	11.22	0.95	-0.7	0.78	0.72
66	- Obs.	176 333	219 957				11.60	0.91			
	- Sim.	183 276	193 343	3.9	0.84	0.84	11.73	0.85	1.1	0.80	0.78
188	- Obs.	535 543	687 409				12.66	0.98			
	- Sim.	568 033	854 441	6.1	0.80	0.68	12.65	0.99	-0.1	0.64	0.59
104	- Obs.	39 232	71 815				8.66	2.47			
	-Sim.	37 873	72 601	-3.5	0.37	0.21	9.10	2.12	5.1	0.60	0.56
147	- Obs.	107 524	156 295				10.24	2.05			
	- Sim.	97 861	136 293	-9.0	0.67	0.66	10.4	1.83	1.6	0.71	0.70

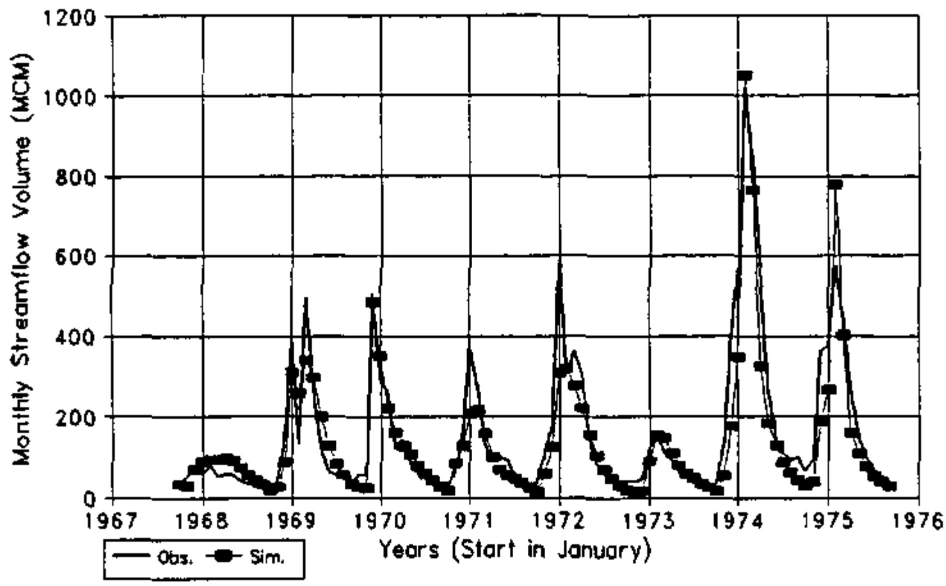


Figure A5.1 Time series of simulation results for the Pungoe River (at gauge 65) for October 1967 to September 1970.

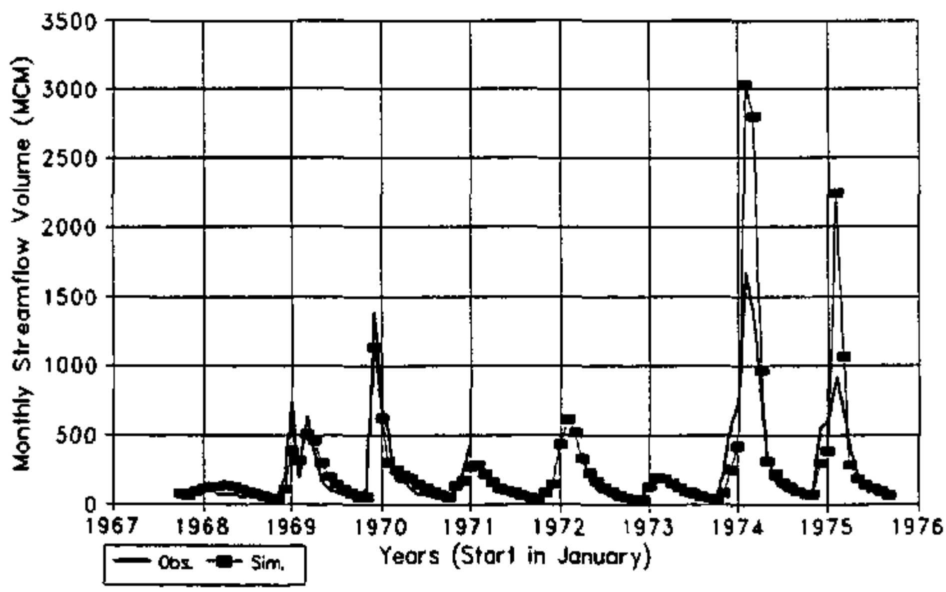


Figure A5.2 Time series of simulation results for the Pungoe River (at gauge 66) for October 1967 to September 1970.

Licuare River

The main feature of the calibrations for the Licuare catchment was the apparent need to include a non-zero value for parameter SL (the lower limit of moisture status, below which runoff does not occur). Most recommendations for the use of the Pitman model suggest that this value is kept at zero. The dry season recession in the Licuare (figure A5.3) appears to be steeper than the normal non-linear relationship between soil moisture runoff and moisture content can simulate, given values of POW in the normal range. The only other approach to steepening this recession is to restrict the occurrence of soil moisture runoff to moisture levels above a value greater than zero. It is possible that the steeper recession in the observed data is related to abstractions, but no information was available to the project team about this and the recessions have been assumed to be natural. Other problems with the Licuare simulations relate to the variable under- or over-simulation of the main wet season month which may be a consequence of inadequate rainfall input or that the model is not satisfactorily representing the real rainfall-runoff processes. The relatively poor correspondence between observed and simulated flows is reflected in the R^2 and CE values provided in Table 5.2.

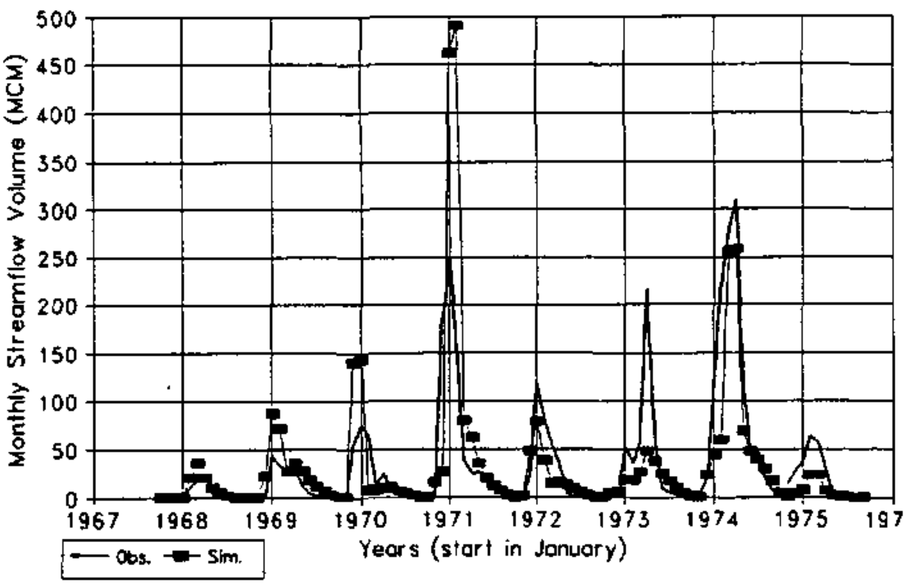


Figure A5.3 Time series of simulation results for the Licuare River (at gauge 104) for October 1967 to September 1975.

Messalo River

A similar problem with simulating the dry season recessions was experienced with the Messalo catchment as with the Licuare. Figure A5.4 indicates that the observed recession is generally steeper than simulated and it was found to be very difficult to reproduce this response. However, in general terms the Messalo simulation results are better than those obtained for the Licuare with fewer errors in the simulations of high flow months.

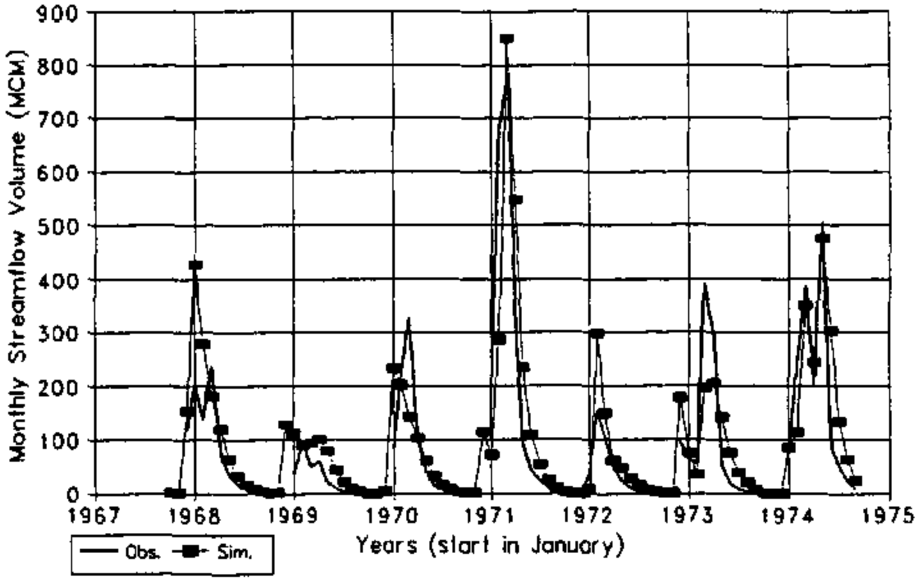


Figure A5.4 Time series of simulation results for the Messalo River (at gauge 147) for October 1967 to September 1974.

General Observations (Pitman Model)

To a certain extent, the problem with simulating the dry season recessions is evident for all the catchments used in this study. While artificial abstractions were previously mentioned as a potential cause, a further possibility is the occurrence of natural transmission losses from the downstream channels of these relatively large rivers. These transmission losses may be occurring as a result of evaporative use of water by riparian vegetation and replenishment of the riparian soil and groundwater storage by bank seepage, as well as through direct channel evaporation. The observed low-flow data for the two gauging stations on the Pungoe tend to support this concept. The upper catchment area is 17 % of the total, the mean flow at gauge 65 is 64 % of that at gauge 66 downstream, while the low flows are usually greater than 75 % of those at gauge 66.

A5.6 Calibration procedure (VTI Model).

The normal calibration procedure for the VTI model of quantifying physiographic variables from the available information about soils, vegetation, topography and geology and using these to provide initial estimates of the model parameters was difficult to apply in the Moçambique catchments. This is mainly because there was very little information that was readily available to the project team. The results of the Pitman model calibrations, and any appreciation of the rainfall-runoff response obtained through the detailed inspection of the monthly and daily time series data were therefore the only guidelines available for setting the initial values of the VTI model. Subsequently, a more direct calibration (less reliance on matching parameter values to known physiographic characteristics) approach than is usually used for this model was followed. The Pitman calibration exercise certainly pointed to relatively high maximum moisture storage (combined soil and groundwater) values, as well as relatively high drainage rates, particularly from the upland areas of the Pungoe and Buzi.

In general terms, approximately the first five years of the total model period (Table 5.1) were used for calibration purposes. Some of the parameter values of the VTI model are listed in Table A5.3, while the results are summarised in Table A5.3, some illustrative graphical diagrams and the paragraphs below.

Table A5.3 Some key parameters of the VTI model for the Moçambique catchments (the values given for those catchments with several sub-areas represent averages over the areas below any upstream gauge unless a range of values is given as for 188).

Parameter / Catchment		65	66	188	104	147
Veg. Cover fraction		0.61	0.64	0.61 - 0.64	0.68	0.64
Canopy capacity (mm)		0.94	1.03	0.94 - 1.03	1.16	1.03
Infiltration Curve	K	0.66	0.66	0.66	0.65	0.65
	C (mm h^{-1})	180.0	180.0	180.0	186.0	183.0
Total Soil Store (mm)		518.0	1 068.0	768.0 - 1 068.0	968.0	670.0
FC/Porosity		0.55	0.55	0.55	0.53	0.54
Soil K (mm h^{-1})		24.0	24.0	24.0	24.0	24.0
Texture dist. factor		0.85	0.72	0.72 - 0.78	0.80	0.80
St. Dev. or Moist. Dist.		0.16	0.10	0.10 - 0.12	0.12	0.14
G'Water K (mm h^{-1})		0.35	0.10	0.10 - 0.25	0.05	0.07

A5.7 Simulation Results (VTI Model).

Pungoe River

Table A5.3 and figures A5.5 to A5.7 suggest that the calibration of the VTI model on the two Pungoe gauged catchments has been successful. The main limiting factor is the general over-simulation of the low-flows (those succeeded some 95 % of the time) for both catchments. Figures A5.5 and A5.6 illustrate that this over-simulation is not always consistent for the same year at the two gauges, while figure A5.7 illustrates that it is a general problem (the comparison of observed and simulated duration curves for gauge 66 looks similar to figure A5.8). The 300 day time series illustrated represents one of the better years, where the peaks of the observed and simulated hydrographs correspond very well. In some of the other years, the degree of correspondence is not as good; some observed peaks are not matched by simulated ones and vice versa. This is the usual pattern when there are insufficient raingauges to fully represent the catchment input. However, the statistics provided in Table A5.3 and the duration curve in figure A5.7 illustrate that the model has been able to simulate the flow regime of these catchments satisfactorily. The correspondence between observed monthly flow and volumes aggregated from the simulated daily data is an improvement on the Pitman simulation results, but only marginally so for most years.

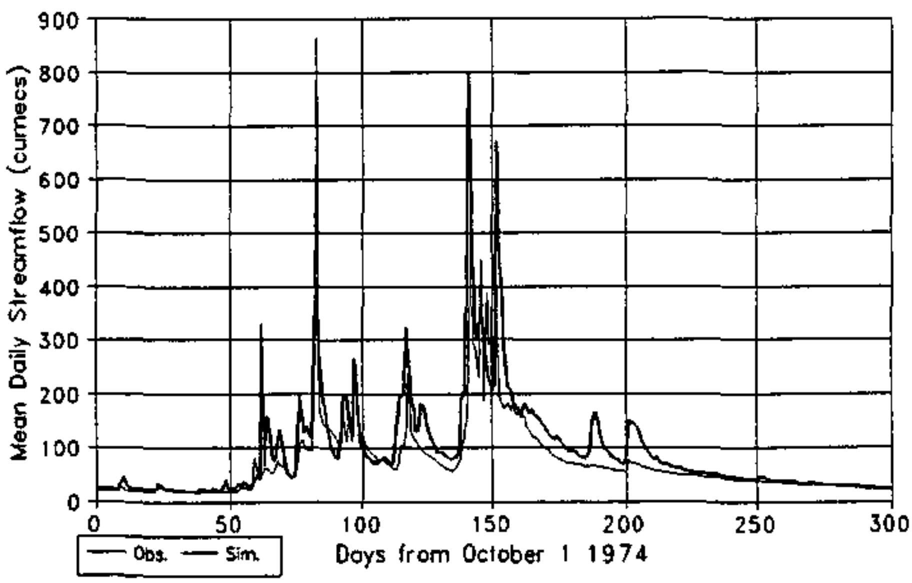


Figure A5.5 Time series of daily (VTI) simulation results for the Pungoe River (at gauge 65) for October 1974 to July 1975.

Table A5.4 VTI model simulation results (daily data), Moçambique catchments.

Catchment		Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
65	- Obs.	56.06	79.47				3.46	0.98			
	- Sim.	50.87	68.45	-9.2	0.61	0.60	3.50	0.83	1.2	0.81	0.80
66	- Obs.	83.98	134.68				3.79	1.03			
	- Sim.	87.8	143.01	4.5	0.75	0.71	3.91	0.96	3.2	0.82	0.80
188	- Obs.	186.66	366.29				4.54	1.01			
	- Sim.	186.62	318.88	0.0	0.69	0.68	4.57	1.04	0.7	0.78	0.76
104	- Obs.	14.69	34.18				0.53	2.54			
	- Sim.	14.61	34.19	-0.5	0.44	0.33	0.55	2.42	3.8	0.62	0.60
147	- Obs.	42.09	87.45				1.96	2.40			
	- Sim.	43.04	91.69	2.2	0.51	0.39	1.82	2.94	-7.1	0.48	0.19

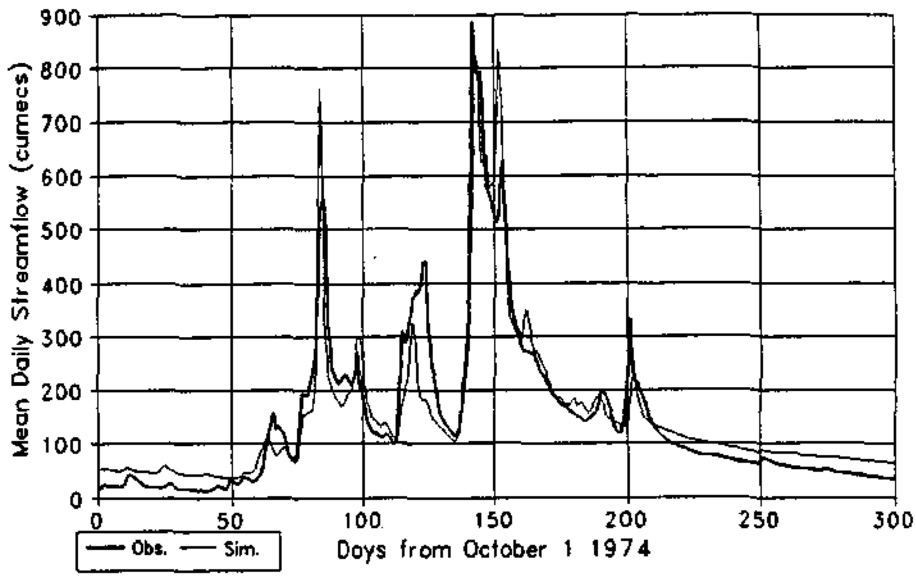


Figure A5.6 Time series of daily (VTI) simulation results for the Pungoe River (at gauge 66) for October 1974 to July 1975.

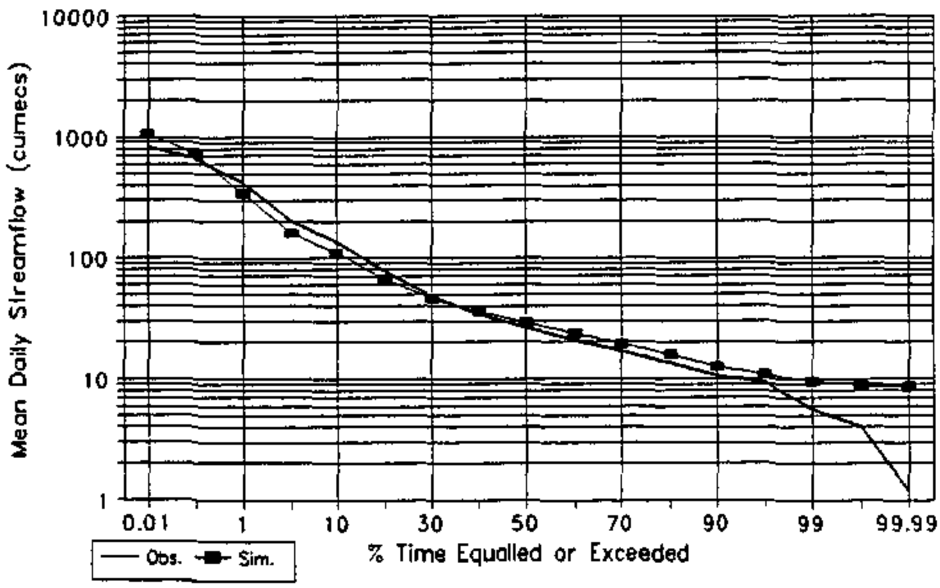


Figure A5.7 Annual 1-day flow duration curves for observed and simulated flow at gauge 65 on the Pungoe River (based on data for Oct. 1963 to Sep. 1975).

Buzi River.

The results of the Buzi catchment are very similar to those for the Pungoe and it can be generally concluded that the calibration exercise has been a success. There are some years where the dry season low flows are over-simulated, but for the majority of the time the degree of correspondence is more than acceptable.

Licuare River.

The values for the statistics given in table A5.4 suggest that the correspondence between observed and simulated individual daily flow is not very good. In fact there are many days when the observed flows are under-simulated and an equal number when they are over-simulated. This balance is partly reflected in the reasonable fit between the observed and simulated flow duration curves shown in figure A5.8. The patters of over- and under-simulation that resulted from the application of the Pitman model and illustrated in figure A5.3 are repeated in the daily model results, but are difficult to account for. The daily results do not indicate a consistent pattern at all, sometimes the events are the problem, while at other times it is the baseflows. Both can be over- or under-simulated and the lack of clear trend makes it difficult to identify which aspect of the model may be at fault, or which parameters to concentrate on to try and correct the problem. When two models generate similarly inaccurate results, it often points to a problem with the representativeness of the input rainfall data, although this is a difficult suspicion to confirm.

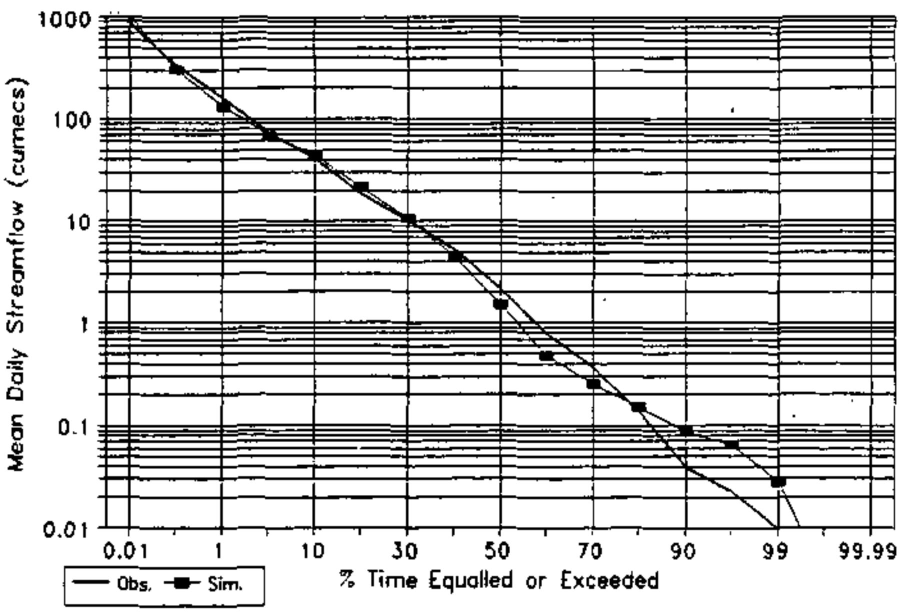


Figure A5.8 Annual 1-day flow duration curves for observed and simulated flow at gauge 104 on the Licuare River (based on data for Oct. 1967 to Sep. 1981).

Messalo River.

The results for the Messalo River are very similar to those for the Licuare, although there do seem to be a greater number of years where the patterns of observed and simulated flows correspond for the Messalo. Considered as cumulative volumes over calendar months, the results are not very much different to those depicted in figure A5.4 for the Pitman model.

General Observations (VTI Model)

There appear to be distinct differences between the Pungoe and Buzi catchments and the Licuare and Messalo catchments, both in terms of some of the parameter values and the success of the simulations. The former have stronger and more sustained low-flow regimes (figures A5.7 and A5.8), which is reflected in the higher values for the groundwater hydraulic conductivity parameter (K) and were generally more successfully modelled than the latter. The groundwater recharge and baseflow contributions from the upland areas bordering Moçambique and Zimbabwe in the Pungoe and Buzi may be higher than are being simulated, while their lower sub-areas should possibly have lower baseflow contributions (more similar to the Licuare and Messalo) than are being simulated. This may make some of the parameter values more uniform across what appear to be similar catchment areas. However, the simulations of catchment 65, representing a relatively headwater area in the Pungoe, have been successfull with the parameters given in table A5.3.

It should be noted that there is a strong interrelationship between many of the model parameters such that adjustments to two or more parameters can generate similar results. This is why, with the VTI model, it is always better to have a reasonable understanding of the physiographic characteristics of the catchments so that at least some of the parameter values can be constrained to a range of acceptable values.

A5.8 General Conclusions.

One of the main problems with the application of the VTI model is the inadequacy of the available information with which to define the physical characteristics the catchments. This has placed a degree of uncertainty on the validity of the parameter values of the VTI model. A better understanding of the differences between the Pitman model parameter values would also have been gained if more catchment information had been available. There are also some obvious deficiencies in the representativeness of the available rainfall data, in that some parts of the catchments are less well covered than others and there are quite large gaps in the records at key stations. It is apparent that the latter could be improved through access to the complete Moçambique rainfall database and the former by the provision of more detailed soils, geology, vegetation and water use data (if available), or a limited programme of field visits.

Given the information that was available to the project team, the results are reasonably encouraging and suggest that both models are applicable to simulating the hydrology of the country. There also seems to be some potential for regionalisation of the parameter values of both models, although whether the sample of catchments used is large enough is questionable.

Appendix A6 TANZANIAN Catchments

Dr Jonathan Matondo of the University of Dar es Salaam spent some time at the Institute for Water Research during 1995, funded by UNESCO under the umbrella of the African Network of Scientific and Tecnical Institutions (ANSTI) with some assistance from the WRC project funds. Part of the purpose of the visit was to allow Dr Matondo the opportunity to familiarise himself with the models and modelling tools that have been used on the FRIEND project, while the remainder of his visit was sent collating the data for Tanzania and calibrating the Pitman and VTI models on several Tanzanian catchments. Many of the results presented in this section of the report are therefore partly attributable to Dr Matondo and based on his calibrations with only a few subsequent modifications.

A6.1 Availability of time-series data.

Flow data.

Daily streamflow data are available for a large number of rivers within Tanzania, but records with an adequate quantity and quality of recordings are not available for all of them. Most of the records begin in the 1950s and 1960s.

Rainfall data.

Daily rainfall data are available, but it is not currently clear for how many stations. The national list of raingauges includes references to 2 042 stations but the data do not appear to be readily accessible. The density of raingauge coverage (with accessible data) appears to be quite low in many areas. While some of the rainfall records begin prior to the flow gauging records, others start at a similar time or later.

Evaporation data.

Daily pan evaporation data are available for about 19 stations covering the whole country and ranging in start date from the 1950s to the 1980s. These data can be used to establish representative monthly distributions of pan evaporation, but are not really of value as input time series to the models.

The initial selection of catchments based on the availability of about 10 years of daily streamflow records yielded 12 stations (table A6.1):

1C1; Sigi River (at Lanconi Sisal Estate) within the Pangani River basin inland of Tanga on the north east coast.

1G5A; Tami River (at Msowero), 1G6; Kisangata River (at Mvumi), 1GB1A; Diwale River (at Ngomeni) within the Wami River basin which drains the inland area to the west and north west of Dar es Salaam and flows to the coast just north of Bagamoyo.

1H5; Ruvu River (at Kibungo), 1J6; Mzinga River (at Matji Matitu) within the Ruvu River Basin draining the area immediately to the west of Dar es Salaam and flowing to the coast at Dar es Salaam.

1KA8A; Great Ruaha River (at Salimwani), 1KA9; Kimani River (at Great North Road); 1KA22; Mtitu River (at Mtitu) within the upper Rufiji River basin which drains the coast to the south of Dar es Salaam.

1RB2; Ruhuhu River (at Masigira confluence), 1TB6; Mngaka River (at Nambunju Road Bridge), 1RC2; Kiwira River (at Kyela) within the Lake Nyasa (also referred to as Lake Malawi) basin draining the areas to the east and north of the lake.

The catchments selected are reasonably representative of the wetter eastern half of the country but no data were available for the western and drier central and northern parts of Tanzania.

A6.2 Availability of catchment description data.

Topographic maps at scales of 1:50 000 and 1:25 000 were made available for some areas through the Department of Civil Engineering at the University of Dar es Salaam. In addition some generalised (1:2 000 000) information on vegetation cover, soil type and geology was made available. Berry (1977) contains a lot of further generalised (but nevertheless useful) information about Tanzanian relief and physical features, soils, vegetation, hydrology, climate, geology and land use, etc. The information is portrayed at a very large scale, but many of the text explanations are of value to someone less than familiar with the country.

A6.3 Brief descriptions of catchments.

Pangani River basin (Sigi) catchment.

The Sigi catchment lies within the coastal hill area, inland of Tanga and is underlain by complex, strongly-folded metamorphic rocks and intrusive granites. The soils are loamy sands with moderately good drainage. The catchment is partly covered by forest and partly by cultivated land. Mean annual rainfall appears to vary from about 1 200 to 2 000 mm but the majority of the 8 available raingauges lie within the lower rainfall areas and largely outside the catchment boundaries. It was therefore necessary to apply a weighting factor to the station rainfalls to ensure sufficient rainfall input to the models. Mean monthly potential evaporation input was based on records from the Tanga meteorological station, but because of the altitude difference, the mean monthly values for the catchment were assumed to be somewhat lower. The catchment was divided into three sub-areas, largely based on the drainage pattern.

Wami River basin (Tami, Kisangata and Diwale) catchments.

The Tami and Kisangata catchments are closely adjacent tributaries draining the upland area to the north west of Morogoro and the Mkata Plain. The geology is similar to the Sigi River catchment and the soils appear to be characterised by sandy loams to sandy clays with good drainage. Vegetation cover appears to be a mixture of grassland, woodland and forest with part of the area occupied by the Mamiwa Forest Reserve. Mean annual rainfall varies from about 1 000 to over 1 600 mm and three raingauges are available to represent spatial variations. The Tami has been subdivided into four sub-areas based on drainage patterns and vegetation cover, while the smaller Kisangata was not sub-divided. Potential evaporation data were taken from the Morogoro meteorological station to the east.

The Diwale catchment drains the upland area in the vicinity of the Nguru Mountains and the geology, soils and vegetation would appear to be similar to other catchments of this area. The rainfall input is represented by two raingauges which record between 1 200 and 1 300 mm of annual rainfall on average. They are not ideally placed within the catchment and the mean catchment rainfall has been assumed to be approximately 1 600 mm, based on regionalised information. Two sub-areas were established for this catchment.

Ruvu River basin (Ruvi and Mzinga) catchments.

The Ruvu catchment is located immediately to the south east of Morogoro and drains the upland ridge occupied by the Uluguru North Forest Reserve. The catchment is underlain by the same complex metamorphic rocks as the previous areas and has soils characterised as sandy clays with excessive drainage. The upper parts of the catchment are largely forested, while the lower areas are cultivated. Mean annual rainfall appears to vary from 1 000 mm to over 2 000 mm and while data for 7 raingauges were provided, few are close to the catchment. The mean annual rainfall at these gauges lies between 820 and 1 100 mm and therefore certainly do not appear to be representative of the higher rainfall areas of the catchment. The catchment was not subdivided and potential evaporation data were derived from Morogoro.

The Mzinga catchment is located to the south east of Dar es Salaam in an area of relatively flat topography. The catchment is underlain by fluviatile-marine sand, gravels and silts and the associated soils are loamy sands to sandy-clay-loams with good drainage. The natural vegetation is wooded or bushed grassland and the area is extensively cultivated. Mean annual rainfall is expected to be of the order of 1 000 mm, but the only available raingauge has a large number of missing months.

Rufiji River basin (Great Ruaha, Kimani and Mtitu) catchments.

No maps or details of the layout of the catchments were available for the Great Ruaha or the Mtitu rivers and therefore no attempts could be made to simulate them. This region is therefore only represented by the Kimani catchment which drains part of the Poroto Mountains and the Kipengere Range to the north of the upper end of Lake Nyasa (Lake Malawi). The underlying geology appears to consist of mudstones, shales, phyllites, sandstones, quartzites and conglomerates giving rise to loam or clay loam soils with good drainage characteristics. The vegetation cover consist of variable density forest cover and woodland in the upper catchment areas. Mean annual rainfall is of the order of 1 000 mm and catchment inputs have been compiled from a single gauge at Kimani, close to the flow gauging station. As the rainfall was expected to increase from the lower catchment to the more elevated upper areas, the station rainfall was weighted to account for this. Potential evaporation data were compiled from records observed at Mbeya to the west of the catchment.

Lake Nyasa basin (Ruhuhu, Mngaka, Kiwira) catchments.

No map information was made available for the Mngaka catchment and therefore it was not used in the simulation exercise. The Ruhuhu catchment is underlain by metamorphic rocks in the lower reaches but by granites in the upper areas. The soils associated with the metamorphic rocks are sandy-clay-loams, while loams appear to dominate in the granite areas. Vegetation appears to consist of wooded or bushed grassland with some forest areas and mean annual precipitation is between 1 00 and 1 200 mm. Unfortunately, records from only a single raingauge were made available from which to compile catchment inputs. This stations is located close to the upper boundary of the catchment. Evaporation data from Iringa meterological station were used and the total area was subdivided into two sub-areas.

The Kiwira catchment has its outlet very close to the northern shore of Lake Nyasa, close to the Malawi border. The majority of this hilly catchment appears to be underlain by metamorphic rocks and is covered by predominantly sandy soils with good drainage. The area seems to be extensively cultivated with some woodland and forest areas. There appears to be a large variation in mean annual rainfall over the area, varying from over 1 000 to at least 2 100 mm. Data for four rainguages have been used and these are distributed reasonably well throughout the catchment area or just outside. The catchment was subdivided into five sub-areas to try and account for the spatial variation in rainfall input.

A6.4 Calibration procedure (Pitman Model).

As previously mentioned, Dr Matondo carried out the initial simulations and the author of this report only carried out limited refinements to the calibrations at a later date. The initial simulations indicated that most of the catchments have relatively high levels of moisture storage (in either the soils or groundwater) and that they also have quite reliable and sustained baseflow regimes. ST and FT parameter values were expected to be quite high, while POW values were expected to be relatively low. ZMAX values were also expected to be relatively high to prevent some of the high monthly rainfalls from generating excessive volumes of monthly runoff. Where possible the other parameters were kept to the normal values used by the South African Surface Water Resources Update study (i.e. PI = 1.5, R = 0.5. TL = 0.25, with the rainfall distribution factor at the default value of 1.28 and ZAVE at the mean of ZMIN and ZMAX). These were therefore the main guiding principles behind the calibration procedure.

A6.5 Simulation results (Pitman Model).

Table A6.1 lists the final parameter values for the catchments simulated and it is clear that three catchments (1GB1A, 1H5 and 1RC2) could not be successfully simulated due to either an underestimate of the catchment rainfall or erroneous streamflow data. In all three cases the observed streamflow depth (as MAR in mm) was almost as high as, if not higher than, the input rainfall depth (as MAP in mm). No further attempts to model these catchments were made after such discrepancies had been discovered.

The Sigi River results are illustrated in figure A6.1 and demonstrate a degree of variability over the period used. In most of the relatively low-flow years in the early part of the record the simulations are quite good. However, towards the end of the record (late 1980s), the

Table A6.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Tanzania catchments.

Catchment	Start Year	End Year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	POW	ST	SL	FT	ZMIN	ZMAX	PI	R	TL
Sigi (1C1)	1966	1990	250	650	1 045	1 800	2.5	700	0	35	20	1 000	1.5	0.5	0.25
Tami (1G5A)	1970	1983	146	741	1 220	1 890	2.0	550	0	30	20	1 000	1.5	0.5	0.25
Kisangata (1G6)	1955	1983	128	140	1 294	1 500	1.5	220	0	100	20	1 000	1.5	0.5	0.25
Diwale (1GB1A)	1966	1989	238	174	1 550	1 700	Runoff depth (1 633 mm) too high for given input of rainfall.								
Ruvu (1H5)	1966	1987	179	420	1 480	1 500	Runoff depth (1 401 mm) too high for given input of rainfall.								
Mzinga (1J6)	1966	1986	189	539	1 060	1 940	3.0	1 200	500	50	20	1 500	1.5	0.5	0.25
Great Ruaha (1KA8A)	1954	1986		803	Not used for model testing as insufficient map data available.										
Kimani (1KA9)	1970	1986	162	442	993	1 350	1.8	400	0	90	20	1 000	1.5	0.5	0.25
Mtitu (1KA22)	1957	1987		456	Not used for model testing as insufficient map data available.										
Ruhuhu (1RB2)	1971	1990	216	1 940	1 370	1 500	1.7	1 500	0	150	20	1 200	1.5	0.5	0.25
Mngaka (1RB6)	1977	1990		839	Not used for model testing as insufficient map data available.										
Kiwira (1RC2)	1954	1990		1 698	2 400	1 500	Runoff depth (6 844 mm) too high for given input of rainfall.								

Table A6.2 Pitman model simulation results, Tanzania catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Sigi (1C1)	- Obs.	18 527	24 488				9.20	1.14			
	- Sim.	17 120	21 695	-7.6	0.46	0.41	9.23	0.97	0.3	0.60	0.59
Tami (1G5A)	- Obs.	10 299	12 040				8.69	1.27			
	- Sim.	9 564	10 989	-7.1	0.57	0.54	8.78	0.89	12.5	0.32	0.29
Kinsangata (1G6)	- Obs.	7 151	10 406				8.06	1.49			
	- Sim.	7 195	8 336	0.6	0.33	0.27	8.23	1.26	2.1	0.19	0.02
Mzinga (1J6)	- Obs.	2 628	4 204				6.64	2.00			
	- Sim.	2 588	4 793	-1.5	0.26	-0.13	6.90	1.61	3.9	0.29	0.21
Kimani (1KA9)	- Obs.	16 266	17 308				9.10	1.13			
	- Sim.	16 797	17 392	3.3	0.69	0.66	9.12	1.19	0.2	0.87	0.86
Ruhuhu (1RB2)	- Obs.	113 951	48 002				11.56	0.42			
	- Sim.	110 878	51 112	-2.7	0.81	0.78	11.51	0.42	-0.4	0.82	0.75

high-flow months, in particular, are over-simulated and during the total period the high-flow months in the wet years are simulated rather erratically. This may be partly a consequence of poor rainfall input and the effect of applying a linear weighting factor to monthly rainfalls observed at gauges distant from the catchment.

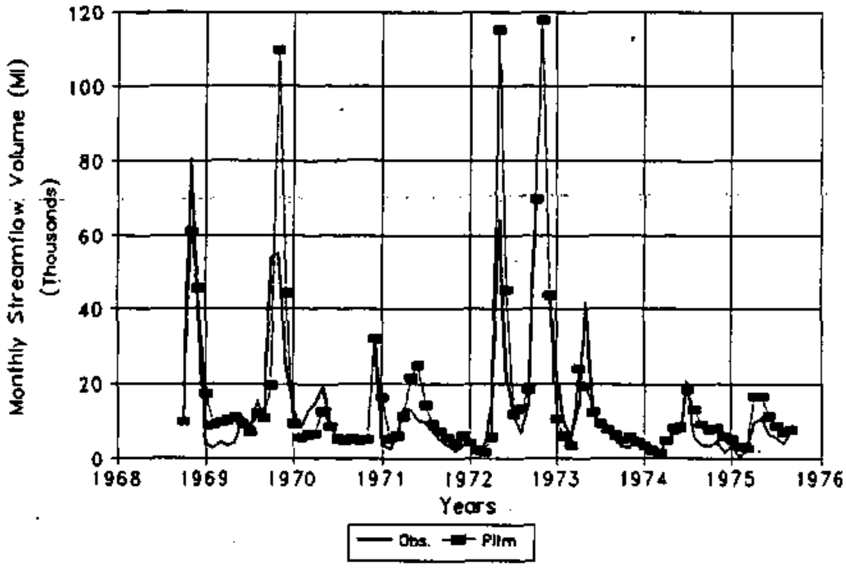


Figure A6.1 Sigi River (1C1), observed and simulated (Pitman) monthly flow time series for hydrological years 1968 to 1974.

Figure A6.2 illustrates the simulation results for the Tami River (1G5A) which are somewhat similar to the Sigi River in that, generally, the low flows are simulated rather more consistently than the high-flow months of the wet years. At the end of the simulation period (early 1980s), however, the observed low flows decrease quite significantly, while the model simulates similar flow volumes as those shown in figure A6.2 and this partly accounts for the relatively poor statistics based on log transformed values. This may indicate some effects of land-use change or increased abstractions that have not been accounted for in the model due to lack of information. It is also worth noting that there are many gaps in the observed flow record during this period, which may suggest generally unreliable data.

The Kisangata River (1G6) is immediately adjacent to the Tami River, but appears to drain an area of steeper topography. This may account for the difference in calibrated parameters (lower storage in the steeper catchment) but the differences do seem to be rather excessive and suggest caution when attempting to regionalise parameter values. The results (figure A6.3) indicate that the simulations have been reasonably successful, but that, at certain times (e.g. 1976), the input rainfall appears to be miss-represented and this has an impact on the overall statistics of correspondence between observed and simulated flows.

The Mzinga River (1J6) is a relatively flat catchment and the only available raingauge is quite distant from the catchment. Table A6.2 indicates that the simulation exercise was not at all successful. Whether this is a result of inadequate rainfall input, or whether it is related to a deficiency in the model is not at all clear.

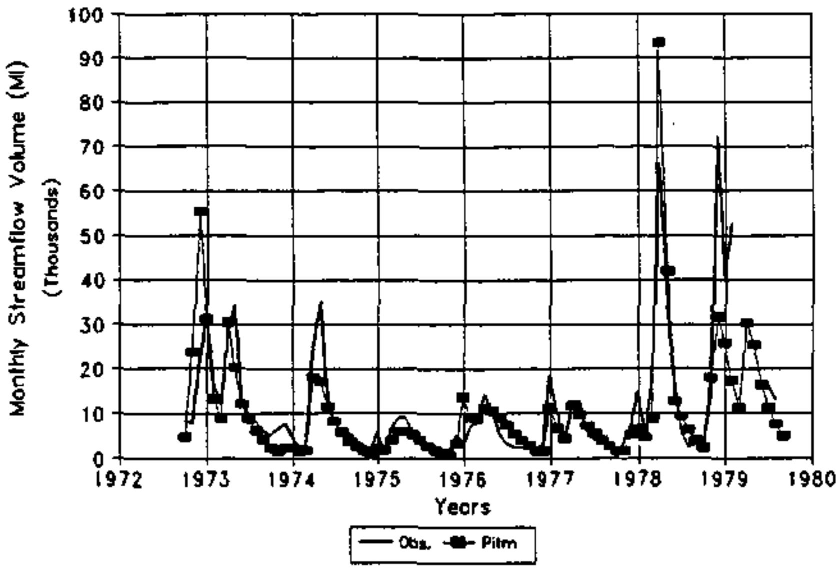


Figure A6.2 Tami River (1G5A), observed and simulated (Pitman) monthly flow time series for hydrological years 1972 to 1978.

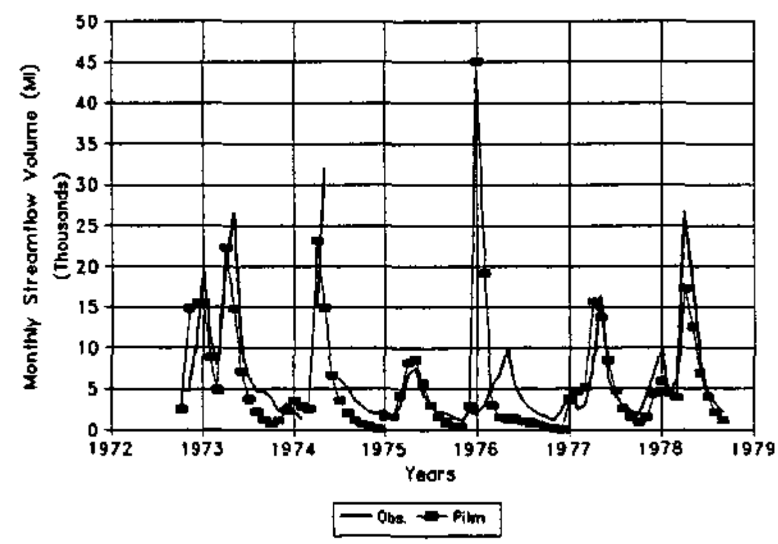


Figure A6.3 Kisangata River (1G6), observed and simulated (Pitman) monthly flow time series for hydrological years 1972 to 1977.

Figure A6.4 and Table A6.2 illustrate that the Kimani River catchment (1KA9) has been successfully simulated by the Pitman model and with parameter values that are broadly similar to some of the other Tanzanian catchments. The general shape of the seasonal streamflow response, as well as the autumn and winter recession, have been simulated very well, while many of the peak flow months are either over-or under-simulated.

The results for the Ruhuhu River (1RB2) are very similar to those for the Kimani (figure A6.5 and table A6.2). The main difference between this catchments response and all the other Tanzanian examples is the very high baseflow response and the generally lower variability in runoff. The coefficient of variation based on monthly flows is 0.42 compared to 1.06 to 1.60 for the other catchments. These differences are expected to be related to the underlying geology and soils but the level of detail in the available information is insufficient to account for them. The ST and FT parameters are also very different for this catchment which is consistent with the differences in observed response characteristics. The period shown in figure A6.5 covers mostly the validation period that was not used for calibration and the major deficiency is in the under-simulation of the low flow months. Setting the POW parameter value to 1.5 improves the simulation for the whole period, increasing the log-transformed coefficient of efficiency to 0.79.

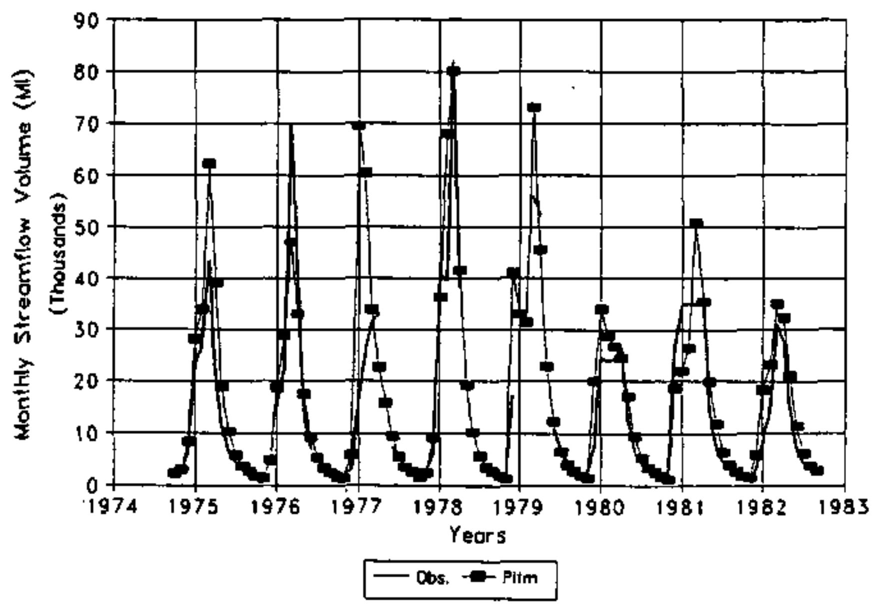


Figure A6.4 Kimani River (1KA9), observed and simulated (Pitman) monthly flow time series for hydrological years 1974 to 1981.

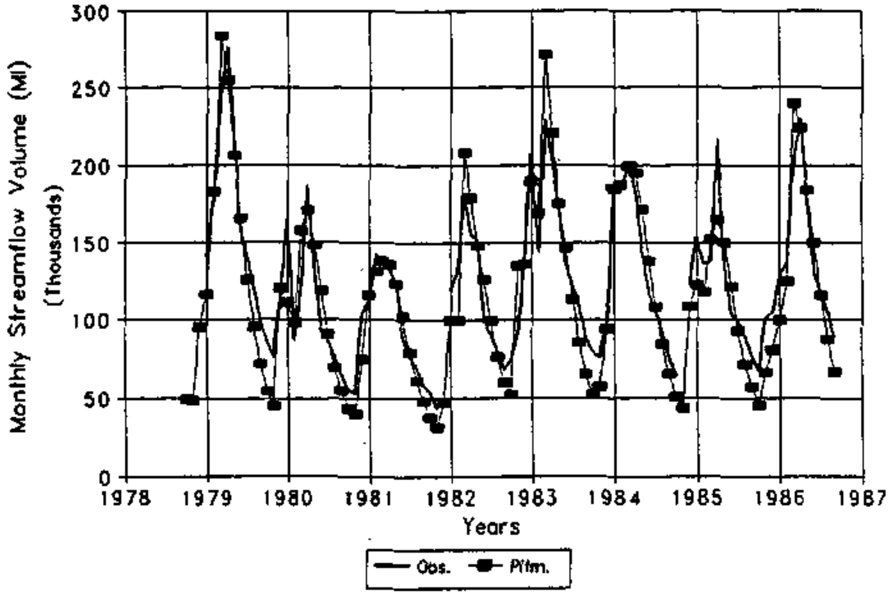


Figure A6.5 Ruhuhu River (1RB2), observed and simulated (Pitman) monthly flow time series for hydrological years 1978 to 1985.

General observations on the application of the Pitman model.

All of the catchments used have limitations in terms of the available hydrometeorological data and background information. There are also doubts about the reliability of at least some of the streamflow data. Despite these difficulties, the simulation exercise has demonstrated that the Pitman model is applicable to Tanzanian conditions and that reasonable results can be achieved. The number of catchments used is too small to be able to reach firm conclusions about the possibilities for regionalisation, but the indications are that such an exercise could prove successful if data for more catchments were made available. It would also be very useful to have access to more detailed information about the physical characteristics of the catchments that have been used to examine whether the parameter differences (table A6.1) can be accounted for.

A6.6 Calibration Procedure (VTI Model).

The normal procedure for calibrating the VTI model would be to evaluate the physiographic variables and allow many of the model parameter initial values to be estimated automatically (using the standard HYMAS procedures) and then refine the values of some parameters through repeated calibration runs. However, there is only a limited amount of physiographic information available for the Tanzanian catchments and while approximate values for soil, vegetation and geological characteristics can be identified, it was anticipated that more reliance would have to be placed on calibration.

As with the other countries, the first several years of the observed record were used for calibration purposes, while the remainder provide a period of validation to ensure that the parameter values can be considered representative.

A6.7 Simulation Results (VTI Model)

Figure A6.6 illustrates part of one year of the calibration period for the Sigi River (1C1) catchment, figure A6.7 shows the observed and simulated 1-day duration curves, while tables A6.3 and A6.4 list some of the parameters and the simulation statistics respectively. The results of the first 10 years of the simulation were far better than are reflected in table A6.4 and it is difficult to reach any firm conclusions about why this should be so. There are good and bad simulations in both periods, in terms of events and low flows, it simply appears that during the last 10 to 12 years, the model has generally under-simulated the response. The duration curve comparison suggests that the range of flows experienced in the river has been reasonably simulated, except in the very low flow period. This is noticeable when viewing the daily hydrographs for all the years, in as much as there are periods when the observed low flows decrease. These periods do not appear to correspond to particularly dry antecedent conditions and may not in fact be related to the natural hydrology of the catchment.

The results for the Tami (1G5A) catchment are somewhat similar to the Sigi (tables A6.3 and A6.4 and figure A6.8). Individual days are not very well simulated despite the fact that the general response characteristics appear to have been reasonably reproduced. The differences between the duration curves in the low flows from 80 % exceedence and higher (figure A6.8) are largely a consequence of about two years, late in the record during dry periods, where the observed flows decrease to zero. Similar dry periods, earlier in the record, do not seem to produce periods of zero flow. While this may be a natural phenomena, it could also be related to some unspecified abstractions.

It was not possible to achieve a satisfactory calibration of the VTI model for the Kisangata (1G6) catchment and the values given in table A6.3 are those which give the best visual fit between observed and simulated flows for a few months in some years of the available record. The statistics given in table A6.4 include the main part of at least two years when there was no rainfall data and monthly mean rainfalls divided by 30 were substituted for each day. There are many responses in the observed record that cannot be accounted for by the rainfall records that were used as input. The calibration procedure was therefore severely constrained by the lack of understandable signals in the data to guide the direction of parameter value modification.

Table A6.3 Some key parameters of the VTI model for the Tanzania catchments.

Parameter/Catchment		1C1	1G5A	1G6	1KA9	1RB2
Veg. cover fraction		0.61	0.95	0.70	0.70	0.62
Canopy capacity (mm)		0.94	2.30	1.20	1.20	0.95
Infiltration Curve	K	0.62	0.59	0.60	0.63	0.65
	C (mm h^{-1})	183.0	156.0	158.0	174.0	186.0
Total Soil Store (mm)		580.0	706.0	274.0	768.0	776.0
FC/Porosity		0.60	0.63	0.60	0.56	0.53
Soil K (mm h^{-1})		19.5	12.2	16.0	21.8	23.0
Texture dist. factor		0.85	0.80	0.85	0.90	0.90
St. Dev. of Moist. Dist.		0.12	0.11	0.16	0.15	0.20
G'Water K (mm h^{-1})		0.13	0.09	0.30	0.12	0.70

It was also not possible to obtain a satisfactory calibration for the Mzinga River (1J6). Part of the reason for this must be related to the fact that the only available raingauge is distant from the catchment, but the model formulation would also seem to be at fault. This is a flat catchment that seems to have a subdued response (about 5.5 % of rainfall) derived from drainage of soil or ground water in the near channel area, with some small amounts of runoff from rain falling directly on the channel and bank areas. The model is not capable of simulating this type of response.

The simulations for the Kimani River catchment (1KA9) were far more successful than the previous catchments, although one-to-one correspondence of individual days events was relatively poor. The main improvement over the previous catchments is related to the better simulations of the short- (post events) and long-term (seasonal) recessions, suggesting that the baseflow generation mechanisms have been simulated correctly. The rainfall input is based on a single gauge, there is therefore no areal averaging of the rainfall input to the model and it might be expected that individual event peaks might not be well simulated. Figure A6.9 illustrates a typical year (taken from the validation period not used in the initial calibrations), where the first part of the wet season has been under-simulated, while the later part and the recession into the dry season have been reasonably well simulated, except for individual peaks. The pattern in other years is different, but there are frequently some parts of each year that are well simulated and others that are less well. This is reflected in table A6.4 and the much better R^2 and CE statistic values for log-transformed data than for ordinary data.

Table A6.4 VTI model simulation results based on daily data, Tanzania catchments.

Catchment	Model Period	Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Sigi (1C1) - Obs.	1966 - 1990	7.36	16.35				1.14	1.30			
- Sim.		6.24	16.17	-15.2	0.26	0.02	1.09	1.03	-20.8	0.53	0.52
Tami (1G5A) - Obs.	1970 - 1983	4.32	7.15				0.98	1.10			
- Sim.		4.31	7.55	-0.2	0.32	0.08	0.96	1.01	-2.0	0.49	0.45
Kisangata - Obs.	1971 - 1982	2.70	4.91				0.06	1.54			
- Sim.		2.40	4.38	-11.1	0.14	-0.13	0.24	1.04	300.0	0.10	-0.04
Kimani (1KA9) - Obs.	1971 - 1985	6.45	7.62				1.22	1.17			
- Sim		6.42	7.95	-0.5	0.51	0.40	1.26	1.08	3.3	0.82	0.82
Ruhuhu (1RB2) - Obs.	1973 - 1990	43.35	20.98				3.67	0.45			
		40.75	20.89	-6.0	0.67	0.62	3.60	0.45	1.9	0.75	0.71

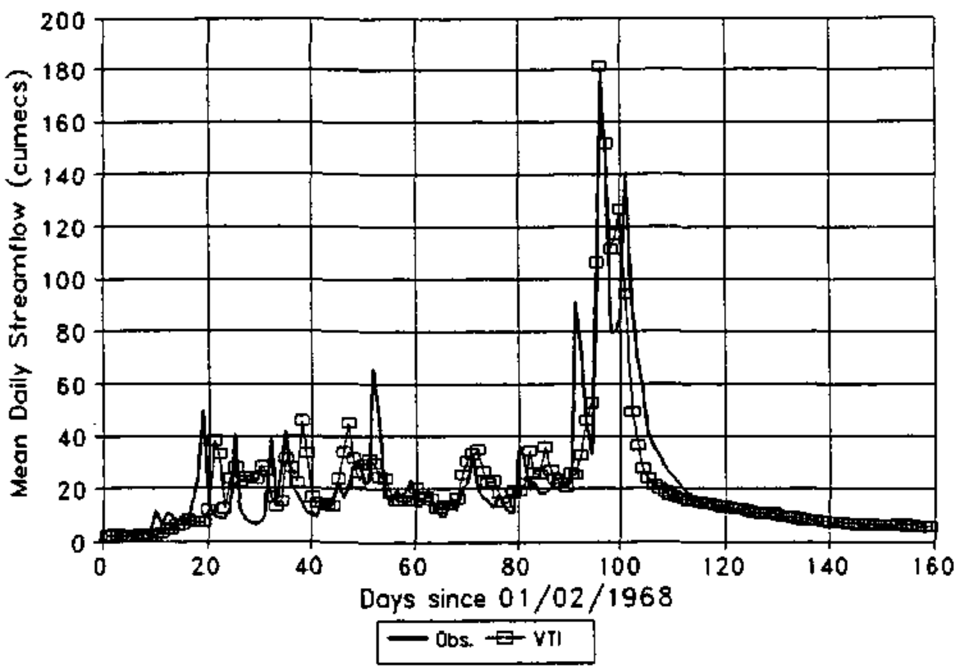


Figure A6.6 Sigi River (1C1): Observed and simulated mean daily streamflow ($m^3 s^{-1}$) for part of the 1967 hydrological year.

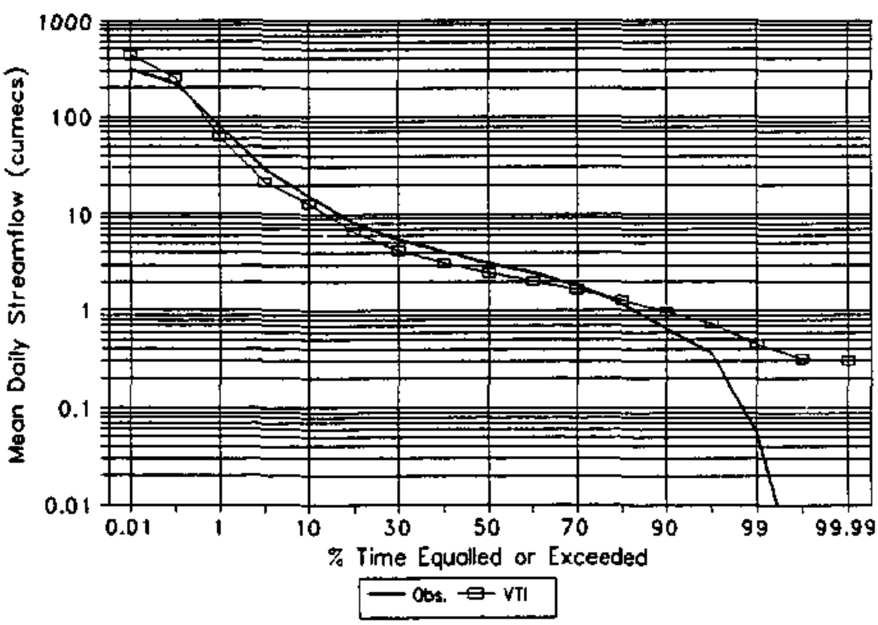


Figure A6.7 Sigi River (1C1): Observed and simulated 1-day flow duration curves using data for the period October 1967 to September 1989.

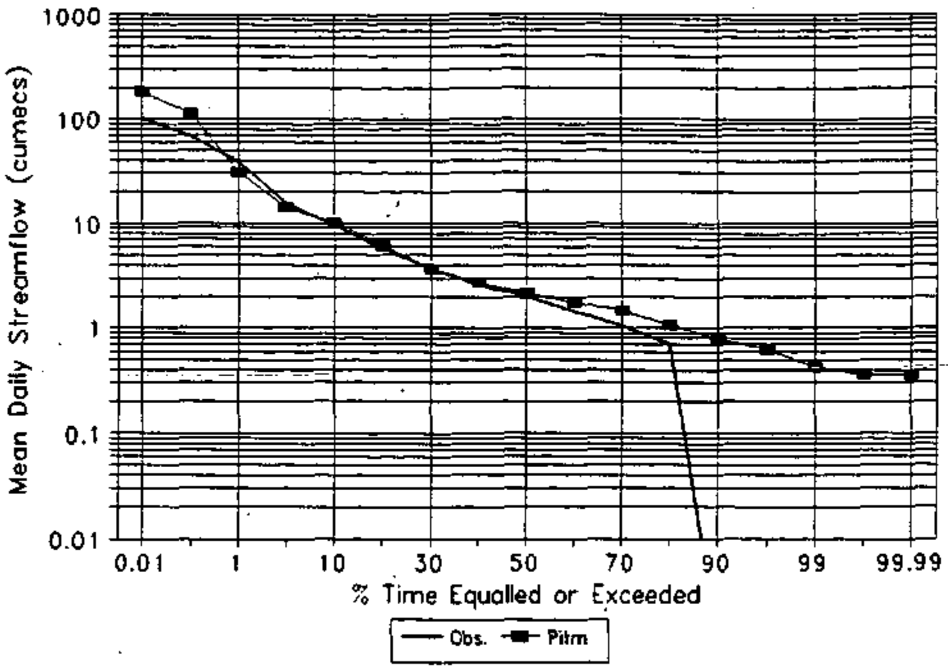


Figure A6.8 Tami River (1G5A): Observed and simulated 1-day flow duration curves using data for the period October 1971 to September 1983.

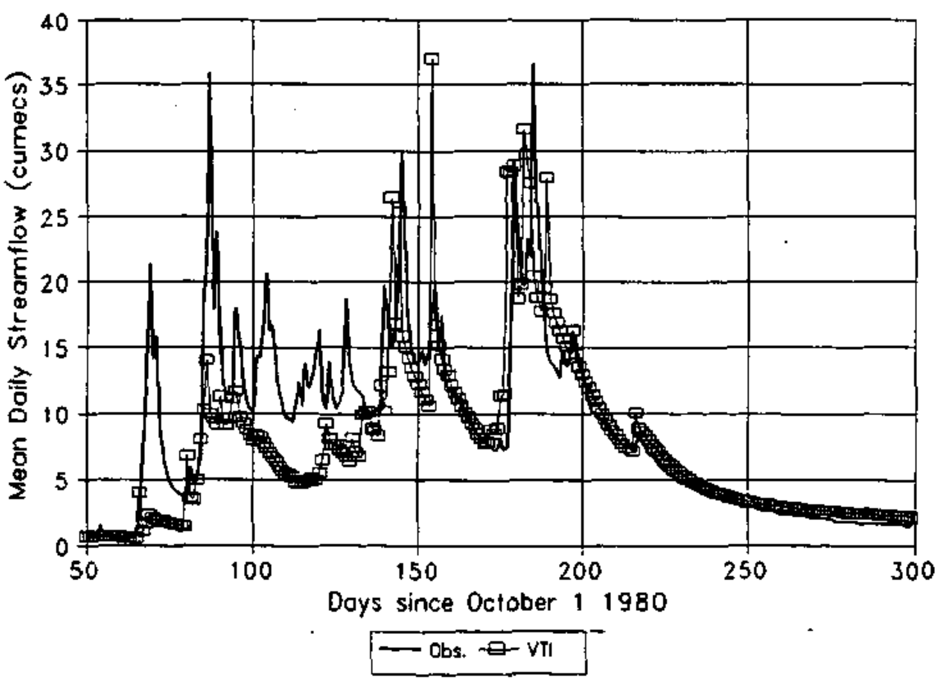


Figure A6.9 Kimani River (1KA9): Observed and simulated mean daily streamflow ($m^3 s^{-1}$) for part of the 1980 hydrological year.

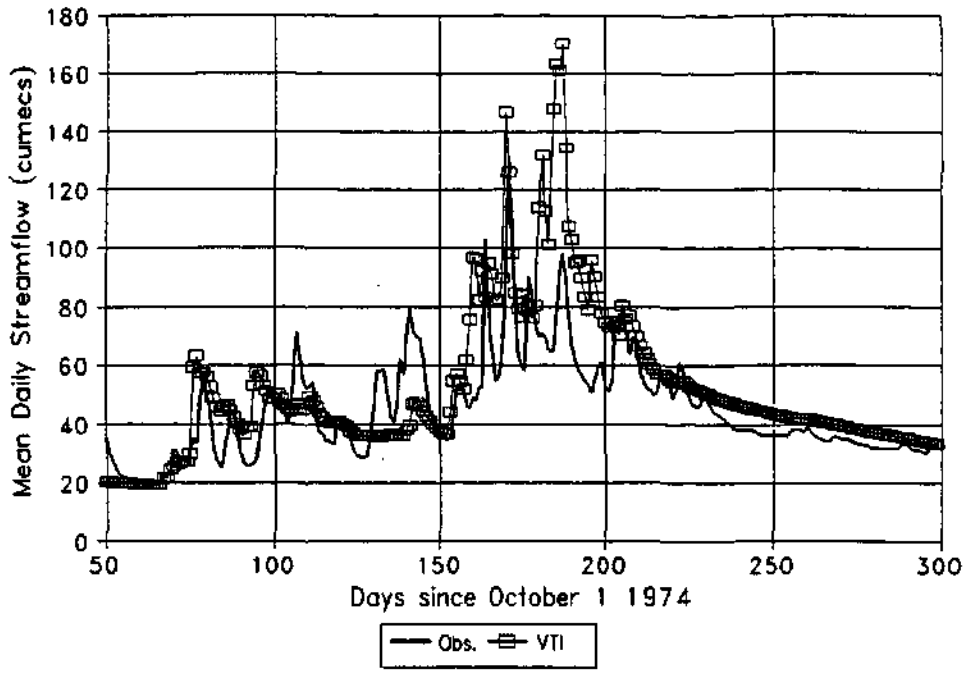


Figure A6.10 Ruhuhu River (1RB2): Observed and simulated mean daily streamflow ($m^3 s^{-1}$) for part of the 1974 hydrological year.

The final catchment, the Ruhuhu River (1RB2) was the most successfully modelled by the Pitman model, despite only having one raingauge to use for catchment inputs. The same applies for the VTI model (table A6.4 and figure A6.10), although low-flows were better simulated for the Kimani. The groundwater parameters, particularly the groundwater hydraulic conductivity, were found to be quite different for this catchment than the others and this is consistent with the much lower coefficient of variation of flow. As with the other catchments, the day to day variation in flow is not simulated all that well, but the general pattern of response is simulated reasonably well in most years. Figure A6.10 illustrates one of the calibration years and it is clear that in some periods the simulated response is much smoother than the observed, while at other times the simulations have greater variability. Overall, however, the simulated response has much the same characteristics as the observed.

General observations on the application of the VTI model.

While the daily model was found to be reasonably easy to obtain a calibration that yielded response characteristics that closely matched the observed (for the catchments where any calibration was possible), the exercise was hampered by the clear inability of a combination of the model and the input data to reproduce hydrograph shapes over short periods. It was therefore quite difficult to get any real improvements once the initial calibration of the general response was achieved. In some cases, this result can almost certainly be attributable to inadequacies in the input rainfall data (too few, or badly located, gauges). However, without better rainfall data, no conclusions can be reached about whether the model would perform more satisfactorily across the range of catchments, if the input data had been more representative.

Some of the parameter differences are consistent with the nature of the observed response, but without further detailed information about the soils, geology and vegetation, no clear statements can be made about whether the model is simulating the individual runoff components correctly. It is therefore difficult to make any comments about the 'realism' of the parameter value differences between the catchments. This also has the implications for the use of the model in ungauged situations, as recommendations or guidelines for parameter value estimation are difficult or impossible to make.

A6.8 General Conclusions.

There are few differences between the two models if simulations of monthly runoff volumes are considered. For those catchments and years where the monthly Pitman model did not perform very well, the daily VTI model did not generally perform satisfactorily either. The application of both models suffer from the same problems of a lack of representative input data and this is illustrated by the fact that three of the originally selected catchments could not be calibrated because either the rainfall was too little, or the runoff volume too high.

Both models also suffer from the same problems with respect to transferring the calibration results to other areas. Without more specific and detailed information about the physiographic characteristics of these areas, it is difficult to decide whether the parameter differences (between catchments) are mere artifacts of the calibration procedure, or have direct relevance which can be potentially exploited for the purposes of regionalising the application of the models.

Given that further information may be available, or could be collected, for a specific study, covering a region smaller than the country as a whole, there is every indication that the models could provide valuable water resource estimation tools for Tanzania. There are, however, several areas of the country that have not been represented by the catchments used and the usefulness of the models in these areas should be tested.

Appendix A7 ZAMBIA Catchments

A7.1 Availability of time series data.

Flow data.

Daily streamflow data were made available for 26 catchments ranging in size from 32 to over 270 000 km², but with most of them in excess of 1 000 km². The data were made available as ASCII type output (1 file each year) from HYDATA. The record lengths vary with some starting before 1960, some during the 1960s and some as late as the early 1970s. Most of the records end during the late 19802 or early 1990s. Many of the gauges, represent sub-areas of other, larger, gauged catchments. The catchment areas were taken from the ARC/INFO coverage and data files for catchment boundaries compiled by the Institute of Hydrology, UK as some of the areas given in the Zambian station register were clearly in error.

Rainfall data.

Monthly rainfall data were made available for 121 stations many of them having records from the 1920 and 1930s to the late 1980s or early 1990s. Their distribution over the whole of Zambia is not very even and there are concentrations of gauges in the more populated and economically active areas. Some daily data were made available for four stations within the Kabompo River catchment (> 66 000 km²).

Evaporation data.

Monthly A-pan evaporation data are available for 9 stations covering the whole country and from these it was possible to estimate mean monthly representative values for the selected catchments.

The initial selection of catchments based on the availability of about 20 years of monthly rainfall records with coincident daily streamflow records yielded 17 stations (figure A7.1 and table A7.1) within six main basins:

1950; Kabompo River (at Watopa) situated in the north west of Zambia.

4350; Kafue River (at Chilenga) situated in the central part of Zambia and including 4340 (Luswishi River) and the main Kafue and several sub-catchments represented by gauges 4280, 4250, 4245, 4240, 4050, 4015 and 4005.

6145; Chambeshi River (at Mbesuma Pontoon), situated in the north east part of Zambia and including two small tributary catchments (6130 and 7005).

6235; Kilunga River (at Kilunga), a tributary of the Chambeshi and gauged downstream of the previous station (6145).

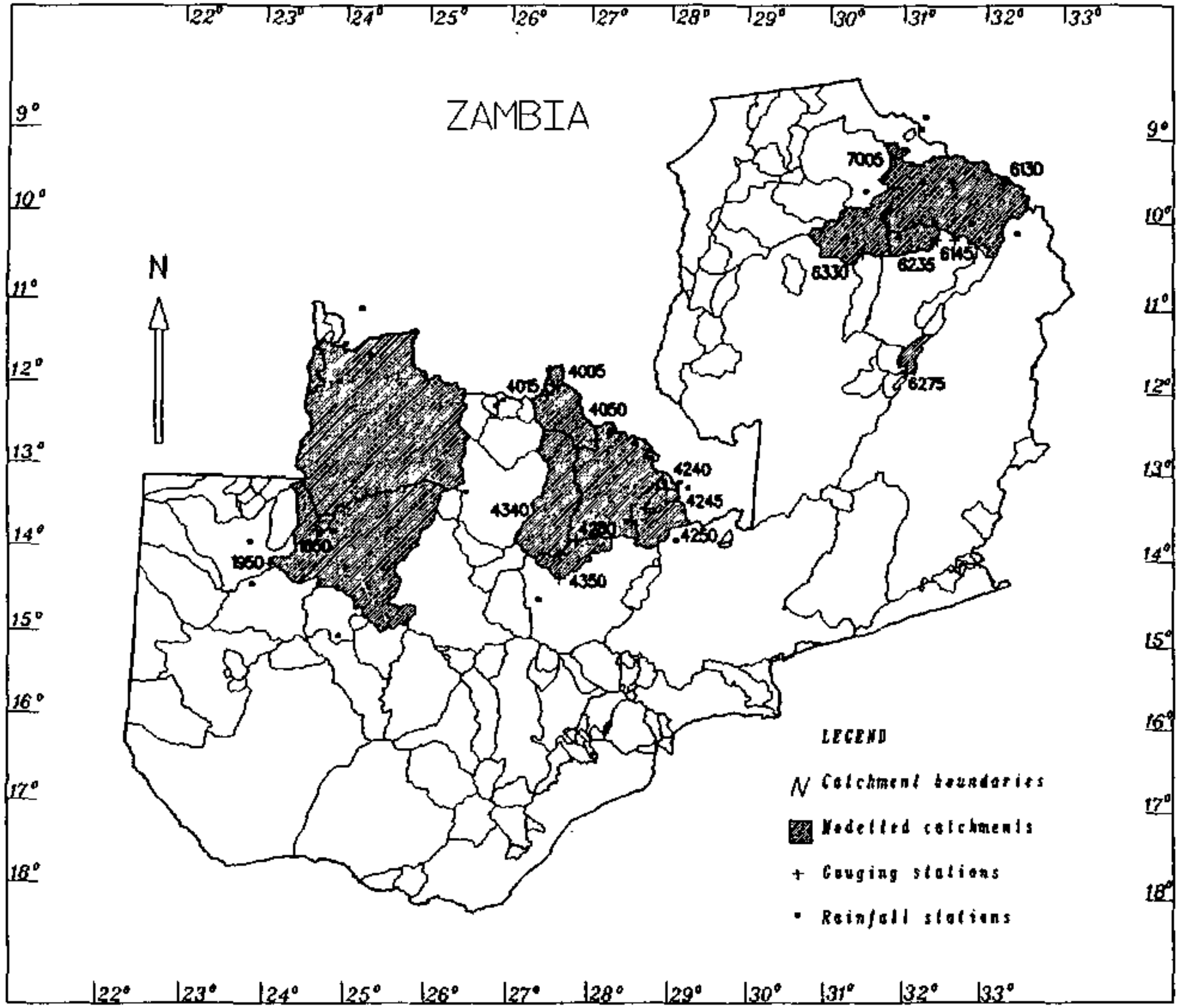


Figure A7.1 Gauged catchments in Zambia and those used in the FRIEND project.

6350; Lukulu River (at Kasama Luwingu Road Bridge), a further tributary of the Chambeshi joining the main river above the Bagweulu swamp.

6275; Manshya River (at Shiwa Ngandu) situated in south east Zambia and a south bank tributary of the Chambeshi rising in the interfluve between the Chambeshi and the Luangwa rivers.

A7.2 Availability of catchment description data.

Topographic maps at a scale of 1:1 150 000, land-use at 1:750 000 and 1:3 000 000 scale soil maps were available for the whole of Zambia. Hywel-Davies (1971) contains a lot of further generalised (but nevertheless useful) information about Zambian relief and physical features, soils, vegetation, hydrology, climate, geology and land use, etc. The information is portrayed at a very large scale, but many of the text explanations are of value to those not familiar with the country.

A7.3 Brief descriptions of catchments.

The location of the 12 gauged catchments is illustrated in figure A7.1.

The relief of Zambia, and all the catchments used, consists of gently undulating to relatively flat plateaux, occasionally broken by hills and ranges of resistant geological formations.

Kabompo River

Most of the upper parts of the Kabompo River are underlain by shales, sandstones, dolomites and quartzites of the Katanga system and the associated soils vary from clays to sandy clay loams with clay contents increasing with depth. They are deep (approximately 1.8 m) and friable soils. The lower parts of the basin are underlain by poorly consolidated sandstones and windblown sands of the Kalahari system, with associated deep, loose and structureless sands. Vegetation cover is largely woodland interspersed with cultivated lands. Rainfall input to the basin can be represented by some 10 raingauges, but most of these are situated around the boundaries of the area and the main part of the catchment is not represented at all. Mean annual rainfall appears to vary from over 1 300 mm in the upper reaches to less than 1 000 mm lower down. An evaporation station exists in the lower part of the catchment.

Kafue River and tributaries

The Kafue River rises in the Zambian Copper Belt and is underlain by similar rocks as the upper Kabompo but with some areas of Basement Complex comprising gneisses, schists and micaceous quartzites. The associated soils vary from clays to sandy clay loams and are generally quite deep. Vegetation and land use consist of natural woodland, forest reserves, cultivated land and urban/industrial areas associated with mining. The rainfall input can be represented by 14 of the available rainfall stations but most of these are located in the Copper Belt area and a large part of the upper and western tributary catchments are poorly covered by rainfall data. Mean annual rainfall varies from about 1 400 mm in the upper basin to below 1 000 mm. Evaporation data are available from two stations within the general region. Although there are 7 gauged tributaries above the basin outlet, it is unlikely that satisfactory calibrations will be possible for some of them due to the lack of a suitable raingauge record to define the local patterns of rainfall input.

Chambeshi River and tributaries

The upper parts of the basin are underlain by granites, while extensive recent alluvium deposits occur lower down. The soils associated with the granites are similar to those overlying rocks of the Katanga system, while those associated with the alluvial deposits are generally hydromorphic derived from siliceous material and have a peaty organic horizon. The upper areas are characterised by woodland, while the alluvial areas by grassland and wetlands. Mean annual rainfall is of the order of 1 000 mm and model inputs can be represented by 6 raingauges. As with the other catchments, the distribution over the catchment is very uneven with large areas not represented at all.

Lukulu, Manshya and Kilunga River and tributaries

The Lukulu, Manshya and Kilunga river catchments are close to the Chambeshi and have very similar characteristics. Rainfall records are available for 3 stations located on or relatively close to the boundary of the Kilunga catchments, while 4 are available for the Lukula catchment. Only 1 of the available rainfall stations lies within or close to the Manshya catchment.

A7.4 Calibration procedure (Pitman Model).

Without further information it was difficult to establish a strict calibration procedure. The starting values of the parameters for calibration were expected to be similar for all catchments, as they have similar broad characteristics. The soils are generally quite deep (high ST values) and the vegetation cover reasonably well developed, suggesting quite high values for ZMIN and ZMAX. Much of the runoff was therefore expected to be generated as drainage from soil moisture, with some contribution from surface runoff during very high rainfall months. Most of the catchments are quite large and the sub-area division yielded similarly large sub-areas. However, while some sub-areas have been set up to correspond to smaller gauged tributaries, the results (compared with observed flow data) were not expected to be that good as most of the smaller gauged catchments are inadequately covered by the available raingauges.

Certain parameters were kept at fixed values for all catchments to simplify the calibration procedure and to maintain some consistency with the results from other countries. These are PI (1.5) and ST (0.0).

The only time when sub-area parameter differences were used was where observed flow data were available to permit calibration at different points within the main basin, or where clear differences in characteristics suggested such changes (i.e. 1950 - sandy clay loam soils in the upper area and sandy soils in the lower areas).

Table A7.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Zambia catchments.

Catchment	Start Year	End Year	Months of Obs.	Area (km²)	MAP (mm)	PEVAP (mm)	POW	ST	FT	ZMIN	ZMAX	R	TL
Kabompo (1950)	1970	1990	226	65 983	1 150	1 750	2.8 & 3.0	1 200 & 1 400	24 & 22	180 & 320	1 000 & 1 200	0.6 & 0.3	0.25
Kafue (4350)	No data			34 914									
Kafue (4280)	1970	1990	228	23 270	1 194	1 600	3.5	1 700	40	150	1 050	0.4	0.25
Kafulafu (4250)	1970	1990	209	4 866	1 183	1 600	4.0	1 800	10	100	1 100	0.4	0.25
Kafuba (4245)	1970	1990	190	1 371	1 207	1 600	4.0	1 000	90	150	1 150	0.4	0.25
Kafuba (4240)	1970	1990	189	974	1 092	1 600	3.5	1 700	70	150	1 150	0.4	0.25
Kafue (4050)	1970	1990	223	4 138	1 233	1 600	4.0	1 000	90	250	1 050	0.4	0.25
Kafue (4005)	1970	1990	228	433	1 270	1 800	3.0	850	0	150	850	0.2	0.25
Muchinda (4015)	1970	1990	235	256	1 242	1 800	3.0	500	25	150	850	0.4	0.25
Luswishi (4340)	1970	1990	157	8 834	1 150	1 800	4.0	1 800	28	300	1 250	0.4	0.25
Chambeshi (6145)	1970	1990	164	16 955	1 150	1 600	2.0	1 300	60	250	1 200	0.4	0.25
Nakonde (6130)	Bad Data			40									
Lunzua (7005)	1970	1990	236	444	1 250	1 600	3.0	1 500	30	250	1 200	0.25	0.25
Kalunga (6235)	1970	1990	218	2 106	1 275	1 600	3.2	1 400	60	250	1 150	0.4	0.25
Lukulu (6350)	1970	1990	234	6 365	1 315	1 600	2 5	1 300	70	200	1 100	0.4	0.25
Lumbe (6330)	No Data			2 523									
Manshya (6275)	1970	1990	219	1 008	1 074	1 500	2.5	1 200	70	200	1 100	0.4	0.25

Table A7.2 Pitman model simulation results, Zambia catchments.

Catchment		Mean (MCM)	SD (MCM)	Mean % Error	R^2	CE	Mean ln (Ml)	SD ln (Ml)	Mean ln % Error	R^2 ln	CE ln
Kabompo (1950)	- Obs.	603.0	521.1				12.99	0.78			
	- Sim.	603.4	497.3	0.1	0.79	0.78	12.99	0.83	0.0	0.77	0.73
Kafue (4280)	- Obs.	394.4	406.8				12.39	1.02			
	- Sim.	383.3	377.6	-2.8	0.62	0.60	12.46	0.92	0.6	0.83	0.82
Kafulafu (4250)	- Obs.	57.9	61.0				10.33	1.20			
	- Sim.	57.2	80.0	-1.2	0.50	0.13	10.39	1.05	0.6	0.80	0.80
Kafubu (4245)	- Obs.	31.1	30.1				9.88	0.99			
	- Sim.	27.2	27.7	-12.5	0.60	0.57	9.76	0.99	-1.2	0.63	0.57
Kafubu (4240)	- Obs.	16.5	12.7				9.28	1.10			
	- Sim.	16.2	15.7	-1.8	0.54	0.29	9.29	0.93	0.1	0.51	0.49
Kafue (4050)	- Obs.	101.1	134.0				10.70	1.34			
	- Sim.	101.9	124.6	0.8	0.67	0.66	10.84	1.30	1.3	0.83	0.82
Kafue (4005)	- Obs.	3.8	8.9				7.89	2.55			
	- Sim.	3.8	8.9	0.0	0.46	0.35	8.04	2.01	1.9	0.12	-0.07
Muchinda (4015)	- Obs.	7.0	16.2				7.72	1.41			
	- Sim.	6.0	9.3	-14.0	0.41	0.40	7.17	2.11	-7.1	0.61	-0.06
Luswishi (4340)	- Obs.	52.5	42.1				10.48	0.96			
	- Sim.	53.2	37.7	1.3	0.51	0.48	10.61	0.79	1.2	0.70	0.68

Table A7.2 (Continued) Pitman model simulation results, Zambia catchments.

Catchment		Mean (MCM)	SD (MCM)	Mean % Error	R^2	CE	Mean ln (Ml)	SD ln (Ml)	Mean ln % Error	R^2 ln	CE ln
Chambehsi (6145)	- Obs.	170.2	108.1				11.78	0.80			
	- Sim.	164.1	94.3	-3.6	0.71	0.70	11.82	0.65	0.3	0.69	0.69
Lunzua (7005)	- Obs.	10.7	5.3				9.16	0.48			
	- Sim.	11.4	5.3	6.5	0.74	0.71	9.23	0.48	0.8	0.78	0.74
Kalungu (6235)	- Obs.	44.9	27.1				10.49	0.73			
	- Sim.	44.1	27.1	-1.8	0.53	0.46	10.49	0.68	0.0	0.47	0.41
Lukulu (6350)	- Obs.	184.6	98.3				11.99	0.53			
	- Sim.	180.8	96.1	-2.1	0.62	0.58	11.95	0.59	-0.3	0.65	0.54
Manshya (6274)	- Obs.	29.9	30.4				10.01	0.75			
	- Sim.	23.9	24.3	-20.1	0.05	-0.32	9.75	0.83	-2.6	0.30	-0.14

A7.5 Simulation results (Pitman Model).

Table A7.1 lists the final parameter values for the catchments simulated. Although the original intention was to retain the standard value of 1.5 for PI (natural vegetation interception capacity), it was found that a value of 2.5 gave better results. This may be accounted for by the fact that many parts of the catchments used have areas of protected natural woodland. Only where the vegetation maps indicated large proportions of the catchments under forest reserves were any values added for forestry.

It is clear from the statistics given in table A7.1 that the simulated flows for the *Kabompo Basin* are reasonable reproductions of the observed. The main problem was that the model did not simulate the rather rapid recession of flow into the dry season, particularly during relatively moderate to dry years. The model recessions were less steep, which could not be corrected if the minimum flows towards the end of the dry season were to be simulated successfully. This feature can be seen in figure A7.2 which shows the observed and simulated duration curves. The parameters in table A7.1 reflect those used for the upper areas (the first figure provided - sandy clay loam soils) and the lower areas (the second figure - sandy soils) and while these gave reasonable results, there is insufficient data to justify the differences. Ultimately, they would have to be confirmed by additional gauged flow data at the outlet of some of the upper areas to ensure that the model is simulating the correct incremental runoff volumes.

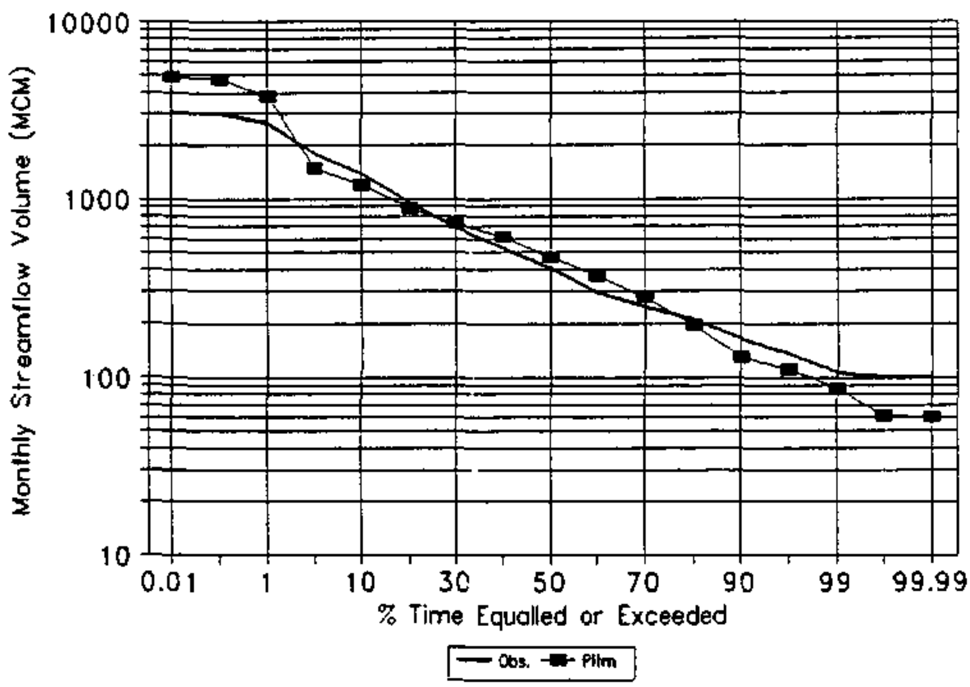


Figure A7.2 Observed and simulated 1-month flow duration curves for the Kabompo River based on data for 1970 to 1990.

The *Kafue River* results are based on observed data for 8 of the total distribution of 12 sub-catchments (including the most downstream one just above gauge 4350 for which there is no observed data). The rainfall and evaporation data (table A7.1) and the calibrated parameter values (table 7.2) are applicable to the incremental areas between the outlet (at the gauges) and any upstream gauging sites. The sub-catchments vary in size from 256 km² to over 7 000 km² and many of them do not have raingauges located within, or even close to, their boundaries. It is therefore extremely difficult to know how representative the rainfall inputs are. The simulations for the small headwater catchments (4005 and 4015) are not very good, particularly for low flows (table A7.2) and the calibrated parameters are somewhat different from those established for the other sub-catchments. Part of the reason for this may be related to the relatively high proportion of these catchments covered by forest reserve. The statistics for the larger areas are generally better (see also the monthly hydrographs for four catchments illustrated in figure A7.3), but somewhat variable and table A7.1 indicates that these results are based on parameter values that differ quite considerably from catchment to catchment. While these differences may be realistic and reflecting true variability of catchment characteristics within the Kafue basin, there is no information available to confirm or deny this possibility. One of the problems with many of the simulated flows is the fact that the model does not seem to be able to reproduce the shape of the recession into the dry season. The observed recession is generally much steeper, particularly during relatively dry years. Even setting the POW parameter to quite high values to establish a strongly non-linear runoff response did not achieve the correct response. An attempt was made to generate more runoff using the catchment adsorption function (using parameters ZMAX and ZMIN) and less from soil water runoff, but this produced too high runoff volumes in the early part of the wet season when rainfall is highest. The geological descriptions of the region refer to the presence of dolomitic limestones and it is possible that some of the response is related to rapid groundwater recharge and outflow and that fixed delay (TL) of 0.25 may be too high, even for the relatively large sub-catchments involved.

The observed streamflow data provided for catchment 6130 appears to be erroneous and gives monthly volumes several orders of magnitude higher than is possible. Two gauging stations were therefore used for the *Chambeshi River*, one upstream at 7005 and one downstream at 6145. Good statistics of correspondence were achieved for the calibration period (1970 to 1980) and although the results are not as good for the later validation period, the simulations have been reasonably successful (table A7.2 and figure A7.4). The peak flow months for the larger catchment (6145) have been generally over-simulated in the validation period and 1987 hydrological year (starting in October) has not been adequately simulated for an unknown reason. For 7005 there is also one year that is badly simulated (1981) and some of the low periods have been under-simulated. However, none of these problems occur throughout the full record and the final calibration parameters are a compromise solution that give a satisfactory overall result. As with the other areas, there are uncertainties about the real representativeness of the input rainfall data which must have some impact on the results.

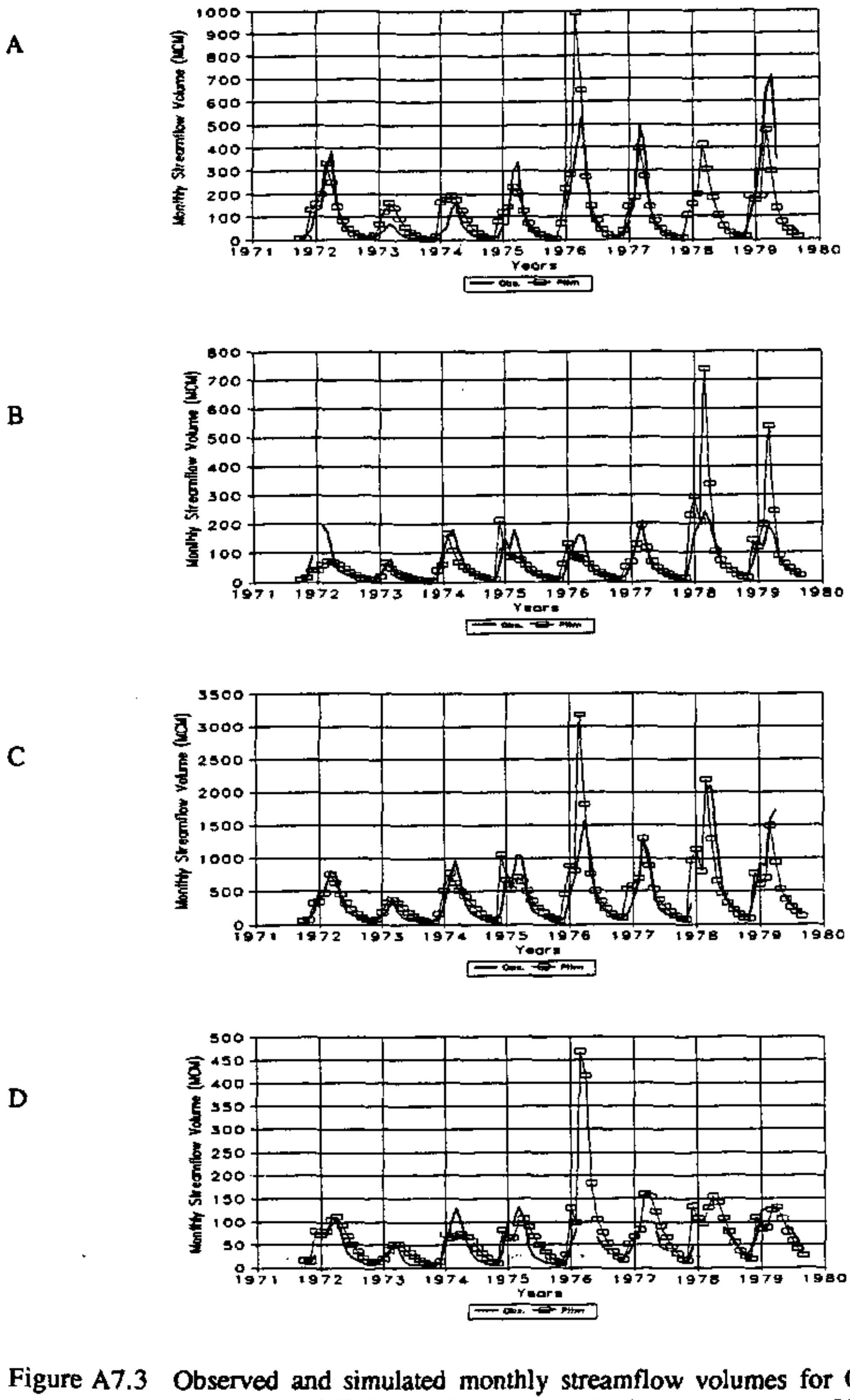
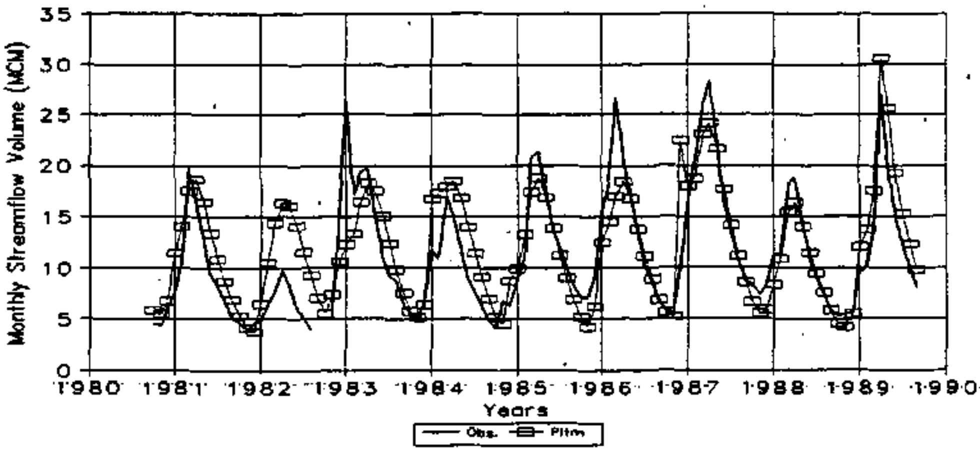


Figure A7.3 Observed and simulated monthly streamflow volumes for October 1971 to September 1979 for catchments: A) Kafue (upstream at 4050); B) Kafulafu (at 4250); C) Kafue (downstream at 4280) and D) Luswishi (at 4340).

A



B

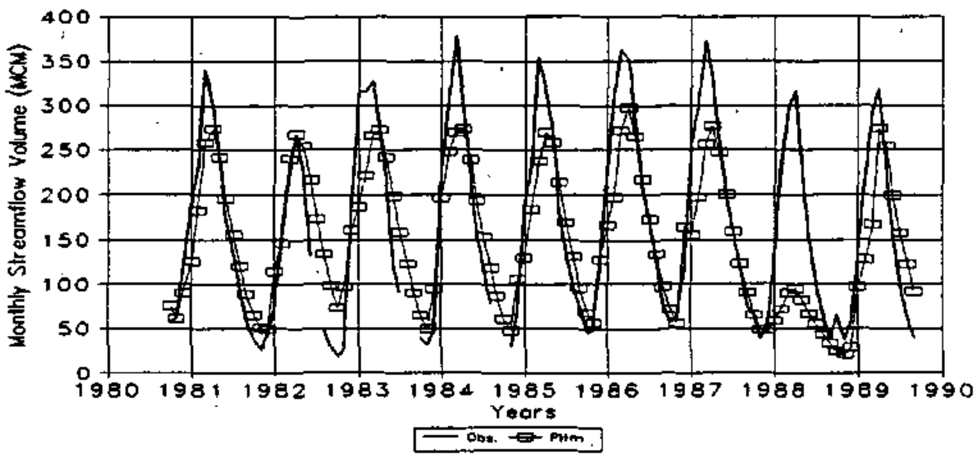


Figure A7.4 Observed and simulated monthly streamflow volumes for October 1980 to September 1989 for catchments A) Lunzua (at 7005) and B) Chambeshi (at 6145).

The results for the other tributary catchments of the Chambeshi are somewhat mixed (table A7.1). The general pattern of observed and simulated flows for 6235 are very similar but it appears almost as if the observed flow is delayed by 1 to 2 months. This apparent delay is possibly related to the same problem with the too slow recession of the simulated flows, but is also evident on the rising limb of the seasonal hydrographs. The simulated flows for 6350 are frequently not high enough during the wet months of the year, while the low flows are often too low. The statistics given in table A7.1 for the Manshya catchment (6 275) are for the total period 1970 to 1990 and there are many badly simulated months during the mid to late 1980s which are clearly caused by miss-matched rainfall input. The results for the first 120 months are much better (R^2 = 0.4, CE = 0.36), although still not really satisfactory. It should be remembered that the available raingauges are very distant from this catchment.

General observations on the applications of the Pitman model.

While there is good rainfall data coverage for parts of the catchments used, there are other areas where very little rainfall data were made available. This will clearly have an impact on the simulation results and means that it is difficult to reach firm conclusions about the applicability of the model. Under such circumstances, it is almost impossible to identify the cause for any simulation limitations. However, one aspect of the results which seems to be unrelated to rainfall data input and which recurs on several catchments is the model's apparent inability to reproduce the seasonal recessions. The observed data has an initial steep decrease from the wetter months, followed by a flatter recession from the middle to the end of the dry season. The simulated recessions are much smoother, which is related to the shape of the relationship between soil water storage level and runoff rate used in the model. If the groundwater component (GW) of the model had been used, all that this would have introduced is a further delay in the runoff routing which would still not have reproduced the recession shape. The problem possibly lies in using a single moisture storage and outflow function, when in reality more than one storage and process is involved.

A7.6 Calibration Procedure (VTI Model).

Daily rainfall data were made available for only one of the catchments, the Kabompo River at site 1950 and these data were limited to only 5 stations within this approximately 66 000 km² area. Nevertheless an attempt was made to apply the model using the same sub-area structure (10 subdivisions ranging in size from 3 222 to 9 570 km²) as used for the Pitman model. The information on physical characteristics is limited to the vegetation cover and the fact that the upper areas are underlain by shales, sandstones, dolomites and quartzites, while the lower parts of the basin are underlain by poorly consolidated sandstones and windblown sands of the Kalahari system. Reasonable estimates of the soil and aquifer properties of these two areas therefore formed the basis of the initial parameter estimation, after which some calibration was carried out. It should be noted that there was no previous experience of applying the VTI model to such large areas and that the first 10 years (1970 to 1980) were used for calibration.

A7.7 Simulation Results (VTI Model).

Figure A7.5 illustrates observed and simulated monthly streamflow volumes for 7 years overlapping the calibration and validation periods, while figure A7.6 shows the annual 1-day duration curves and table A7.3 list some of the parameter differences between the area underlain by the Katanga and Kalahari systems. While these are some problems with the seasonal recessions, as occurred with the Pitman model, these are confined to the very low flows and are more related to an over-estimation of dry season flow than the general characteristics of the recession. For the whole period (1971 to 1990 - the first year is used as a 'warm-up' year for the VTI model), the mean daily flow was simulated with a 5 % error, the untransformed R^2 = 0.64, CE = 0.51. The statistics based on monthly volumes were a slight improvement on the Pitman model results given in table A7.2

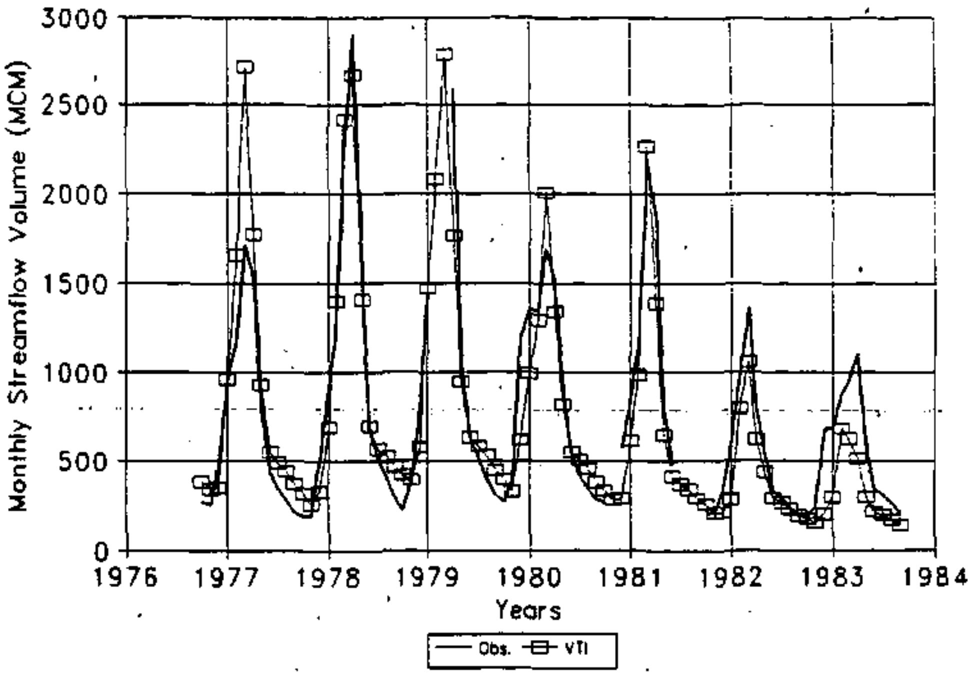


Figure A7.5 Observed and simulated (VTI model) monthly streamflow volumes for October 1976 to September 1984, Kabompo River at gauge 1950.

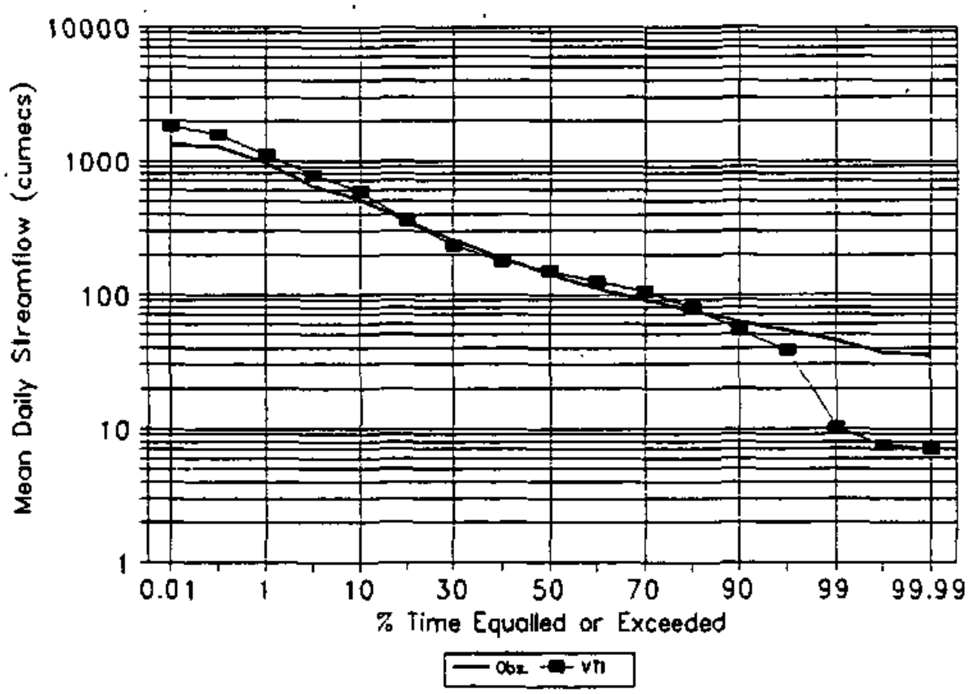


Figure A7.6 Observed and simulated (VTI model) annual 1-day duration curves based on data for October 1971 to September 1990, Kabompo River at gauge 1950.

Table A7.3 Some key parameters of the VTI model for the two regions of the Kabompo catchments.

Parameter/ Catchment		Katanga (sandy clay loam soils)	Kalahari (sandy soils)
Veg. cover fraction		0.69	0.69
Canopy capacity (mm)		1.2	1.2
Infiltration Curve	K	0.62	0.73
	C (mm h^{-1})	161.0	223.0
Total Soil Store (mm)		1 325.0	1 004.0
FC/Porosity		0.60	0.45
Soil K (mm h^{-1})		19.5	30.5
Texture dist. factor		0.78	0.88
St. Dev. of Moist. Dist.		0.11	0.10
G'Water K (mm h^{-1})		0.12	0.30

One of the notable features of calibration the model on such large sub-areas was the need to revise the approaches to estimating the channel routing parameters. The initial estimates were far too low (k values of between 6 and 17) and generated many false, short term, peaks. After calibration, these peaks were removed and the simulated hydrographs became smoother with channel routing k values of the order of 200 to 620. For smaller catchments, the channel routing parameter has very little effect and can be set to a very small value without impacting on the simulation results (most of the attenuation is achieved through the sub-area routing function). For much larger catchments, no other model function can satisfactorily achieve the required attenuation and hydrograph smoothing. This was a valuable lesson in the application of the model to catchments of this size.

A7.8 General conclusions.

The results for the Zambian catchments are encouraging, despite some of the problems that were experienced. Where the density of raingauges available to define the model input was reasonably high, the results were generally acceptable. However, while there is evidently some degree of consistency in parameter values between apparently similar catchments, there are also many differences that cannot be explained given the available level of information. It is therefore difficult to reach any conclusions about the future prospects for regionalisation and the application of the Pitman model to ungauged catchments. Only one catchment was used for the VTI model and therefore it is premature to form any opinions on the widespread applicability of this model to Zambian catchments.

Appendix A8 NAMIBIA Catchments.

A8.1 Availability of time series data.

Flow data.

The flow data provided to the project consists of monthly flow volumes and generally dates from the 1970s. Most of the sites for which data were provided are located at dam sites, some of which were completed during the period of record. Prior to the construction of any dam, the flow records are based on observations at a flow gauging weir. After construction, the inflow volumes are based on a reservoir water balance estimate using measurements of water levels, overflows, releases, abstractions and transfers at variable intervals, plus leakage and evaporation loss estimates. Because of the potential for error in any water balance estimate it is difficult to quantify the accuracy of the observed flow volumes. The same uncertainty could apply to the flow volumes derived from weir gauging records depending upon the flow capacity of the weir and the technique used to estimate flows that exceed this capacity.

Rainfall data.

Daily rainfall data are available from a number of stations within Namibia, but within the context of this study, sub-catchment average rainfalls, previously compiled by the Department of Water Affairs in Namibia were used. These monthly rainfall inputs were estimated from available station data using a multiquadratic surface approach (Mostert, et. al., 1993).

Evaporation data.

The monthly distribution of annual total evaporation in Namibia has been demonstrated to vary between several regions within Namibia. All of the catchments used in this project fall into region B (wetter parts of the central and northern areas, excluding the far North-East). The same monthly distribution and pan factors have therefore been used for all the catchments and the mean annual gross total for each catchment taken from the map developed by Crerar, et. al. (1988).

A8.2 Availability of catchment description data.

Brief catchment descriptions and maps showing sub-areas and main drainage networks are available from the SLW Joint Venture Consultants (1992) report and this has been used as the main source of information.

A8.3 Selection of catchments and brief descriptions.

Nine catchments have been selected (table A8.1). The rainfall characteristics for all the catchments can be considered similar and consists mostly of convective storms during the period from December to April. The runoff response is almost immediate and there is little or no delayed response. Channel transmission losses to alluvial material adjacent to and below channels are common. The sub-area divisions were carried out by the Department of Water Affairs in Namibia and were not changed for this project as they had to match the rainfall data provided.

Friedenau Dam (constructed in 1972) is located on a tributary of the Kuiseb River and the catchment upstream has been divided into four sub-areas. The vegetation cover consists of highland and thornbush savannah, while the catchment is underlain by Damara mica schist, quartzite and marble.

The **Oanob River** is a tributary of the Nossob River and rises on the western flank of the Auas Mountains to the southeast of Windhoek. The site used in this study is at Oanob Dam (constructed in 1990) and the catchment has been simulated with a single sub-area. Vegetation cover is highland and camelthorn savannah and the dominant underlying geology consists of Damara schist with quartzite in the north, quartzite schist and Rehoboth lava in the south and southeast.

The Etemba River site is located at a gauging station on the Omaruru River and the catchment has been divided into 8 sub-areas. The catchment is covered by semi-desert and savannah transition vegetation and underlain by Salem granite, Damara mica schist and Karoo basalt in the southwest.

The **Henopsrus Dam** is located on the Black Nossob River and the catchment has been divided into 4 sub-areas. No further information was made available for this catchment.

Nauaspoort Dam (constructed in 1980) is situated on the Auob River. The catchment has been divided into three sub-areas and the vegetation consists of mixed trees and shrub savannah. Kalahari sand is the main underlying formation.

Otjivero Dam (constructed in 1983/84) is situated on the White Nossob River and the catchment has been divided into four sub-areas. Highland savannah is the dominant vegetation cover and the catchment is underlain by Damara schist, quartzite and marble with metamorphic rocks in the south and central areas. Flow data for 1969/70 to 1979/80 are of doubtful accuracy due to problems with the stage-discharge curve used to calculate flow rates.

Ousema weir is upstream of the Omatako Dam (constructed in 1981) in the Omatako River catchment, which has been divided into six sub-areas above the dam site. The flow data measured at the weir refers to the outlet of sub-area 5 (309 km^2 less than the total of the catchment), but it is not clear where the flow records from 1981 onwards are measured. Thornbush savannah is the main vegetation type and the area is underlain by Karoo mudstone and shale.

Swakoppoort Dam (constructed in 1977) is within the Swakop River catchment and the upstream area has been divided into 6 sub-areas. Highland savannah is the main vegetation cover, while the area is underlain by Damara mica schist, quartzite and marble, with granites in the north. The flows for this site include spills from Von Bach Dam (constructed in 1970 with an upstream area of 2 920 km^2) that occurred during the second and third quarters of

1973/74 hydrological year and during January to March 1976. Only the incremental area of 5 463 km^2 was simulated for this project, but no information was supplied on the volumes of spillage from Von Bach Dam and therefore these could not be accounted for.

Vingerklip is the site of a weir on the Ugab River and the upstream catchment has been simulated with 3 sub-areas. The area is covered by mopane savannah trees and underlain by Damara mica schist, marble and quartzite. It has pronounced drainage channels in the central part and drains a flat area with relatively high rainfall. Runoff is low because some Karst formations are also present. A dam break (Omatjenne Dam - catchment area of 829 km^2) occurred in February 1985, but no information is available about the volume that passed downstream to Vingerklip.

A8.4 Calibration procedure (Pitman Model).

Mr Walto Metzler of the Department of Water Affairs in Namibia, spent 1996 as an honours student at Rhodes University and attempted to calibrate both the standard Pitman model and the new version (currently referred to as NamPit), which has a dynamic vegetation function included, as part of the work for his honours project. No real calibration procedure was established prior to this subject and both version were found to be quite difficult to calibrate for the Namibian catchments. Mr Metzler's contribution to setting up the data sets for the catchment and carrying out the trial simulations is gratefully acknowledged. Subsequently, the present author reviewed Metzler's results and developed a calibration procedure which appears to give somewhat better and generally more consistent results. The following observations led to a series of principles upon which to base the calibrations in a regional context:

- In general terms, the minimum value of the ST parameter in the original model was set to avoid runoff being generated through storage exceedence by the remaining rainfall after surface runoff and interception. Increasing ST beyond this value has no effect on the runoff and therefore cannot be calibrated. The values given in table A8.2 are therefore the minimum values.

- The ST value was kept unchanged for the NamPit model, despite the fact that this parameter can affect the time series patterns of the vegetation index.

- The usual recommendations for the use of the Pitman model suggest a value of 0.25 for the TL parameter. However, for semi-arid to arid catchments with many zero flow months this has the effect of extending the simulated duration curves (albeit in the zone of very low flows). The value was therefore set at 0.0 for both versions of the Pitman model.

- Similarly, the PI parameter is commonly set at 1.5 for natural veld (or bush). These dry catchments are known to have low vegetation cover and interception was assumed to be much lower and PI was set at 0.5 for the standard Pitman model. This was then allowed to vary between 1.2 and 0.0 for vegetation cover conditions lying between 'fully vegetated' and 'bare soil', respectively.

- If soil water runoff is not an effective process, the parameter R has a negligible effect in the original Pitman model and was set to fixed value of 0.5. To ensure that the correct interpretation of the evapotranspiration function and the likely impact of better vegetation cover were maintained, the values for R_v (vegetated) and R_B (bare soil) were set at 0.4 (more effective drying) and 0.6, respectively.

- A starting value of 2.0 was used for the power of the vegetation recession curve and only changed when there was clear indication that it would improve the calibrations when other parameters would not.

- The consequence of the above procedures is that the ZMIN, ZAVE and ZMAX parameters were the main values that were used in calibrating the original model and the equivalent values for the vegetation and bare soil catchment absorption parameters in the NamPit model. It was soon noted that the best type of triangular distribution was one which is non-symmetric where (ZMAX - ZAVE) is greater than (ZAVE - ZMIN).

- While all the statistics, as well as visual fitting criteria, were used to achieve the 'optimum' calibration, greater emphasis was placed on ensuring that the simulated mean monthly runoff was reasonably (within 5 %) close to the observed. One reason for this was because the final time series (observed and simulated) were to be used in a reservoir yield analysis (see later) and big differences in mean runoff volume would have a dominating effect.

The application of these principles simplified the calibration procedure and ensured that easier comparisons could be made between the parameter values across the 9 catchments. It is doubtful if significantly better calibrations could have been achieved if more of the parameter values were allowed to vary.

A8.5 Simulation Results (Pitman Model).

The parameters used for both versions of the Pitman model are provided in table A8.1, while the results of the Pitman, NamPit and NAMROM (Mostert, et. al., 1993 and de Bruine, et. al., 1993) model simulations are presented in table A8.2. All of the NAMROM results are based on simulated data sets provided by the Department of Water Affairs in Namibia and analyzed (in comparison with observed flows) using the same statistical comparison procedures in HYMAS as those used for the Pitman and NamPit simulated data. As with other semi-arid to arid examples, the Pitman results for log-transformed data (low-flows) are generally quite poor. The results are discussed below and compared with those obtained using the NAMROM model.

Table A8.1 List of catchments (local naming convention), model period, area, rainfall and model parameters for the Namibia catchments.

Catchment	Start Year	End Year	Months of Obs.	Area (km^2)	MAP (mm)	PEVAP (mm)	ST	ZMIN	ZAVE	ZMAX	PI	R	TL
Friedenau	1970	1990	240	212	367	3 300	260	0	380	1 200	0.5	0.5	0.0
Oanob	1970	1990	219	2 730	314	3 300	175	20	500	1 200	0.5	0.5	0.0
Etemba	1967	1990	276	3 310	345	3 100	325	10	280	1 200	0.5	0.5	0.0
Henopsrus	1969	1990	252	5 360	387	3 100	600	45	1 800	4 000	0.5	0.5	0.0
Nauaspoort	1969	1989	234	702	392	3 250	260	90	500	1 250	0.5	0.5	0.0
Otjivero	1969	1991	247	2 205	388	3 100	250	25	600	1 200	0.5	0.5	0.0
Ousema	1960	1990	350	5 355	373	3 000	375	20	350	1 250	0.5	0.5	0.0
Swakoppoort	1970	1990	240	5 463	356	3 200	480	20	450	1 500	0.5	0.5	0.0
Vingerklip	1967	1990	265	14 096	410	3 100	350	20	800	3 200	0.5	0.5	0.0
	Nampit Parameters (V = Vegetated, B = Bare Soil)						$ZMIN_V$	$ZMIN_B$	$ZAVE_V$	$ZMAX_B$	$ZMAX_B$	VPOW	
Friedenau							0	0	300	1 600	1 150	2.1	
Oanob							20	0	320	1 600	900	2.0	
Etemba							12	0	250	1 400	920	2.0	
Henopsrus							45	35	1 600	4 000	3 600	1.5	
Nauaspoort							105	90	310	1 500	1 100	2.2	
Otjivero							30	10	480	1 380	950	2.0	
Ousema							25	15	300	1 450	1 000	2.0	
Swakoppoort							30	0	400	1 900	1 100	2.0	
Vingerklip							22	0	670	3 600	2 600	1.8	

Table A8.2 Pitman model simulation results, Namibia catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Friedenau	- Obs.	137	370				4.80	1.77			
	- Pitm.	136	455	-0.2	0.59	0.38	3.93	2.80	-18.1	0.46	-0.59
	- NamPit	133	421	-2.5	0.71	0.62	4.00	2.76	-16.7	0.49	-0.46
	- Namrom	131	323	-4.1	0.74	0.74	5.60	1.23	5.7	0.58	0.55
Oanob	- Obs.	648	2 183				7.26	5.38			
	- Pitm.	643	2 632	-0.7	0.06	-0.84	5.38	2.95	-25.9	0.21	-4.79
	- NamPit	650	2 214	0.3	0.19	-1.15	6.09	2.61	-14.8	0.32	-1.49
	- Namrom	636	2 006	-1.9	0.25	0.08	7.69	0.97	2.7	0.38	0.35
Etemba	- Obs.	2 813	10 174				7.61	2.37			
	- Pitm.	2 812	9 476	-0.0	0.68	0.67	7.67	2.42	0.8	0.41	0.27
	- Nampit	2 851	9 310	1.4	0.82	0.82	7.73	2.45	1.6	0.46	0.33
	- Namrom	2 827	9 712	0.5	0.90	0.90	9.03	1.27	5.6	0.52	0.45
Henopsrus	- Obs.	105	398				5.88	1.51			
	- Pitm.	103	473	-1.4	0.64	0.49	5.73	1.28	-2.5	0.63	0.61
	- NamPit	105	466	0.4	0.73	0.62	5.80	1.26	-1.4	0.69	0.68
	- Namrom	95	624	-13.4	0.50	-0.17	5.61	1.72	-15.6	0.11	-2.83
Nauaspoort	- Obs.	145	854				5.12	2.05			
	- Pitm.	146	664	0.6	0.23	0.15	3.94	4.66	-23.0	0.17	-3.67
	- NamPit	144	697	-0.8	0.22	0.10	4.97	2.78	-6.6	0.07	-1.17
	- Namrom	148	671	2.26	0.62	0.62	6.92	1.15	15.33	0.21	-0.07

Table A8.2 (Continued) Pitman model simulation results, Namibia catchments.

Catchment		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Otjivero	- Obs.	493	2132				6.56	1.83			
	- Pitm.	500	1 894	1.5	0.43	0.37	5.70	3.06	-13.1	0.33	-1.10
	- NamPit	497	1 852	0.8	0.59	0.58	5.52	3.44	-15.5	0.29	-1.82
	- NamRom	406	1863	-17.5	0.75	0.75	7.29	1.38	0.3	0.39	0.34
Ousema	- Obs.	2 761	10 079				8.01	1.99			
	- Pitm.	2 704	10 309	-2.1	0.72	0.68	7.53	2.69	-6.0	0.53	0.09
	- NamPit	2 720	10 499	-1.5	0.80	0.78	7.55	2.70	-5.7	0.54	0.12
	- Namrom	2 711	9 190	-1.8	0.39	0.30	8.60	1.42	2.0	0.47	0.44
Swakoppoort	- Obs.	1 700	6 142				7.30	2.02			
	- Pitm.	1 709	6 442	0.5	0.57	0.49	6.60	3.33	-9.6	0.51	-0.50
	- Nampit	1 761	6 074	3.5	0.68	0.65	6.88	3.50	-5.4	0.47	-0.57
	- Namrom	1 666	5 494	-2.0	0.80	0.80	8.39	1.36	3.7	0.31	0.18
Vingerklip	- Obs.	1 569	6 939				7.21	2.08			
	- Pitm.	1 539	5 783	-1.9	0.40	0.36	6.97	2.55	-3.3	0.35	-0.07
	- NamPit	1 543	6 289	-1.6	0.66	0.65	6.69	3.24	-7.2	0.26	-0.90
	- Namrom	1 652	5 686	5.3	0.73	0.73	8.67	1.25	9.0	0.30	0.15

Note: The results for the log-transformed means and standard deviations are not easily comparable across the three models as they could be based on a different number of data values, depending on how frequently zero flows (excluded from the analysis as log values of zero are not possible) correspond in the observed and simulated time series.

Friedenau Dam:

The main problem with the calibration of the original version of the model was the difficulty of keeping the flow down for the maximum flow month, while maintaining runoff in other months, as well as the usual problem of negative serial correlation in the annual response to rainfall. The inclusion of the initial modifications (Hughes, 1995), involving the new parameters, RDF and ZAVE helped to a certain extent, while the NamPit model produced even better results (table A8.2 and figure A8.1). Despite reducing the delay parameter (TL) to zero, the model still stimulates additional months of low flows compared to the observed record (figure A8.1), a characteristic which is repeated for all of the catchments considered. It was not possible to eradicate this effect through calibration and still maintain reasonable fits to those months when low flows were observed. This is possibly related to the need for a transmission loss function within the Pitman model.

The NAMROM model appears to produce slightly better overall results, although not for the central part of the duration curve between the 5% and 30% points. The better log-transformed statistics are clearly influenced by the extended flow period (albeit at flow of less than 10 Ml month^{-1}) within the Pitman simulations that do not occur within the NAMROM data.

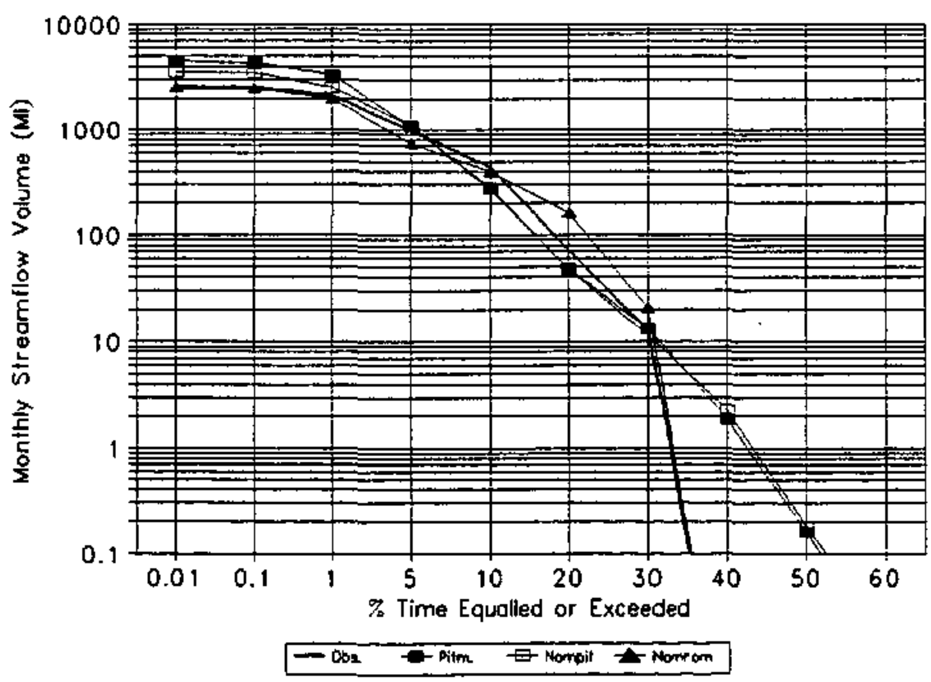


Figure A8.1 Monthly flow duration curves for Friedenau based on all available data for the period October 1970 to September 1990.

Oanob River:

This catchment was identified as a problem area by the Department of Water Affairs in Namibia, partly related to the difficulty in defining catchment average rainfall input. That was one of the reasons why the catchment was not sub-divided. The NAMROM results are certainly better than the results obtained from either of the Pitman model versions, but all three results are less than satisfactory.

Etemba catchment:

The results of this catchment (table A8.2, figures A8.2 to A8.4) were reasonably good, even for the Pitman model without the vegetation factor modification. However, the reduction of some peak flows following a wet year (e.g. 1975) that resulted from the application of the NamPit model certainly improved the results. Despite this improvement, overall the NAMPIT model still appears to generate better simulations, largely as a consequence of the fact that it does not over-simulate the number of months when flow occurs (figure A8.2). The effect of a relatively high vegetation index, on reducing simulated flow, can be seen during the 1975 hydrological year (figures A8.3 and A8.4).

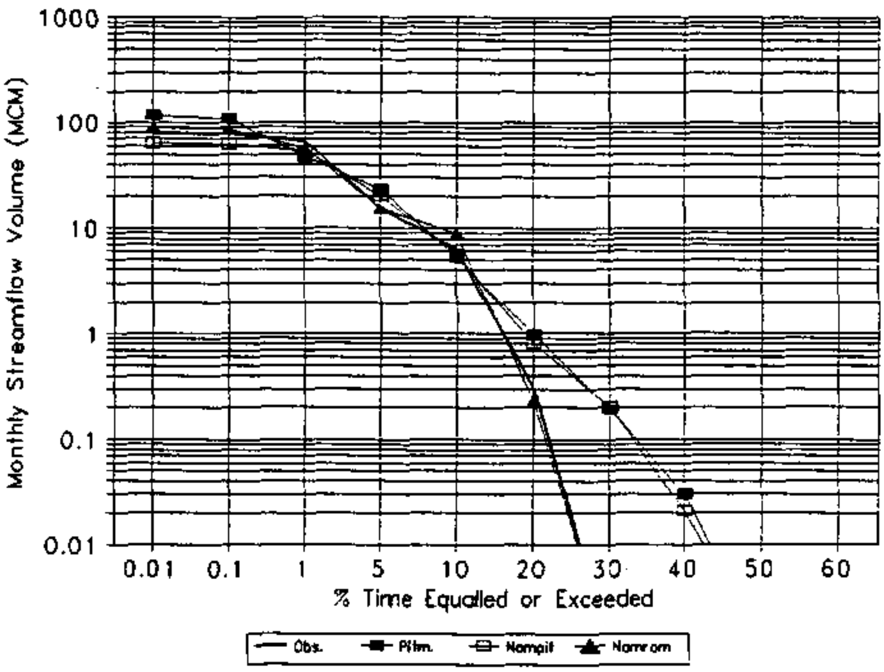


Figure A8.2 Monthly flow volume duration curves for Etemba based on all available data for the period October 1967 to September 1990.

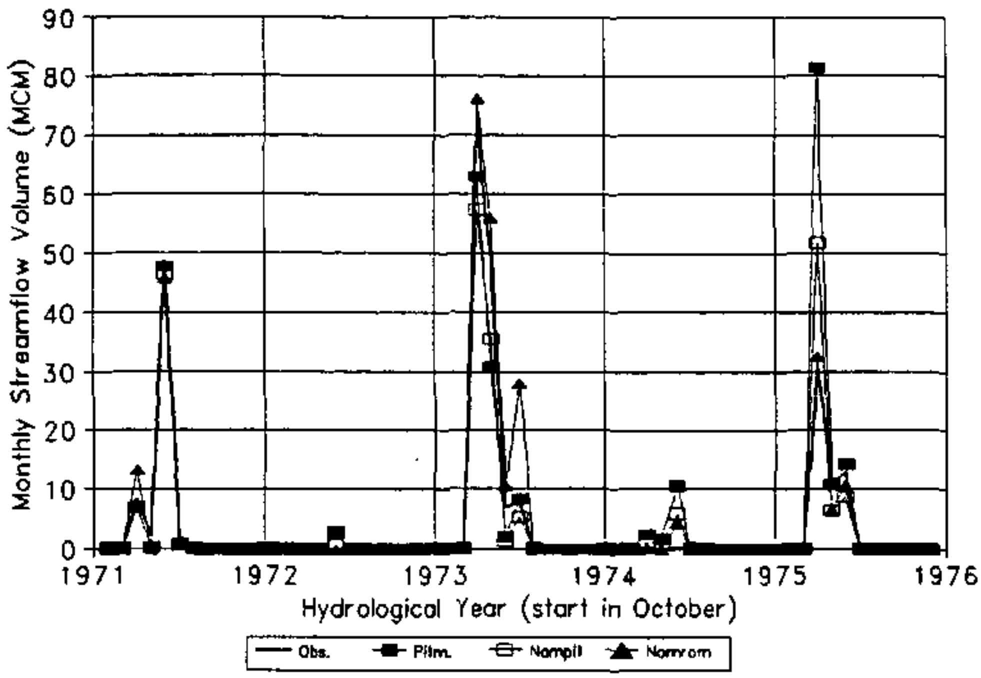


Figure A8.3 Observed and simulated time series of monthly flow for Etemba (Omaruru River) for the period October 1971 to September 1976.

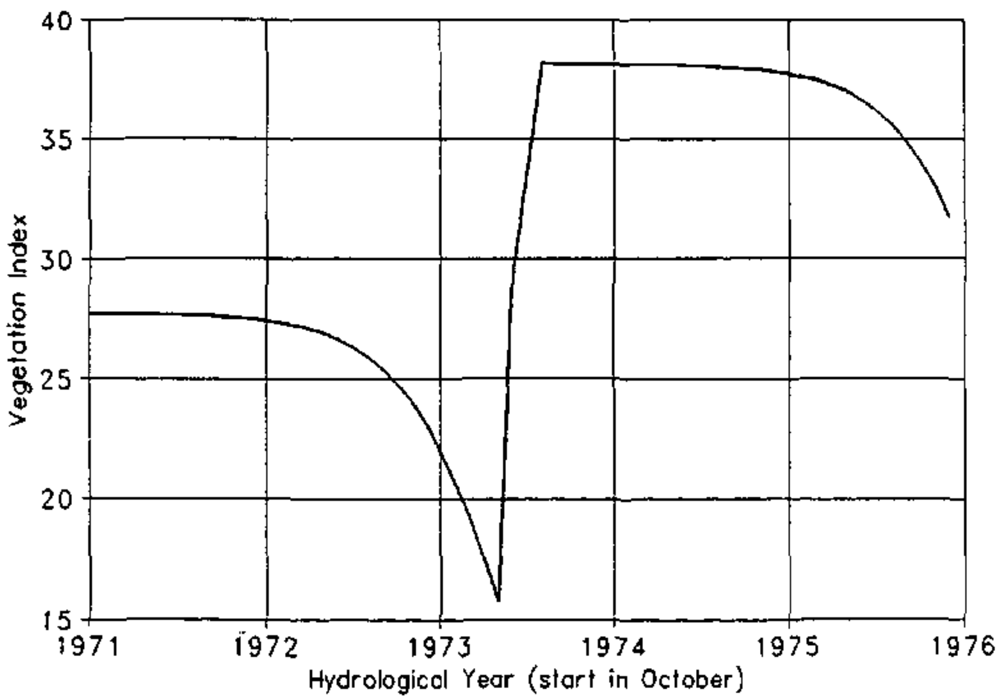


Figure A8.4 Simulated vegetation index for the period October 1971 to September 1976, Etemba catchment simulations.

Henopsrus catchment :

This is a relatively large catchment divided into only four sub-areas, has gentle slopes with grassy vegetation (de Bruine, et al., 1993) and a very low runoff response. The gentle slopes and large scale of the catchment may account for the unusually high values of the ZAVE and ZMAX parameters (table A8.1) and relatively high value of ZMIN. The implication is that less runoff is generated and, of that which is, less survives to the outlet of such a large catchment. As the Pitman model does not have a transmission loss function, the only way in which the model can deal with this situation is to generate less runoff. Unfortunately, this probably implies that the runoff volumes simulated at sub-area outlets are less than realistic (see similar observations in some Botswana catchments). Table A8.2 indicates that, despite these problems, the Pitman model (both versions) has performed better than the NAMROM model, largely due to the under-simulation of flows in the 1% to 10% range (figure A8.5). The statistics for log-transformed flows are surprisingly good considering the fact that the Pitman model simulates zero flow conditions for about 65% of the time, while the observed record suggests that this figure should be over 80%. As with the previous catchments, the NamPit model generates somewhat better results than the ordinary Pitman model, although the vegetation response parameter value of 1.5 implies less variation in vegetation cover.

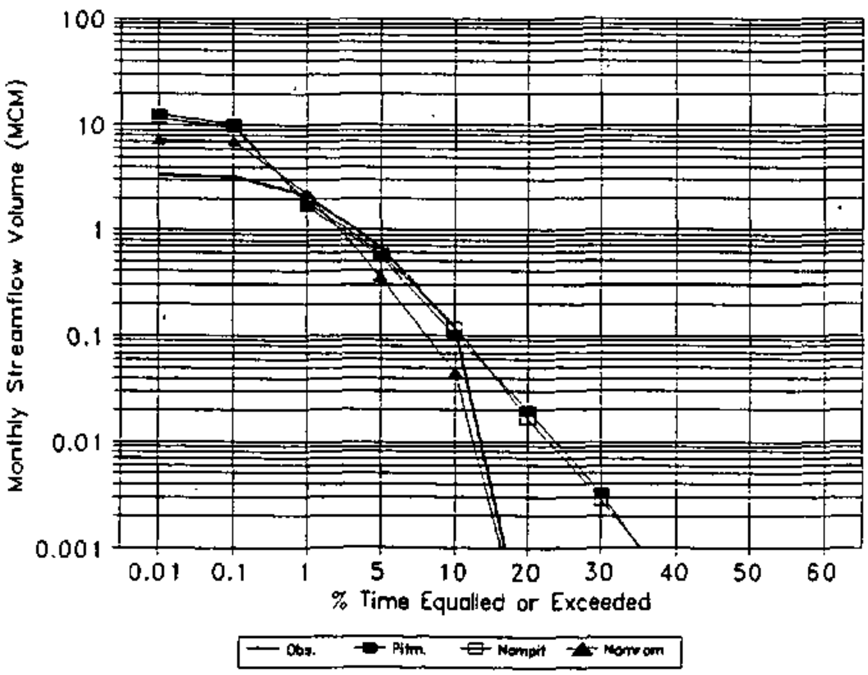


Figure A8.5 Monthly flow volume duration curves for Henopsrus based on all available data for the period October 1969 to September 1990.

Nauaspoort Dam catchment :

The Pitman model results for this catchment are very poor, particularly with respect to low and moderate flows (table A8.2). The NamPit model showed some improvement (higher standard deviation of untransformed flows and lower standard deviation of log-transformed flows), but the degree of improvement is very small compared to the much better results obtained using the NAMROM model.

Otjivero Dam catchment :

Moderate results were obtained for this catchment using the Pitman and NamPit models (table A8.2), with the NamPit simulations being somewhat better. Apart from the relatively high percentage error in mean monthly flow, the NAMROM model results are definitely better.

Ousema catchment :

The two versions of the Pitman model generated relatively good results for this large catchment which was subdivided into six sub-areas, and the NamPit model version demonstrated an overall improvement (table A8.2). The NAMROM model results are less than satisfactory, although this is not apparent from a comparison of the observed and simulated flow duration curves (figure A8.6). de Bruine, et al. (1993) indicate that this catchment lies within the Acacia savannah area in the north-east of Namibia, where the vegetation is of a more permanent nature and where possibly the advantages of the NAMROM modelling approach are less necessary.

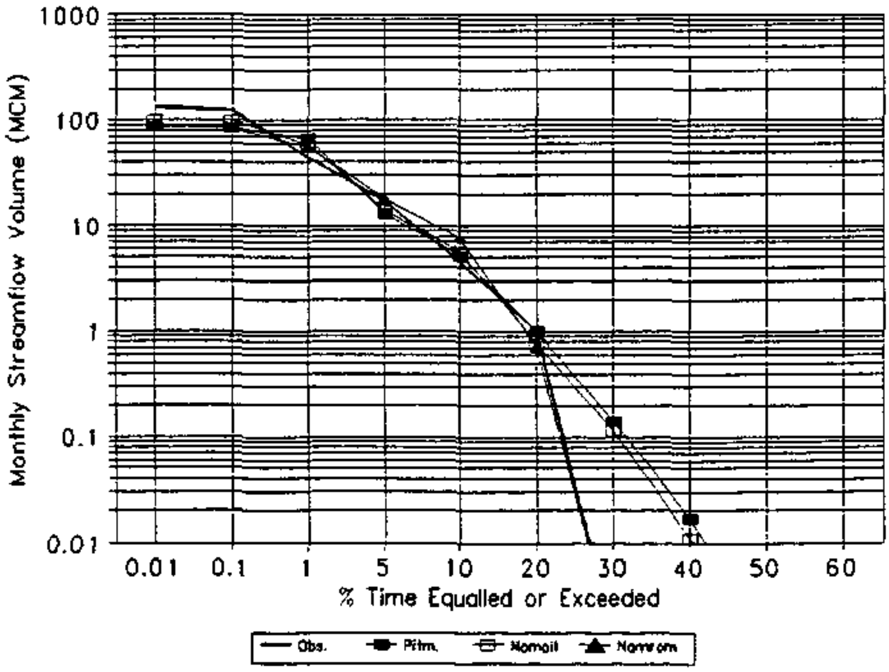


Figure A8.6 Monthly flow volume duration curves for Ousema based on all available data for the period October 1960 to September 1990.

Swakoppoort Dam catchment :

The Pitman models also performed reasonably well for this large catchment, and again the NamPit version gave the better results overall (table A8.2). This improvement is largely reflected in the closer one-to-one correspondence between observed and simulated flows and a better simulated standard deviation of monthly flows. There was, however, no improvement in the simulation of low flows. The NAMPIT model results are an improvement on both Pitman versions despite apparently over-simulating peak flows (figure A8.7).

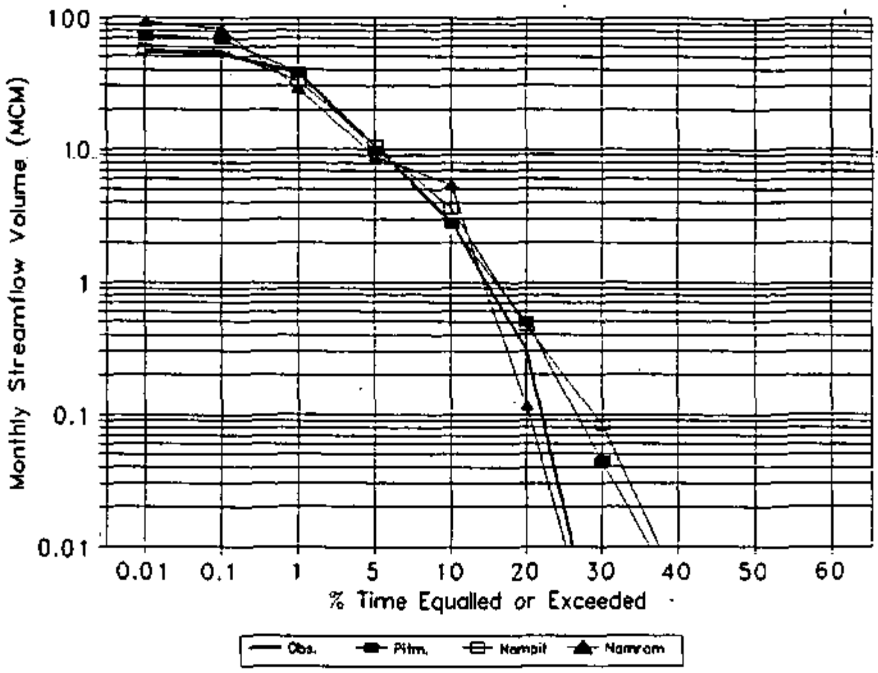


Figure A8.7 Monthly flow volume duration curves for Swakop based on all available data for the period October 1960 to September 1990.

Vingerklip catchment :

This catchment is the largest of all those used in the project and, in similar to the Henopsrus catchment appeared to require a high value for ZMAX and a relatively high value for ZAVE to achieve reasonable calibration results for the Pitman model versions (table A8.1 and A8.2). As with nearly all the other catchments, the NamPit model demonstrates improved results over the earlier version of the Pitman model, while the NAMROM model appears to give the best results.

General Observations about the Pitman Model calibrations.

Table A8.1 indicates that there is quite a high degree of stability in the value of parameter ZMAX except for the two catchments Henopsrus and Vingerklip, where much higher values appeared to be necessary to allow for greater losses. Unfortunately, the same is not true for ZMIN and ZAVE and the values of these parameters (particularly ZAVE) are very different for most of the catchments. The ZAVE parameter has a large influence on runoff generated during high rainfall months and it is possible that some of the differences in the value of this parameter are related to inaccuracies in the definition of catchment average rainfall input. While the approach of using multiquadratic surfaces is undoubtably as good as any other that could be suggested, it is still dependent upon the spatial representativeness of the point gauge data. To establish a raingauge network that is truly representative is almost impossible in a semi-arid area dominated by spatially varying convective rainfall. The variations in the value of the parameter ST are largely related to the way in which this parameter was calibrated. It was set at approximately the smallest value that ensured that excessive runoff was not generated through rainfall (after interception and surface runoff) exceeding available storage. This value could then be strongly influenced by the maximum amount of rainfall during the period of record used.

Similar comments about parameter stability across the catchments can be made with respect to the NamPit model. The ST parameter values were kept the same as for the original version, although it was recognised that this parameter has an influence on the way in which the vegetation index varies over time. Most of the values of the power parameter of the vegetation recession curve could be kept at 2.0, but there is no adequate explanation for those situations where a lower or higher value gave improved results. Similarly, the two ZMIN and ZMAX values (for vegetated and bare soil conditions) differ quite substantially across the range of catchments used.

A8.6 Assessment of reservoir yield.

To assess the impacts of the various simulated time series of runoff volume on the planning of a water resource scheme, the Friedenau Dam (fully supply capacity of 6.72 MCM) and catchment has been used as an example. The monthly reservoir simulation model (part of HYMAS) has been set up for Friedenau Dam using the observed inflow sequence and observed dam volumes for 1970 to 1990. Rather than entering the observed abstractions, which vary quite substantially over this period and are not available for the whole period, a mean representative annual volume of abstraction (100 Ml), evenly distributed over the year has been used. The actual abstractions varied between zero and close to 13 Ml month^{-1}. Table A8.3 lists some of the statistics of correspondence between observed and simulated dam volumes, for the period 1974 to 1990, given observed inflows and inflows simulated by the three models (Pitman, NamPit and Namrom). The starting year of 1974 has been used because it follows a wet year when the dam reached full capacity. This avoids the necessity to accurately estimate the starting volume of the dam at the beginning of the simulation.

Table A8.3 Simulation results of Friedenau Dam for the period 1974 to 1990 with inflows determined by different methods.

	Mean monthly Dam volume (Ml)	St. Dev. monthly Dam Volume (Ml)	Coeff. of Determination (R^2)	Coeff. of Efficiency (CE)
Observed Dam Volume	3 594	1 502		
Observed inflows	3 874	1 445	0.98	0.95
Pitman inflows	3 775	1 597	0.19	-0.21
Nampit inflows	4 235	1 384	0.28	-0.06
NAMROM inflows	3 807	1 117	0.88	0.82

The high R^2 and CE values resulting from the use of observed inflows indicate that the other parameters of the reservoir simulation model have been reasonably estimated despite the fact that the pattern of abstractions has been smoothed. Table A8.3 also emphasises the fact that the NAMPIT inflow simulations are much better from the point of view of correspondence wit observed flows for individual months. Both the Pitman and NamPit models tend to over-simulate the flows during the mid- to late 1970s (following the early 1970s wet period) and under-simulate the inflows during the 1980s.

Table A8.4 lists some of the results of applying longer simulated inflow records (1920 to 1990) to the same reservoir model setup, to determine what impacts the different simulations would have on the estimated long term yield of the dam.

Table A8.4 Yield simulation results with an extended inflow period (1920 to 1990). The reliability is based on the percentage number of months in the record when the required draft was totally satisfied.

Model used for simulated inflows	Mean annual inflow volume (Ml)	Mean annual net evaporation (Ml)	Mean annual spillage (Ml)	Mean annual shortfall (Ml)	Reliability	
					Wet Season	Dry Season
Required draft = 200 Ml a^{-1} or approximately 14 % of mean annual inflow.						
Pitman	1 294	991	121	4.4	97	95
NamPit	1 382	1 068	108	1.6	100	98
NAMROM	1 439	1 080	161	0.7	100	98
Required draft = 500 Ml a^{-1} or approximately 35 % of mean annual inflow.						
Pitman	1 294	807	86	70.3	92	80
Nampit	1 382	854	75	36.4	95	85
NAMROM	1 439	875	103	20.3	98	91

The table indicates that for relatively low required drafts, there is very little difference between the NamPit and NAMROM models as planning tools for reservoir design, but as the required draft increases, the NAMROM model will predict a higher level of reliability. While this results is partly attributable to the somewhat higher mean annual inflow volume predicted by the NAMROM model, it must also be related to other characteristics of the flow time series. Given that the NAMROM model appears to be able to simulate observed flow patterns more accurately, based on the 1970 to 1990 period, the indications are that the longer period simulations for this model present the most accurate impression of yield reliability. Certainly, the deficiencies in the pattern of simulated flows given by the Pitman model are such that yield estimates would be too low.

A8.7 General Conclusions.

In general terms the NAMROM model appears to generate more representative time series of monthly flow volumes than either of the Pitman model versions. In some catchments the NamPit model is almost as successful and in two it is better. The revised version of the Pitman model can certainly be considered an improvement on the original and has allowed at least some of the effects of negative serial correlation to be accounted for. With respect to the regionalisation of parameter values, none of the models emerge as a clear favourite and it would seem that standardising parameter values across groups of catchments is not possible at this stage, indicating that parameter estimation for ungauged sites remains a problem for the future.

In many arid to semi-arid water resource problems the accurate simulation of individual months flow volumes may not be the most important issue, as long periods of very low or zero flows imply that relatively high volumes of storage are required to satisfy relatively low yields (for example, Friedenau Dam with full supply storage capacity or about 4.7 *MAR with a moderately reliable yield of about 0.2 *MAR). The implication is that the reservoir is able to smooth the effects of individual months inflows to the extent that the accurate reproduction of monthly flows are less important than simulating other, longer term, characteristics of the flow regime. The sample analysis carried out for the Friedenau Dam suggests that the issue of accurate simulation of individual monthly flows will only become important at higher required drafts, relative to the mean inflow. It is unfortunate that more reservoir data were not available to allow the reservoir yield simulation exercise to be repeated for the other sites.

One issue that has not been addressed is related to the influence of using mean monthly pan evaporation values in the simulations rather than historical time series of actual pan values. It is unlikely that the impact on the catchment simulations will be very great, as the runoff generations is dominated by surface processes, which are largely independent of the moisture status of the catchment. However, the reservoir simulations could be affected.

Appendix A9 LESOTHO Catchments

Lesotho is drained by three main tributary catchments of the Orange (Senqu) River; the Senqu (20 710 km^2) flowing from the mountain regions of the country, the Makhaleng (3 050 km^2) flowing from the Maluti foothills and joining the Senqu on the South African side of the border and the Mohokare (Caledon - 6 950 km^2 within Lesotho) which forms the north-western border with South Africa.

While flow data were provided to the FRIEND project and rainfall data are available for some stations within Lesotho, no rainfall-runoff modelling exercises were carried out during the course of this project. There were two reasons for this. Firstly, the main drainage areas of the Senqu have been the subject of intensive monthly modelling studies in recent years as part of the Lesotho Highlands Water Project (LHWP) and it was considered unnecessary to repeat that work. Secondly, from the point of view of daily modelling, there are very few raingauges in the mountainous parts of Lesotho and it was initially thought that it would be very difficult to adequately represent spatial and temporal patterns of catchment rainfall inputs at the daily scale.

This section of the report is therefore confined to summarising the experience of the application of the Pitman model to a number of tributaries of the Senqu that was undertaken as part of the LHWP (1986) and providing some limited results of the application of the daily 'patching' model to several stations within the country.

A9.1 LHWP Pitman model experience.

During the course of the LHWP hydrological studies it was noted that several anomalies had been identified in the Lesotho river flow measurements and that these contributed to a great deal of confusion during the initial stages of the LHWP feasibility study (LHWP, 1986). The report serves to illustrate and emphasise the importance of accurate flow gauging records and the effort required to re-process and check records that are considered to be erroneous. The report also represents one of the most in-depth studies of the potential errors in different flow recording systems ever carried out within the southern African region and places into context, the accuracy of all the flow data that has been used in the Southern African FRIEND project - most of which has probably never been subject to the same level of accuracy checking.

The Pitman model studies reported in LHWP (1986) used 8 gauges on the River Senqu and 2 on the Sequnyane. The rainfall input to the catchments was based on weighted averages of several raingauges close to the catchments, where the weighting factors were determined from correlation coefficients between the rainfall and runoff records and an assessment of the mean annual catchment rainfall from an isohyetal map.

The Pitman model was slightly modified during the LHWP and these are summarised below.

Evaporation losses :

The report suggests that the original model has some inconsistencies in the way in which the net evapotranspiration demand (after part of the potential demand is satisfied by interception) is applied to calculate losses from soil moisture storage. The suggested modification reduces evapotranspiration from soil moisture by an amount equal to the interception loss. The version used in the FRIEND project assumes that the potential demand is partly satisfied by the evaporation from interception storage and that the net demand, applied to losses from soil moisture, is reduced accordingly such that no inconsistencies can occur. The potential problem with the LHWP modification is that if the interception storage is high and the soil moisture level low, the evaporative losses from interception could exceed those from the soil. This would mean that no evaporation from the soil would take place.

Loss rates from soil moisture :

The modified model corrected some inconsistencies in loss rates from soil moisture when the soil moisture capacity was exceeded.

Soil moisture balance :

The LHWP report suggests that the original method of balancing average loss rates over a period with the volume of storage did not give a true water balance. The revised model added an iteration procedure to ensure a water balance.

Groundwater flow :

The original model lags soil and ground water flow separately but the lagging method limits the lag times to a maximum of 1 month. The modification uses a ground water storage which has the same characteristics as the soil moisture storage. Runoff from ground water is then simulated using a similar power relationship as that used for soil moisture runoff. This therefore represents an attempt to include a more explicitly defined ground water component in the Pitman model and, while adding a further four parameters (the equivalents of ST, SL, FT and POW) could be very useful. There are several examples in the previous appendices where a more independently responding ground water response might have improved the simulations.

Seasonality :

Seasonality in interception loss and catchment absorption rates were added by weighting the parameters by the ratio of monthly potential evapotranspiration to the maximum value. Seasonality is accounted for in the version used in the FRIEND project through winter and summer extreme parameter values and a monthly distribution.

The model appears to have been operated with a lumped distribution system for all the catchments and no attempt has been made to account for spatial variations in rainfall or catchment response. Table A9.1 provides some details of the catchments used, while table A9.2 lists the calibrated parameter values. It should be noted that the FT values are frequently less than the GW values, which is not possible in either version of the model if these parameters are interpreted in the normal way. It must therefore be assumed that the actual value of FT is the sum of the tabulated values of FT and GW.

Table A9.1 Catchments used in the LHWP modelling study (the mean annual rainfalls - MAP and runoffs - MAR, have been taken from Schultz, 1994).

Catchment Name (River)	Lesotho Code	Area (km^2)	Records	MAP (mm)	MAR (10^6 m^3)
Bokong (Bokong)	G41	403	1971 ->	930	108
Pelaneng (Malibamatso)	G45	1157	1972 ->	1013	447
Seshotes (Matsoku)	G42	652	1970 ->	759	99
Paray (Malibamatso)	G08	3240	1966 ->	872	761
Mokhotlong (Mokhotlong)	G06	1660	1964 ->	908	286
Tlokoeng (Khubala)	G36	852	1969 ->	924	145
Koma-Koma (Senqu)	G05	7950	1966 ->	847	1471
Tsoelike (Tsoelike)	G07	797	1963 ->	791	142
Marakabei (Senqunyane)	G17	1087	1964 ->	1040	351
Nkaus (Senqunyane)	G32	3480	1967 ->	808	680

The report (LHWP, 1986) also provides comparative parameter values for the original model version for catchments G05 and G08, but unfortunately the values given in the separate table (just the two catchments) for the modified version are not consistent with those given in the main table (all catchments). It is therefore difficult to draw any sensible conclusions. Regional parameter values consistent with the original model are provided in the Surface Water Resources of South Africa 1990 and the main differences are that ZMIN and ZMAX are not used (i.e. no surface runoff generated), the ST value is recommended to be 40 mm, POW to be 3.0 and FT to be 18 mm. These are not substantially different to the values given in table A9.2 and are expected to give similar results. The exclusion of the surface runoff function means that no runoff is generated as a direct result of high monthly rainfall totals. However, the ST value is very low, suggesting that it will be exceeded regularly producing a relatively peaked monthly flow regime.

Unfortunately, the model results are not provided in the main report (and the relevant data volume was not made available) for all the catchments and therefore it is difficult to assess the performance of the model. However, one set of results (1967 to 1983) for G45 is included. The percentage error in simulated MAR was -0.7, coefficients of determination (R^2) and efficiency were both 0.77.

Table A9.2 Model parameters (LHWP modifications). The parameters for G08, G05 and G32 represent the simulations for the incremental areas below all upstream gauges (SG, SGL, FG and POWG are the ground water storage equivalents of ST, SL, FT and POW, while RFACT is a correction factor to adjust catchment rainfalls)

Parameter	G41	G45	G42	G08	G07	G36	G05	G07	G17	G32
AI	0	0	0	0	0	0	0	0	0	0
PI	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
POW	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
ST	40	33	75	90	70	55	58	45	27	62
SL	0	0	0	0	0	0	0	0	0	0
FT	10	5	20	15	5	3	5	5	5	10
R	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
ZMIN	45	90	45	45	45	90	65	45	45	45
ZMAX	450	300	450	450	450	450	450	450	500	450
GW	20	10	0	0	0	5	5	0	5	0
POWG	2.5	2.5	0	0	0	2.5	2.5	0	2.5	0
SG	100	100	0	0	0	100	120	0	100	0
SGL	0	0	0	0	0	0	0	0	0	0
FG	10	5	0	0	0	5	2	0	10	0
TL	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
GL	0	0	0	0	0	0	0	0	0	0
RFACT	1.00	1.00	1.00	1.00	0.92	0.91	1.00	1.00	1.05	0.90

A9.2 Application of the daily 'patching' model.

The daily Patching model was applied to all data up to September 1995 for the stations G41, 42, 45, 05 and 08; i.e. those that are on the main stem of the Malibamatso River and its tributaries and the station on the Senqu River just below the confluence with the Malibamatso. Figure A9.1 illustrates the location of these catchments, while table A9.3 provides the matrix of stations that were used to patch the data from the gauges referred to in column 1, as well the weights used for each substitute station.

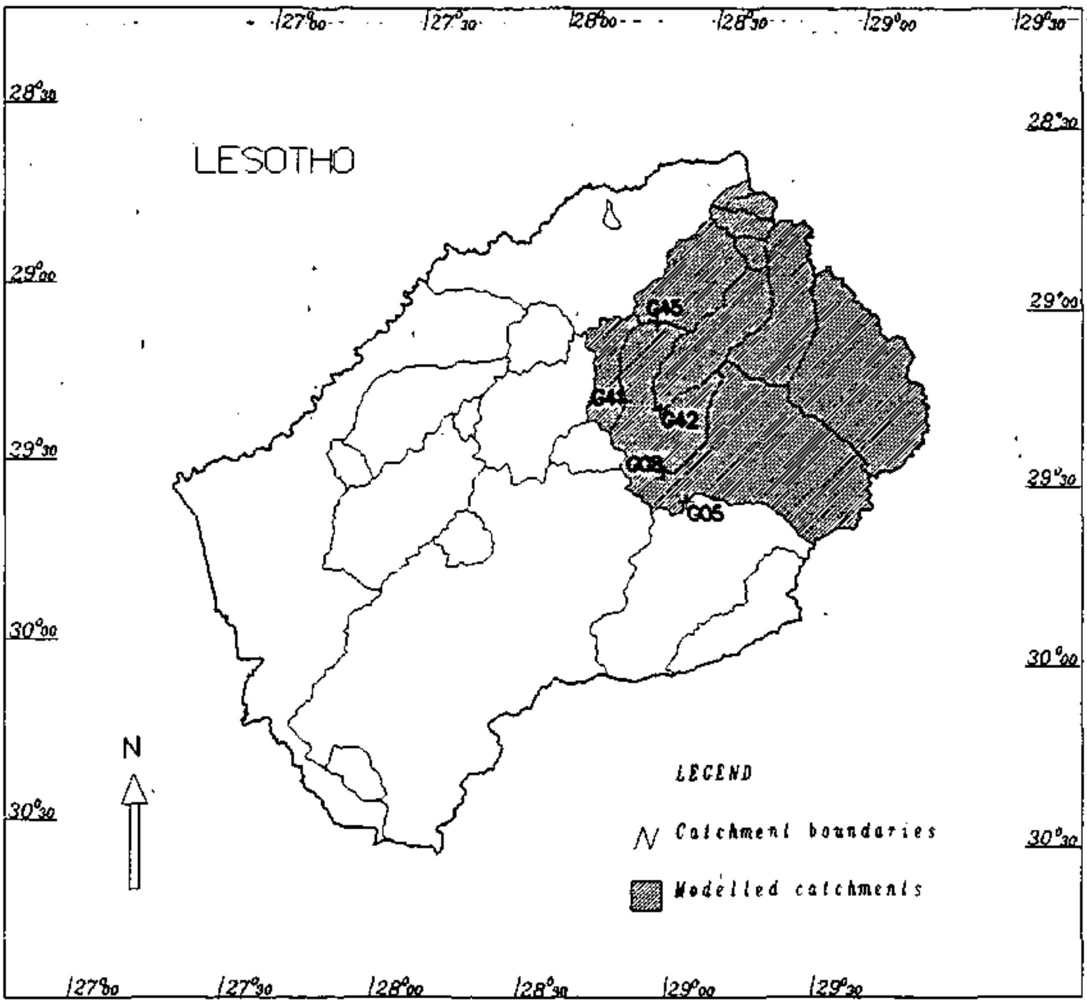


Figure A9.1 Gauged catchments within Lesotho and those used with the Patching model.

Figure A9.2 illustrates that the response characteristics of the catchments are very similar (using standardised 1-day flow duration curves for all months of the year) and suggests that the patching model exercise should be, at least, relatively successful. Table A9.4 illustrates that in terms of low to medium flows (based on logarithm transformed statistics) the results are excellent and that the model is certainly suitable for extending or patching streamflow records within this region. Most of the results are satisfactory from the point of view of higher flows as well, although the high flows on the three smaller catchments (particularly G41) are less than well simulated. This problem is the cause of the low CE values. A more detailed inspection of the daily flow hydrographs reveals that the problem is almost exclusively with the highest flows of each month and is partly related to an inherent problem with the model. The patching is based on the use of the calender month duration curves which are constructed from observed data. The number of non-missing data points available in the records for G41, 42 and 45 is such that the duration curves for percentage points less than about 0.2% have to be estimated and this is done in the model by a simple extrapolation procedure. Application of the model to other catchments has already demonstrated that this can cause a problem, particularly when the extrapolation produces a relatively steep line for some catchments (G41 in this example) and a much flatter one for others (G42 and G45). The result is that when the two sets of duration curves are used to transform flows from the source to the destination station, peaks can be highly over- or under-estimated.

Table A9.3 Patching model parameters (see section 2.6.2 in this report)

Catchment	Substitute Stations							
	1	Weight	2	Weight	3	Weight	4	Weight
G05	G08	0.6	G42	0.3	G45	0.3		
G08	G45	0.5	G42	0.2	G41	0.2	G05	0.1
G41	G45	0.5	G42	0.4	G08	0.1		
G42	G41	0.45	G45	0.45	G08	0.1		
G45	G41	0.45	G42	0.45	G08	0.1		

There would therefore appear to be a great deal of potential for making use of the patching model to extend and fill some existing streamflow records for the Lesotho highlands catchments. Given that regionalised, non-dimensional, flow duration curves can be generated and dimensionalised using estimates of mean annual runoff, the model may also be useful for obtaining approximate daily time series at ungauged sites. This latter aspect of the application of the model is currently being investigated within the IWR at Rhodes University. This is an encouraging conclusion, given that the availability of suitable rainfall stations in this very mountainous area is very limited and therefore it will never be a simple task to generate adequately representative catchment rainfall inputs to daily rainfall-runoff models.

Table A9.4 Patching model simulation results, Lesotho catchments (based on a comparison of observed versus completely substituted daily streamflows).

Catchment		Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Senqu (G05)	- Obs.	45.3	113.0				2.55	1.62			
	- Sim.	43.9	108.7	-3.3	0.81	0.81	2.50	1.59	-2.0	0.87	0.87
Malibamatso (G08)	- Obs.	24.2	56.8				1.85	1.77			
	- Sim.	25.0	57.6	3.3	0.83	0.82	1.99	1.71	7.6	0.89	0.88
Bokong (G41)	- Obs.	3.6	11.2				-0.14	1.77			
	- Sim.	3.8	14.1	4.4	0.40	0.02	-0.16	1.81	-12.5	0.83	0.82
Matsoku (G42)	- Obs.	3.3	8.6				-0.36	1.87			
	- Sim.	3.3	9.0	0.0	0.57	0.48	-0.36	1.82	0.0	0.82	0.82
Malibamatso (G45)	- Obs.	14.4	36.7				1.35	1.73			
	- Sim.	14.9	34.0	3.5	0.64	0.64	1.45	1.71	7.4	0.87	0.87

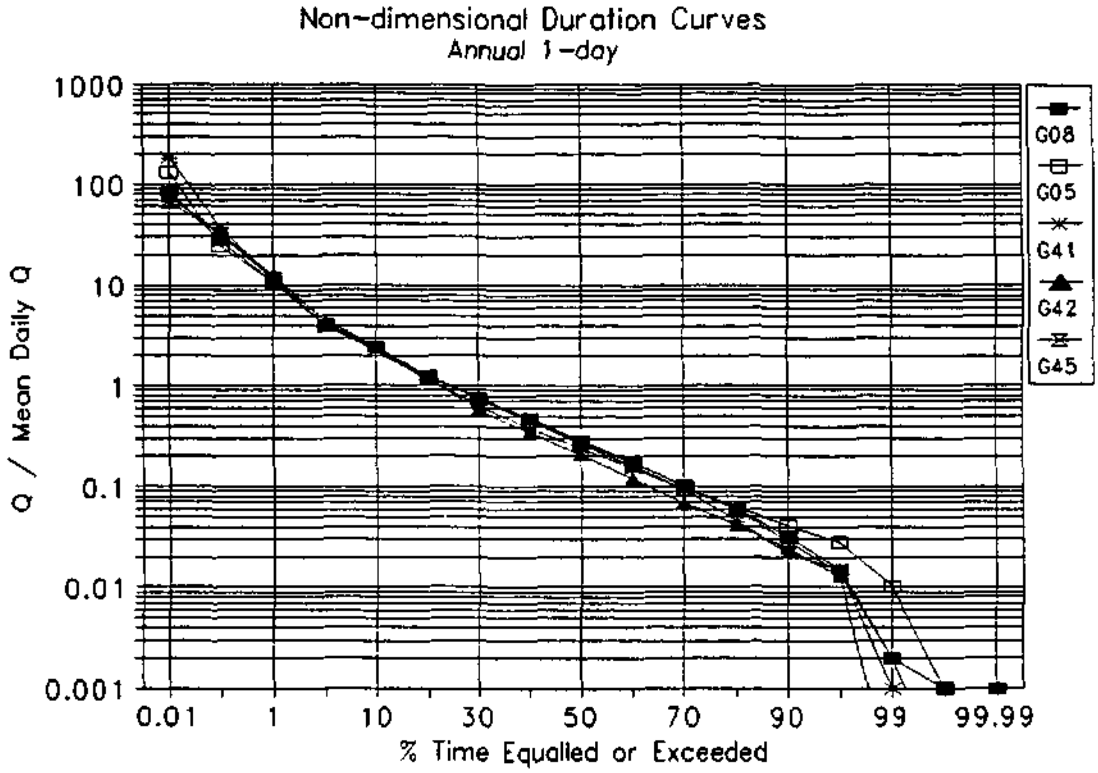


Figure A9.2 Non-dimensional 1-day flow duration curves for the five Lesotho catchments referred to in table A9.3

Appendix A10 SOUTH AFRICA Catchments

During the course of the FRIEND project, other modelling work on South African catchments was being carried out within the Institute for Water Research for the benefit of several research and consultancy projects. One of the more long term programmes was the 'Low Flow' project (Smakhtin and Watkins, 1997) and many of the simulation results are discussed in that project's final report. Some of the shorter term projects were related to the need to provide daily streamflow data for the purposes of Instream Flow Requirement (IFR) workshops or other consultancy work. Consequently, a great deal of experience has been developed in the application of the VTI and Pitman models.

Most of the simulations using the Pitman model have been carried out following the guidelines provided by the various volumes of the Water Resources of South Africa 1990 (WR90, 1994) and, in general terms, using very similar parameter sets. The main differences have occurred when the model has been applied to catchments which are substantially smaller than the scale of the quaternary catchments used in WR90 and specifically when there are big differences in catchment or rainfall characteristics within a quaternary area. Guidelines on how to modify the recommended parameters for simulating smaller catchments have yet to be developed and it is unlikely that any generalised relationships will be forthcoming. It is largely a matter of careful and experienced use of the model and interpretation of the recommended parameter values.

This section of the report will therefore only deal with the VTI model and will not discuss all the South African results to the same level of detail as for the other countries. This appendix will mainly try and summarise the experience of applying the model to different parts of South Africa, identifying any problem areas or special issues that need to be considered in the application of the model. The South African catchments that have been used are illustrated in figure A10.1, which also includes those used for the landuse change impact modelling.

The results that are presented have been achieved from regional applications of the model to more than one gauged catchment within a drainage area. The parameter value calibration exercises have therefore been carried with this in mind and frequently, values determined for one catchment or sub-area have been transferred to others with similar characteristics and no repeat calibrations carried out. Similarly, it is usual for a period of about five years to be used for calibration, while the results reflect the whole period available. Consequently, the results discussed below relate to both calibration and validation situations in terms of catchments and periods.

A10.1 General comments on data availability within South Africa.

Daily flow data are available from the Department of Water Affairs and Forestry (DWAF) for over 1500 stations throughout the country. Most of these are based on gauging structures, although a few rated sections are used. Many do not have the flow capacity to record large events and have relatively wide low flow widths, suggesting that low flows may not always be accurately estimated. However, DWAF also have a programme of continuously updating their records and re-rating some of the older structures. Much of the flow data collected from before the 1960s were based on manual stage plate observations, while subsequent to that, most of the mean daily flow data are based on digitised autographic charts which should provide more realistic estimates.

Daily rainfall data are collected in South Africa by various organisations, the Weather Bureau and the Department of Agriculture being the two main groups. Most of the available data is also stored at the Computing Centre for Water Research at the University of Natal, Pietermaritzburg, where on-line access is possible. The Department of Agricultural Engineering at the same University has also produced a 1' * 1' grid of median and mean monthly rainfalls for the entire country (Dent, et al., 1989), which can prove extremely useful in catchment modelling studies. The available raingauge station data are of variable lengths (some extending back into the previous century) and have variable amounts of missing or bad data. It is often a problem to find a group of stations within the same area that have coincident records that are also coincident with the flow records in the same region. However, in general terms, South Africa is reasonably well endowed with long time series of daily rainfall, except in some remote arid and mountainous areas.

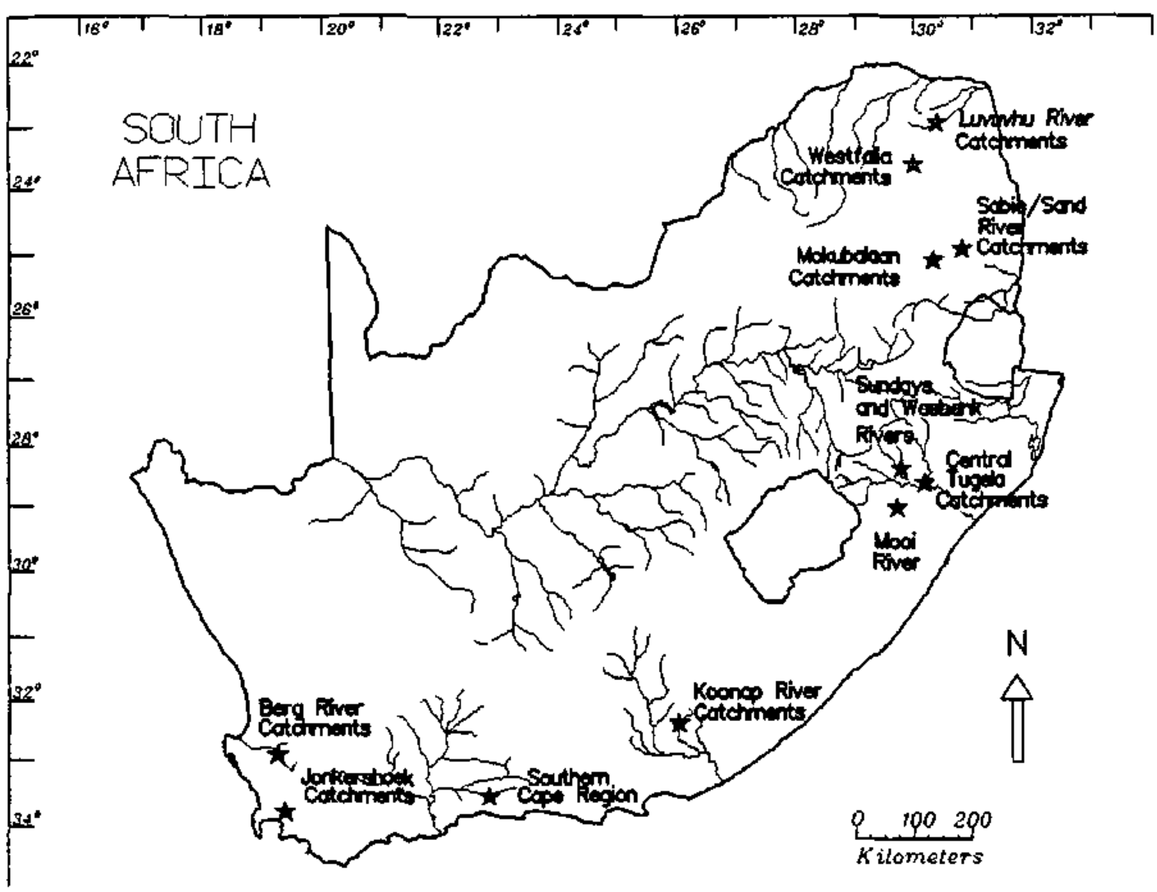


Figure A10.1 South African catchments used in this study.

Daily and monthly pan evaporation data (mixed S and A pan) are available for a number of meteorological stations, but the records are often short and incomplete and not always very useful as time series. They do, however, allow a reasonable impression of regionalised mean monthly pan evaporation to be developed. Schulze and Maharaj (1991) have also created a 1' * 1' gridded database of mean monthly A-pan equivalent evaporation values for the whole country.

There are many areas where detailed catchment descriptions are available through basin studies carried out by consultants to DWAF or other reports. There are also many other sources of soils, ground water and vegetation information for various parts of the country, although some of this is not available free of charge.

In general terms, South Africa is well covered by both hydrometeorological data and the necessary supporting information that is required for catchment modelling exercises. However, this information is not always well documented and a potential user often has to be familiar with the various sources to be able to recognise the existence of the data and how to access it.

A10.2 Southern Cape region.

These are all relatively steep catchments draining the Outeniqua Mountains and the three gauging stations are located at different points within the catchments of three rivers (Hughes and Görgens, 1981; Hughes, 1982 and Hughes and Filmalter, 1994). One is located in the headwaters, one in the middle reaches and one in the lower reaches. This arrangement has allowed the catchments to be sub-divided into between three and four sub-areas and the observed data used to assist with calibrating suitable parameter values for the different sub-regions of the catchments.

One of the problems, common to many mountain areas is the relatively high degree of spatial variability of rainfall (Hughes and Wright, 1988) coupled with a low raingauge density, particularly where rainfall gradients are steepest in the areas that are generally inaccessible. The spatial rainfall variations are frequently variable in time as well, such that there is rarely a consistent relationship between rainfall at one point compared to another. This makes it quite difficult to establish any adequate gauge-to-catchment rainfall weighting procedures. The 1'*1' gridded median monthly rainfall database has been used to compile the weights, but there are some problems in parts of the upper mountain areas where the rainfall is known to be high (> 1000mm) but the grid database suggests much lower values (closer to 800mm). This is largely due to the interpolation method used to generate the gridded data, which is affected by rainfall stations in rainshadows at high elevations on both sides of the mountains.

In terms of the observed flow data, the main problem is that the gauges are not able to measure over the full range of high flows experienced and there is a degree of truncation of flood events.

Despite these problems, the results are reasonably satisfactory with observed and simulated duration curves being very close to each other. Coefficients of determination and efficiency for un-transformed data are between 0.5 and 0.6, a reflection of the fact that some observed events are missed, while some simulated events do not have corresponding observed responses (related to the rainfall input problem). The flow regime is quite 'flashy' and the rainfall occurs throughout the year. There is no real seasonal baseflow response and baseflows are more related to individual events, with relatively low flows between events. The statistics of correspondence based on log-transformed data are therefore very similar to those based on un-transformed data.

The catchments are underlain by sandstones in their upper reaches and by granites, phyllites, schists and shales in the lower reaches. The ground water response in the upper, steeply sloping topography has been simulated as springs, which seems to be consistent with field observations, while intersection of the water table with the ground surface has been assumed to occur in the lower areas. The soil parameters used in the models are also consistent with descriptions of soils provided for the area (Schafer, 1991). The vegetation cover and landuse in the catchments vary between natural fynbos bush, dense indigenous forest, managed pine plantations and farming land (pasture and cultivated). All of these characteristics have been properly represented by the model parameters. The general shape of individual hydrographs is simulated quite well in most cases and it has been concluded that the model is more or less simulating the correct balance of runoff generation processes (surface, soil and ground water responses).

A10.3 Berg River catchments.

The Berg River basin, in the Western Cape Province, has its source in the Franschoek/Drakenstein Mountains and flows north and northwest until it reaches the Atlantic Ocean approximately 130 km north of Cape Town. The catchment area at the point of the lowest gauging station is 4012 km^2 and all the area above this has been simulated using the VTI model. There are a large number of gauges (29 with catchment areas varying between 1.7 and 2934 km^2) in the upstream areas against which to calibrate the sub-catchment parameter values and assess the simulation results on a regional basis.

Rainfall varies from 400-500mm in the middle to lower reaches, but can exceed 2500mm in the high lying areas of the Groot Drakenstein, where rainfall gradients are steep and spatial variations apparently quite high. There are certainly not a sufficient number of raingauges to represent the variations in the mountain areas and one of the observations made during the modelling exercise was the extent to which this might affect the results for the basin as a whole.

The mountain areas are underlain by quartzitic sandstones, while lower down these give way to shales. Mountain soils are predominantly shallow sandy loams, while in the flatter parts of the basin the soils are moderate to deep clayey loams. Fynbos bush covers a large part of the steep and uncultivated land with plantation forestry being also quite widespread. The remainder is primarily used for wine and fruit farming. Irrigation is widespread, with water taken from either the large number of farm dams or directly abstracted from the river. The streamflow regimes are also affected by several major impoundments and abstractions for water supply to the Cape Town area.

The total area was divided up into 5 modelling 'projects' each one having a gauge at the downstream end and several internal gauged sub-catchments. The gauged sub-catchments represent a wide variety of conditions, from purely mountain catchments, through combined mountain and lowland areas to only lowland areas with flatter topography and lower rainfalls. They also represent a variety of topography, landuse, soils and climate assemblages.

The results were highly variable, as might be expected with the number of uncertainties associated with defining both the rainfall input and the patterns of water use and abstractions. Low flows for the majority of the catchments were quite well simulated with log-transformed coefficients of determination normally between 0.7 and 0.8 and coefficients of efficiency only slightly less. Simulation of individual events within the record was less successful, despite the fact that the general shapes of event responses (short term recessions, for example) was usually adequate. Further details of the overall modelling exercise is provided in Smakhtin and Watkins (1997), who also identify the problem of ill-defined transmission losses in the downstream parts of the catchment.

A10.4 Koonap River catchments.

The Koonap River rises in the Winterberg Mountains of the Eastern Cape Province and flows toward the much drier areas closer to the coast. Two gauges are located on the river, one in the upstream reaches (489 km^2) and one quite close to the confluence with the Great Fish River (1245 km^2). The vegetation cover is largely grassland, with some areas of bush and the area is mainly used for grazing, although irrigated lands exist in the flatter valley bottoms. The stock farming and irrigation practices are supported by a large number of small to medium sized farm dams. These, coupled with natural channel transmission losses to alluvial deposits and fractured bedrock (interbedded mudstones and sandstones with frequent dolerite dykes), result in downstream decreases in streamflow during some events and an increase in the duration of zero flow periods. There are a number of raingauges available throughout the area, but it is difficult to be sure that they are adequate to represent the actual spatial variations in a mountain area.

Given the difficulties of simulating transmission losses, the results are reasonably good with the upstream site's streamflows being reproduced somewhat more successfully (non-transformed $R^2 = 0.74$, $CE = 0.63$ compared to 0.63 and 0.48, respectively for the lower site). Low flows are less well simulated, largely due to fairly frequent poor simulations of the recessions of individual events. There is a degree of uncertainty whether the simulated components of runoff are satisfactorily representative of the real hydrological processes prevailing in these catchments.

A10.5 Luvuvhu River catchments.

The Luvuvhu catchments are situated in the Northern Province and the gauging stations used consist of one station (area 915 km^2) below Albasini Dam (at 509 km^2) and two on tributaries to the main river (Latonanda River - 47 km^2 and Livhungwa River - 16 km^2). The streamflow is strongly affected by irrigation abstractions which were reasonably well defined in terms of mean monthly values and long term trends, but were not well defined in terms of short term variations. As Albasini Dam is a substantial size ($25.6 * 10^6$ m^3) it was considered necessary to simulate its effects separately using the daily reservoir simulation model. The sequence of modelling was therefore to simulate the inflows to Albasini using the VTI model, simulate the reservoir, then simulate the downstream contributions as far as the lower gauging station. Only the latter modelling project has observed daily data for calibration purposes and simulated flows from the two initial projects could only be checked against published mean monthly data.

There are a reasonably adequate number of rainfall stations situated within the region and generalised descriptions of soil, geology, vegetation and landuse are available. Certain assumptions had to be made about the ground water processes prevailing within the region as there is little information available. However, observed data from the two small gauged headwater tributaries did allow some of the assumptions to be tested against observed low flow responses.

The results for the two tributaries are highly variable and partly related to the fact that abstractions are made from behind the same structures that are used to measure streamflow. The results for the gauge on the main Luvuvhu River are satisfactory with coefficients of determination and efficiency (un- and log-transformed) exceeding 0.7, as well as the mean and standard deviations of daily flow being accurately reproduced.

A10.6 Sabie/Sand River catchments.

The details of the VTI model simulation exercises carried out in the Sabie/Sand catchments are given in Smakhtin and Watkins (1997) and only a brief summary is provided in this report. The catchments rise in the Drakensberg escarpment and flow through the Mpumalanga Lowveld region, passing through the Kruger National Park. Most of the runoff is generated in the upstream areas, where fortunately a greater density of raingauge information is available. Many of the streamflow records are affected by truncated high flow recordings and some doubt has been expressed about the accuracy of low flow gauging at some stations. The pre-1960 records are also based on single daily observations rather than digitised continuous records. Landuse in the headwater areas is dominated by pine and eucalypt plantations which have been in place since most of the observed flow data records began. Landuse in the middle reaches is dominated by extensive areas of irrigation and associated medium and small sized dams. The irrigation water usage (from dams and direct pumping) has been increasing over the period of observed streamflow data recording and it was necessary to account for these changes during calibration. This aspect of the application of the model proved to be the most difficult due to the highly variable nature of the irrigation abstractions and the fact that these are not very well documented.

In general terms the simulations were successful and parameter values were used that were consistent with the available descriptions of the natural and artificial characteristics of the catchments. The comparative statistics based on log-transformed data were almost always good (R^2 and CE above 0.8), while most of the un-transformed statistics were generally satisfactory (R^2 above 0.7), but somewhat affected by the high flow truncation effect (giving low and often negative CE values). Certainly, the general response characteristics of all the catchments were satisfactorily modelled and the simulated 1-day duration curves are very similar in shape to the observed.

The VTI model was also used to simulate virgin flow conditions for all the sub-areas within the total catchment and the results were generally compatible with previous studies using the monthly Pitman model or simply naturalising observed flow data.

The Low-Flow project also attempted a regionalised application of the daily time-step 'patching' model with reasonable success (Smakhtin and Watkins, 1997). There were found to be some variations in the catchment response characteristics within the region that suggested that a single set of non-dimensional duration curves could not be used. The study also looked at the possibility of using transformed (to daily) monthly duration curves and found that, while a degree of stability did exist in the relationships between monthly and daily flows at individual percentage points for the Sabie/Sand data, there was also a high degree of variability at the high and low flow extremes. Part of this problem must also be related to the highly variable landuse and water abstraction influences.

A10.7 Tugela catchments.

The modelling exercises carried out in the Tugela Basin, located in KwaZulu-Natal province, consisted of separate projects for the Mooi River, Sundays River and Wasbank River tributary areas and one for the central area close to where these tributaries meet to form the main Tugela River.

Mooi River catchments.

The Mooi River has its headwaters in the Drakensburg Mountains and the underlying rocks are generally of low permeability, giving rise to frequent surface saturation and the occurrence of vleis and wetlands in topographic lows. Soils are generally moderate to deep with clay loam to clay textures, but with reputedly high infiltration rates and permeabilities. Irrigation farming is widespread and there are a large number of farm dams. Rainfall data are available from a number of stations but problems with concurrency of records (and with observed flow data for calibration purposes) limited the number that could be used such that some parts of the total catchment were not very well represented.

The flow regimes of the rivers are characterised by a relatively pronounced seasonal baseflow component, which was more than adequately simulated, with large and small events superimposed on top of this. These events have variable recession characteristics and in general terms these were quite well reproduced by the model in most of the gauged sub-areas.

Overall, the low flow simulations were very good (log-transformed R^2 values better than 0.65 and frequently above 0.8 with similar values for CE), while the un-transformed statistics were often adversely affected by the input rainfall not matching the occurrence of observed flow events. Despite this problem and others, associated with defining water use and abstractions, some of the sub-catchment results are extremely good and the un-transformed R^2 and CE values at the lowest gauge that could be simulated (1546 km^2) were 0.8 and 0.79 respectively.

Sundays and Wasbank River catchments.

The results for these areas were not as good as for the Mooi River catchments and this must mainly be attributed to the lack of sufficient raingauge stations within or close to the catchment areas. The general pattern of streamflows in the Sundays Rivers was satisfactorily reproduced, but was spoilt by over-simulation of many peaks and low flows in dry years.

The calibration exercise for the Wasbank River resulted in limited success and further demonstrates the need for adequately representative rainfall input. There is also some evidence for the fact that low flows are not measured correctly at the weir site on the Wasbank River.

Central Tugela catchment.

The Central Tugela is the name used in the 'Low-Flow' project report (Smakhtin and Watkins, 1997) for the incremental area between two gauges (one at 4176 km^2 and one at 12862 km^2) on the Tugela River and where the larger tributary inflows are gauged close to the confluences. The VTI model was therefore set up to simulate several sub-areas and minor tributaries that constitute the incremental area and observed inflows from the other (gauged) tributaries were used as upstream inflows in the model. Where missing data occurred in the observed data, these were patched using the 'patching' model.

In general terms the simulations were more than satisfactory, with relatively high values for all the fit statistics. However, it should be recognised that the incremental area does not contribute a very large percentage of the overall flows at the downstream end.

A10.8 General conclusions.

Additional simulation exercises using the VTI model have been carried out on the Umzimvubu and Umzimkulu Rivers draining the Drakensburg Mountains and parts of KwaZulu-Natal and the former Transkei (now the Eastern Province), as well as a number of smaller catchments from other parts of South Africa. The success of the simulations was very similar to the experiences referred to in the sections above and largely relate to the ability of the model user to establish adequate input rainfall data, satisfactorily conceptualise the actual mechanisms of the hydrological response and translate these into the best way of setting up the model. The latter is assisted by general or detailed information about the physical characteristics of the catchments, which also helps to ensure that the model is set up and calibrated in such a way that reasonable confidence can be expressed in the balance between the volumes of runoff generated from the different components of the model. The results reported for the South African catchments have been generated by various members of the Institute for Water Research Hydrology section and it is clear that the calibration exercise progresses much faster when it is carried out by those with experience and knowledge of the inner workings of the model, coupled with experience and an understanding of the physical hydrology processes operating in the catchments.

Appendix A11 LANDUSE CHANGE IMPACTS

The majority of the landuse impacts simulated during this project are related to afforestation or clear felling plantations. Unfortunately, no data were made available to assess other typical landuse changes that are considered to potentially impact on streamflow in southern Africa (e.g. natural vegetation clearance for agriculture, overgrazing, construction of many small farm dams, urbanisation, etc.).

A11.1 Availability of data.

Flow data

The flow data were supplied by either the Institute of Hydrology, UK or the CSIR (South Africa) and consisted of reasonably complete records of mean daily flow.

Rainfall data

Rainfall data were obtained from the same sources as the flow data and in some cases consisted of mean catchment rainfalls, rather than individual station data. Many of the small experimental catchments involved are located in mountainous areas with potentially steep rainfall gradients and access difficulties. Consequently, it is not always a simple matter to generate representative rainfall inputs.

Evaporation data

The potential evaporation data that have been used consist of mean monthly data from the closest possible source. Given the likely importance of the evaporation component of the models in assessing landuse changes, it is possible that the lack of detail (spatial and temporal) in the quantification of potential evaporation could influence the results.

Catchment description data

Descriptions of the catchments physical characteristics have been drawn from various reports and scientific papers that have been published. As all the catchments were established for research purposes it might be expected that quite detailed information would be available. While that was not always the case, the general level of detail is far better than most of the other catchments used in the FRIEND project. Certainly, it was essential that a high level of detail about the cover characteristics was available, otherwise there would be a high degree of uncertainty in any conclusions reached about the parameter value changes required to simulate different effects.

A11.2 Brief descriptions of the catchments.

The South African catchments used in the landuse change modelling are illustrated in figure A10.1 in the previous appendix.

Erin Catchments, North Eastern Highlands, Zimbabwe

The data and information on the Erin catchments was made available from the Hydrological Branch of the Ministry of Lands, Agriculture and Development, Zimbabwe through the Institute of Hydrology, UK. Most of the documentation of catchment characteristics and landuse changes have been taken from Andrews and Bullock (1994). The catchments are located in the headwaters of the Odzi River at 18° 54'S and 32° 53'E and consist of a gauged control area of 0.21 km^2 and a treated area of 0.76 km^2, the total area also being gauged. The catchments are relatively steep (approximately 20% slopes) and the soils (du Toit, 1961) vary from shallow and stoney sandy loams and sandy clay loams on the ridge tops and steep slopes to deeper sandy loams over sandy clays in the flatter areas. There are also areas of hydromorphic soils (peaty sandy clay loams) along the river margins. The underlying bedrock consists of weathered and fractured granites, which are expected to play a major role in the catchments baseflow response.

The original vegetation consisted of relatively short montane grassland with some low shrubs and relict montane forest trees. The grassland is affected by winter frosts and the above ground shoots would normally die back by July. The sequence of afforestation in the Lower catchment (0.76 km^2) is outlined below :

07:1980	Land clearance, except for south eastern part.
11:1980	Burning.
01:1981	Planting of *Pinus patula* (spacing 2.7 * 2.7m or 1372 stems ha^{-1}).
09:1981	Land clearance and burning in south eastern part.
01:1982	Planting of *Pinus patula* in the south eastern part.
10:1985	Date of first pruning.
12:1985	Date of first thinning (reduced to 858 stems ha^{-1}).
1986/87	Year of second pruning (part of area).
1987/88	Year of second pruning (remaining area).
1992/93	Year of second thinning (no information on intensity).

Rainfall data were available (as catchment averages compiled from 7 raingauges within or close to the catchments) for the period October 1975 to September 1991, while flow data were available from October 1977. Hydrological years 1977 and 1978 could therefore be used to calibrate the models under grassland conditions, after which the parameter values could be changed to reflect the treatment applied to the Lower catchment. The mean monthly potential evaporation values were estimated from data collected at an evaporation pan in the vicinity of the catchment.

Jonkershoek Catchments, Western Cape, South Africa

The Jonkershoek research catchments consist of 6 gauged areas draining the Jonkershoek Mountains to the Eerste River in the Western Cape, South Africa (van Wyk, 1987). In this study, three of the gauged areas have been used; Bosboukloof (200.9 ha), Lambrechtsbos B (65.5 ha) and Langrivier (245.8 ha). All of these have been subjected to different impacts and all of the data were supplied by the Water, Environment and Forestry Technology Division (Environmentek) of the South African CSIR.

The area is underlain by sandstones of the Table Mountain Group, which overlay deeply weathered Cape Granites. The soils are deep sandy to silty loams with high gravel and rock content, which are friable and have high infiltration rates. The soils are affected by fires that occur in these catchments and can become highly water repellant at depth (Scott and van Wyk, 1990) after intense fires. The natural vegetation is a tall (2 to 3 m) open to closed shrubland, dominated by protea species, with evergreen tall forests occurring along permanent streams.

Rainfall data were provided from the stations closest to the catchments, but it must be noted that rainfall gradients are very steep in this mountainous region, varying from approximately 1300 mm over Bosboukloof to over 2200 mm for Langrivier. Estimation of rainfall inputs to the latter are particularly difficult as the only raingauge is in the lower part of the catchment and the streamflow response (about 1600 mm) suggests a much greater rainfall input over the upper parts.

The landuse treatments and period of data availability for the three catchments are summarised below :

- Bosboukloof (data from January 1978 to December 1990)

1940	Planted to *Pinus radiata* (57% of the catchment with a rotation period of 40 years).
1980/82	Clear felled, rapid re-establishment of fynbos cover and replanted within 1 year of felling.
02:1986	80% of the second rotation burned in a high intensity wildfire.

The first two years of the record can therefore be used to establish parameter values for mature forest cover and the remaining period used to assess the parameter value changes to account for clear felling and burning.

- Lambrechtsbos (data from January 1972 to September 1995)

1964/65	82% of the catchment planted to *Pinus radiata* with 1370 stems ha^{-1}.
1973	Thinned to 770 stems ha^{-1}.
1978	Thinned to 510 stems ha^{-1}.
1983	Thinned to 324 stems ha^{-1}.

As the trees can be assumed to have not reached maturity when the hydrological data start, there is no stable cover period that can be used to calibrate the models. The approach was therefore to compare the results of fixed parameter values for the whole period versus changing values to try and account for a combination of growth and thinning.

- Langrivier (data form January 1971 to September 1995)

10:1987	Natural Fynbos catchment burnt in a wildfire.

Mokubalaan Catchments, Mpumulanga, South Africa

These catchments are situated (at 25°17'S, 30°34'E) in the Uitsoek State Forest on the Transvaal Drakensburg escarpment and full descriptions of their characteristics are provided in Nänni (1971). The area is underlain by basal shales which are highly arenaceous and are crossed by a number of diabase dykes. The bedrock is semi-weathered, broken to 30 m below the surface and permeable to roots and water for much of this depth. In contrast, the soil is considered to be only a few centimetres deep and therefore plant growth relies upon water stored within the shale bedrock for survival. The original vegetation is a sub-climax grassland with evergreen forest in the riparian strips. Three catchments were established in this area; A (26.2 ha) planted to eucalypts, B (34.6 ha) planted to pines and C (36.9 ha) kept as a grassland control. Unfortunately, only data for Mokobulaan B were made available to this project. The catchments are relatively steep (slopes > 20%) and experience mean annual rainfalls of 1100 to 1200 mm. Rainfall data are derived from a single gauge located within catchment B. The data made available cover the period from October 1971 to September 1982 after which all runoff ceased. The treatment record is as follows :

01:1971	100% of the catchment (including riparian strip) planted to *Pinus patula* with a density of 1370 stems ha^{-1}.
1979	Thinned to 650 stems ha^{-1}.

As the data do not cover the period prior to planting, the opportunity to calibrate the models during natural conditions was not possible. Consequently, the approach has been to carry out a rough calibration on the first two to three years of data, before the trees would be expected to have a great influence and then to test the parameter value change principles developed for the other catchments for the remainder of the period.

Westfalia Estate, near Tzaneen, Northern Province, South Africa

These are mountain catchments (slopes > 20%) underlain by granite gneiss with friable, well drained and deep, clay loam soils. The mean annual rainfall is of the order of 1600 mm and the natural vegetation consists of scrub forest and they situated close to 23°43'S, 30°04'E.

Data were made available for the treated catchment (D, area 40 ha) from October 1975 to September 1991 and the treatment record is as follows :

02:1981	Riparian vegetation (17% of the area) cleared.
12:1982	Remaining natural vegetation cleared.
03:1983	Planted to *Eucalyptus grandis* with 1370 stems ha^{-1}.
1986	Thinned to 700 stems ha^{-1}.
1988	Thinned to 450 stems ha^{-1}.
1991	Thinned to 300 stems ha^{-1}.

The first six years of data could be used for model warming up and calibration, after which the parameter values could be changed to account for clearing and forest growth.

A11.3 Calibration procedure, Pitman Model

The data for the Erin catchments was received much earlier during the project than any of the other data and therefore was used to establish a calibration/model testing procedure for assessing the application of both models to simulating landuse change. The model was first calibrated against the control (no change) catchment and any part of the record for the modified catchment that occurred before the afforestation. Some of the parameters were then changed according to an intuitive understanding of the effects of parameter value changes in relation to the perceived likely impact of afforestation. In the case of the Pitman model this is relatively straightforward as there are separate parameters for interception from forestry (compared to natural veld or bush), a parameter to increase the amount of evapotranspiration from forest areas and a parameter specifying the proportion of the catchment covered by forest.

In previous versions and applications of the model, the PI (interception) parameter has often been set at 1.5 for natural vegetation and 10.0 for forest, which tends to over-estimate the amount of interception from forest compared to measured amounts. This has been compensated for by assuming that the ratio of evaporative demand from forest to that from veld is unity. Thus, the impact on streamflow may be correct, but the balance between that which is intercepted and evaporated from the canopy and that which is lost through evapotranspiration from the soil is inconsistent with experimental results. Although not really important from the point of view of the application of the Pitman model, it could be serious if a similar principle were applied to such as the VTI model which more explicitly simulates the various runoff generation processes. If the wrong increments to soil moisture were simulated, then the soil water baseflow and groundwater recharge components would not operate correctly.

It was therefore decided to attempt to set up the parameter differences, between natural vegetation and afforested conditions, in the Pitman model to represent the actual processes and nature of additional water loss in a more representative manner. The forest PI parameter value was assumed to be approximately 4.0, while the soil evaporative demand ratio was assumed to be close to 1.5. It was further assumed that infiltration rates would be higher in forest areas such that the ZMIN parameter would increase in value and that evapotranspiration would dry the soil out more effectively, suggesting lower R parameter values.

The Pitman model (as with other HYMAS models) has been set up to allow 'time-slices' of varying parameter values to be established. That is, defined periods within the total simulation period can be set up so that parameter values either increase or decrease linearly over the 'time-slice', or are raised or dropped instantaneously at the start of the 'time-slice'. The procedure for simulating new afforestation is therefore to gradually increase parameters ZMIN and AFOR (area of forest), while decreasing parameter R. Although the area of forest may remain static, this approach should have the effect of simulating growth. It was accepted that there may be several stages of growth with different rates and that several separate 'time-slices' may be required to simulate the situation from initial planting to maturity, with some intermittent thinning. The same principle would apply for a managed plantation under different harvesting and re-planting (rotation) practices.

Once the Erin catchments had been calibrated and a set of guidelines established, the same principles were applied and tested on the other catchments and the guidelines extended or further refined.

A11.4 Simulation results, Pitman model.

Erin catchments.

Table A11.1 provides information about the parameter values used to simulate the two Erin catchments and it can be noted that the initial phase of afforestation (first 2 to 3 years) has been simulated with no forest cover, but a return to interception characteristics similar to summer grassland and more effective evapotranspiration loss from storage (parameter R decreased). The following time-slice of three years then introduces the main impacts, which have been assumed to remain stable for the remainder of the period to September 1991.

Table A11.1 Pitman model parameters, Erin catchments.

Parameter name	Parameter values				
	Control (21 ha)	Afforested (76 ha)			
		Before Nov. 1980	Nov. 1980 for 1 month	Feb. 1981 for 43 months	Oct. 1984 for 36 months
Impervious fraction (AI)	0.05	0.06	0.06	0.06	0.06
Storage-Runoff (POW)	2.5	2.0	2.0	2.0	2.0
Max. storage (ST)	1000.0	800.0	800.0	800.0	800.0
Runoff at ST (FT)	65.0	120.0	120.0	120.0	120.0
Max. G'water runoff (GW)	30.0	100.0	100.0	100.0	100.0
Min. abs. rate (ZMIN)	320.0	320.0	320.0	320.0	350.0
Max. abs. rate (ZMAX)	950.0	950.0	950.0	950.0	950.0
Summer grass interception (PIV)	1.5	1.5	1.0	1.5	1.5
Winter grass interception (PIV)	1.2	1.2	1.0	1.5	1.5
Forest interception (PIF)	4.0	4.0	4.0	4.0	4.0
Evap-storage coeff. (R)	0.5	0.5	0.75	0.4	0.1
Forest area (AFOR)	0.0	0.0	0.0	0.0	92.1
Forest/grass PE ratio (FF)	1.5	1.5	1.5	1.5	1.5
Surface runoff lag (TL)	0.1	0.1	0.1	0.1	0.1
G'water runoff lag (GL)	0.3	0.3	0.3	0.3	0.3

Table A11.2 lists some statistics for the simulation results divided into three periods and the two catchments. The afforested catchment results are presented for the simulations with fixed grass parameters (derived from the calibration period; 1977 to 1979) and for the parameters that were used to simulate the landuse changes. The same calibration period was used for the control catchment and it is apparent that some revision of the parameter values would be appropriate to achieve better overall simulations for the three periods.

There is little doubt that the time-sliced parameters produce must better simulations over the second two periods than the fixed grassland parameters and suggest that the runoff volume (from the treated part of the catchment) was reduced by some 13% during the first 5 years and 42% during the 4 year period after 1987 (after removing the effect of over-simulating the control part of the total catchment).

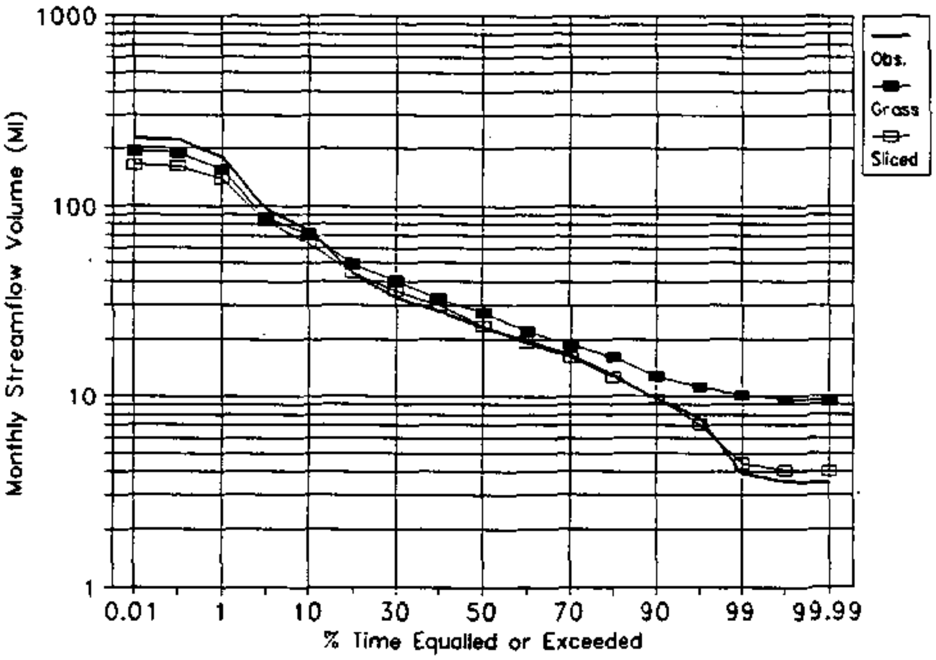


Figure A11.1 Erin total catchment (97 ha, 70 ha afforested), monthly flow duration curves for observed and simulated (using fixed grassland and sliced parameter values) based on data from October 1977 to September 1991.

Figure A11.1 also illustrates the results and the improvement in the simulations due to the use of the parameter values to represent the afforestation programme. The improvement is particularly noticeable in the low flow region of the curve.

Table A11.2 Simulation results, Pitman model, Erin catchments.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Control 21 ha	10:1977 to 09:1982	Obs.	6.6	5.8				1.63	0.68			
		Sim.	7.1	7.0	7.6	0.90	0.83	1.73	0.62	6.1	0.87	0.85
	10:1982 to 09:1987	Obs.	4.4	4.6				1.41	0.80			
		Sim.	5.2	4.7	19.7	0.88	0.83	1.11	0.65	21.3	0.88	0.73
	10:1987 to 09:1991	Obs.	3.9	3.3				1.41	0.80			
		Sim.	4.9	3.0	25.8	0.85	0.76	1.05	0.60	25.5	0.87	0.63
Total 97 ha (Fixed grass parameters for 76 ha)	10:1977 to 09:1982	Obs.	49.3	44.7				3.65	0.65			
		Sim.	42.5	34.7	-13.7	0.94	0.88	3.54	0.62	-3.0	0.88	0.85
	10:1982 to 09:1987	Obs.	29.3	27.5				3.11	0.66			
		Sim.	33.4	27.4	14.0	0.72	0.68	3.28	0.64	5.5	0.78	0.71
	10:1987 to 09:1991	Obs.	21.5	17.1				2.78	0.77			
		Sim.	33.1	21.2	53.9	0.88	0.32	3.31	0.63	19.1	0.81	0.34
Total 97 ha (Time-sliced parameters for 76 ha)	10:1977 to 09:1982	Obs.	49.3	44.7				3.65	0.65			
		Sim.	43.0	34.7	-12.8	0.94	0.89	3.55	0.62	2.7	0.89	0.86
	10:1982 to 09:1987	Obs.	29.3	27.5				3.11	0.66			
		Sim.	29.8	25.2	1.8	0.76	0.75	3.15	0.67	1.3	0.79	0.78
	10:1987 to 09:1991	Obs.	21.5	17.1				2.78	0.77			
		Sim.	21.3	15.9	0.9	0.89	0.89	2.79	0.76	0.3	0.82	0.82

Jonkershoek catchments, Bosboukloof.

Table A11.3 lists the parameter values that were used to simulate the effects of clearing forest (1981 to 1982) and of the wildfire (1986) in Bosboukloof. The period from 1978 to early 1981 was used to calibrate the model for forested conditions and then similar (but reversed) parameter value changes were made as in the Erin example. It was found necessary to make the relative difference between the forested and cleared ZMIN values even greater for this situation than for Erin. Table A11.4 lists the simulation statistics for three periods, before and after applying the new parameter values, while figure A11.2 shows the differences between the resulting duration curves.

The calibration period is relatively short and it was found to be difficult to achieve a satisfactory result, particularly with respect to summer baseflow response. Some revisions to the initial calibration parameters were therefore essential after applying the time-sliced parameters, so that a longer period could be used. While there are still some differences in the simulated volumes for the two main time-slice periods (1981 to 1985 over-simulated and 1986 to 1990 under-simulated), the results suggest that the parameter changes used can be considered to reasonably represent the effects of clearance and subsequent re-growth. The impact of the wildfire (Scott and van Wyk, 1990) has been less than satisfactorily simulated and this is probably why the second period is under-simulated.

Table A11.3 Pitman model parameters, Bosboukloof catchment (200.9 ha).

Parameter name	Parameter values				
	Before Feb. 1981	Feb. 1981 for 2 months	Feb. 1982 for 2 months	Feb. 1986 for 1 month	May 1986 for 36 months
Impervious fraction (AI)	0.05	0.05	0.05	0.05	0.05
Storage-Runoff (POW)	1.5	1.5	1.5	1.5	1.5
Max. storage (ST)	540.0	540.0	540.0	540.0	540.0
Runoff at ST (FT)	70.0	70.0	70.0	70.0	70.0
Max. G'water runoff (GW)	30.0	30.0	30.0	30.0	30.0
Min. abs. rate (ZMIN)	140.0	100.0	60.0	20.0	60.0
Max. abs. rate (ZMAX)	800.0	800.0	800.0	800.0	800.0
Veld interception (PIV)	1.5	1.5	1.5	1.5	1.5
Forest interception (PIF)	4.0	4.0	4.0	4.0	4.0
Evap-storage coeff. (R)	0.2	0.5	0.6	0.9	0.6
Forest area (AFOR %)	55.4	27.3	0.0	0.0	0.0
Forest/grass PE ratio (FF)	1.5	1.5	1.5	1.5	1.5
Surface runoff lag (TL)	0.15	0.15	0.15	0.15	0.15
G'water runoff lag (GL)	0.8	0.8	0.8	0.8	0.8

The mean monthly runoff appears to have increased by some 30% during the first 5 years after clearfelling began, while the increase appears to have risen to as high as 40% based on a comparison between the observed and simulated (using forest parameter values) flows. Comparison of the two sets of simulated flows for the second period suggests an increase of only 30%, further indicating that the wildfire impacts have possibly not been successfully simulated.

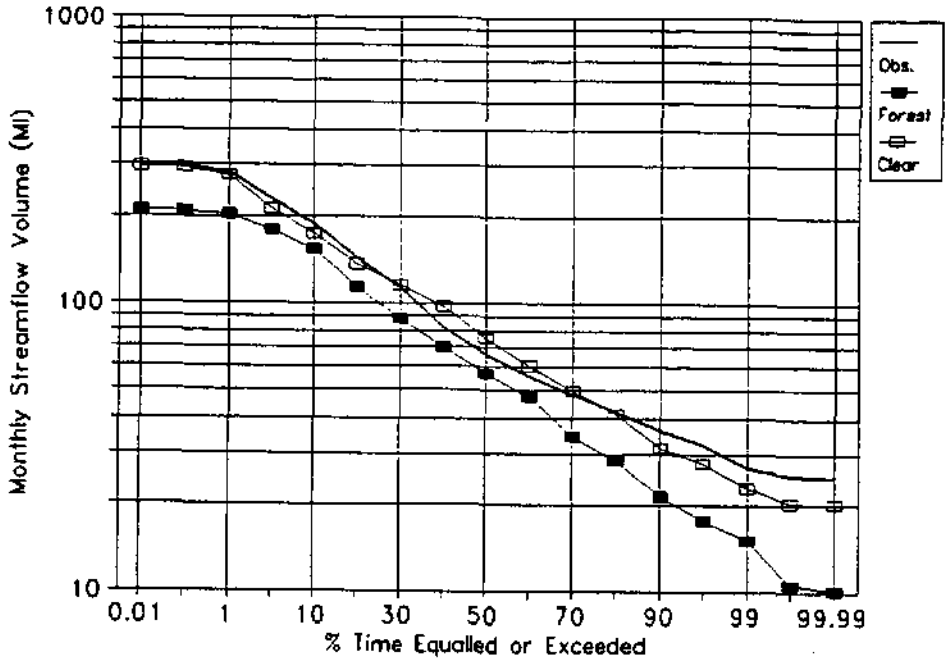


Figure A11.2 Bosboukloof catchment (200.9 ha, 111 ha afforested), monthly flow duration curves for observed and simulated (using fixed forest and sliced parameter values for clearance and wildfire) based on data from January 1981 to December 1991.

Jonkershoek catchments, Lambrechtbos.

The available data covers a period when the pine plantation was still growing and was subject to thinning. There is therefore no suitable period to use for calibration when the landuse was stable. Consequently, it was necessary to use the early growth period (1972 to 1977, trees 8 to 14 years old at 770 stems ha^{-1}), with some parameter value slicing and then to assess the ability of the model to simulate additional thinning as the trees mature further using the parameter sets given in table A11.5. The area of forestry has been reduced in the last two periods to try and simulate the effects of thinning to 510 and 324 stems ha^{-1}, respectively. The results of applying the model with these parameter values has been compared to the results based on a parameter set (the same values as column 2 in table A11.5, except with ZMIN = 140 and R = 0.25) designed to represent average conditions prior to the second and third thinning processes.

Table A11.4 Simulation results, Pitman model, Bosboukloof catchment.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Fixed forest parameters	01:1979 to 12:1980	Obs.	53.3	26.5				3.85	0.53			
		Sim.	56.6	29.1	6.2	0.81	0.75	3.87	0.63	0.5	0.87	0.80
	01:1981 to 12:1985	Obs.	89.3	60.3				4.29	0.62			
		Sim.	70.3	41.4	-21.3	0.79	0.65	4.07	0.64	-5.1	0.87	0.72
	01:1986 to 12:1990	Obs.	98.3	70.1				4.37	0.65			
		Sim.	62.8	38.3	-36.1	0.76	0.39	3.93	0.67	-10.1	0.81	0.32
Sliced parameters for clearance	01:1981 to 12:1985	Obs.	89.3	60.4				4.29	0.62			
		Sim.	92.1	58.2	3.1	0.86	0.86	4.33	0.64	0.9	0.91	0.90
	01:1986 to 12:1990	Obs.	98.3	70.1				4.37	0.65			
		Sim.	90.8	60.7	-7.6	0.92	0.90	4.31	0.64	-1.4	0.92	0.91

Table A11.5 Pitman model parameters, Lambrechtbos catchment (65.5 ha).

Parameter name	Parameter values			
	Before Oct. 1972	Oct. 1972 for 62 months	Jan. 1978 for 3 months	Jan. 1983 for 3 months
Impervious fraction (AI)	0.05	0.05	0.05	0.05
Storage-Runoff (POW)	2.2	2.2	2.2	2.2
Max. storage (ST)	1000.0	1000.0	1000.0	1000.0
Runoff at ST (FT)	45.0	45.0	45.0	45.0
Max. G'water runoff (GW)	10.0	10.0	10.0	10.0
Min. abs. rate (ZMIN)	130.0	150.0	130.0	105.0
Max. abs. rate (ZMAX)	860.0	860.0	860.0	860.0
Veld interception (PIV)	1.5	1.5	1.5	1.5
Forest interception (PIF)	4.0	4.0	4.0	4.0
Evap-storage coeff. (R)	0.3	0.2	0.3	0.4
Forest area (AFOR %)	82.0	82.0	0.66	0.41
Forest/grass PE ratio (FF)	1.5	1.5	1.5	1.5
Surface runoff lag (TL)	0.1	0.1	0.1	0.1
G'water runoff lag (GL)	0.5	0.5	0.5	0.5

The results are presented in table A11.6 and are not very easy to interpret. While the model results for the second period (after the final thinning) have been improved through the use of parameter values considered appropriate for less dense forest cover, the first period flows were generally over-simulated by the so-called forest parameters, and the application of the relatively modest parameter changes, only makes this situation worse. Applying the average parameter values to the whole 23 year period results in a mean annual runoff depth of some 253 mm, which increases to 294 mm if the time-sliced parameter values are used (compared to 287 mm observed). This suggests that a 16% increase in runoff was achieved from thinning practices in this catchment (with 82% of the area afforested); approximately half the value obtained by clearfelling the 55% cover forest in Bosboukloof.

Jonkershoek catchments, Langrivier.

The first difficulty with this catchment is that the gauge rainfall is not considered to be representative of the catchment rainfall such that it was necessary to increase the gauged monthly rainfalls by 50% to achieve an input that closely approximates the assumed mean annual rainfall (> 2200 mm; van Wyk, 1987). Unfortunately, this type of linear scaling factor is unlikely to be satisfactory.

Table A11.6 Simulation results, Pitman model, Lambrechtbos catchment.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Average forest parameters	10:1972 to 09:1978	Obs.	18.3	19.3				2.51	0.87			
		Sim.	18.5	24.0	1.1	0.86	0.76	2.44	0.94	-2.8	0.84	0.81
	10:1978 to 09:1983	Obs.	8.5	7.1				1.85	0.76			
		Sim.	10.3	4.9	21.2	0.40	0.33	2.20	0.53	18.9	0.59	0.36
	10:1983 to 09:1995	Obs.	17.3	12.6				2.60	0.70			
		Sim.	12.9	11.2	-25.4	0.44	0.26	2.31	0.69	-11.1	0.67	0.47
Sliced parameters for growth and thinning	10:1972 to 09:1978	Obs.	18.3	19.3				2.51	0.87			
		Sim.	18.5	23.8	1.1	0.86	0.76	2.45	0.93	-2.4	0.84	0.81
	10:1978 to 09:1983	Obs.	8.5	7.1				1.85	0.76			
		Sim.	11.6	5.5	36.5	0.47	0.27	2.33	0.52	25.9	0.63	0.20
	10:1983 to 09:1995	Obs.	17.3	12.6				2.60	0.70			
		Sim.	16.6	13.5	-4.0	0.47	0.32	2.59	0.66	-0.3	0.69	0.68

The first ten years of the record (from 01:1972) were used for calibration and two time-slices established; one to simulate the wildfire effects immediately after October 1987 and one to simulate the return to more normal fynbos veld cover over the 5 years from October 1988. The parameter values are given in table A11.7, while the results statistics for two periods are given in table A11.8. Simulation results are provided for the calibration parameter values applied to the whole period and for the application of the time-sliced values. It is evident that both sets of parameter values under-simulate the 8 year period after the wildfire, although the wildfire parameters do indicate some improvement. It is likely that the calibration parameter values are not really representative of the period as a whole and tend to generate too low a runoff response. This may also be partly caused by the rainfall input not being high enough, or the effects of a non-linear relationship between the gauge and true catchment average rainfall manifesting itself to a greater extent outside the calibration period.

Whatever the problem is, the end result is that it is difficult to conclude whether the parameter value changes used are satisfactorily generating the correct response to the wildfire. The model suggests that the increase in runoff, averaged over the 8 years following the fire, would have been some 100 mm, or about 7%. While previous studies have examined the effects of wildfires (Scott and van Wyk, 1990; Scott, et al., 1991) they have not reported on the longer term runoff volume response, rather concentrating on shorter term and more detailed storm responses.

Table A11.7 Pitman model parameters, Langrivier catchment (245.8 ha).

Parameter name	Parameter values		
	Before Oct. 1987	Oct. 1987 for 1 month	Oct. 1988 for 60 months
Impervious fraction (AI)	0.1	0.1	0.1
Storage-Runoff (POW)	1.5	1.5	1.5
Max. storage (ST)	250.0	250.0	250.0
Runoff at ST (FT)	80.0	80.0	80.0
Max. G'water runoff (GW)	30.0	30.0	30.0
Min. abs. rate (ZMIN)	80.0	0.0	80.0
Max. abs. rate (ZMAX)	500.0	150.0	500.0
Veld interception (PIV)	1.5	0.5	1.5
Evap-storage coeff. (R)	0.7	1.0	0.7
Surface runoff lag (TL)	0.15	0.15	0.15
G'water runoff lag (GL)	0.5	0.5	0.5

Table A11.8 Simulation results, Pitman model, Langrivier catchment.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Normal parameters	01:1972 to 12:1987	Obs.	334.4	390.7				5.35	0.95			
		Sim.	317.8	316.9	-5.0	0.72	0.72	5.27	1.02	-1.5	0.85	0.81
	01:1988 to 09:1995	Obs.	331.5	336.1				5.32	1.02			
		Sim.	269.7	269.6	-18.6	0.77	0.73	5.09	1.06	-4.3	0.87	0.80
Sliced parameters for wildfire	01:1988 to 09:1995	Obs.	331.5	336.1				5.32	1.02			
		Sim.	289.6	276.1	-12.6	0.75	0.74	5.16	1.09	-3.0	0.86	0.82

Mokobulaan catchment.

The first four years (October 1971 to September 1974) were used for calibration as the impact of afforestation was only expected to be observed in the fourth year after planting (1974). Table A11.9 lists the calibration parameter values (column 2) and the values used to simulate the effects of forest growth and the thinning in 1979. Table A11.10 list the simulation results statistics, while figure A11.3 clearly demonstrates the impacts that were observed, although the heavy line representing observed flows is somewhat obscured by the lines with the symbols representing the simulated flows using the time-sliced parameters. The observed data stop in 1982 as the runoff ceased after that year.

Table A11.9 Pitman model parameters, Mokobulaan catchment (34.6 ha).

Parameter name	Parameter values		
	Before Oct. 1973	Oct. 1973 for 72 months	Nov. 1979 for 1 month
Storage-Runoff (POW)	3.5	3.5	3.5
Max. storage (ST)	1000.0	1000.0	1000.0
No runoff below storage (SL)	200.0	200.0	200.0
Runoff at ST (FT)	160.0	160.0	160.0
Max. G'water runoff (GW)	0.0	0.0	0.0
Min. abs. rate (ZMIN)	120.0	160.0	160.0
Max. abs. rate (ZMAX)	800.0	800.0	800.0
Veld interception (PIV)	1.5	1.5	1.5
Forest interception (PIF)	4.0	4.0	4.0
Evap-storage coeff. (R)	0.5	0.2	0.2
Forest area (%)	0.0	92.5	86.7
Forest/veld PE ratio (FF)	1.5	1.5	1.5
Surface runoff lag (TL)	0.1	0.1	0.1

Figure A11.3 illustrates very clearly that the forest influence begins during the fourth year and is quite dramatic. As the forest influence appears to begin during the calibration period, a degree of over-simulation was also expected and therefore the % error in the mean monthly flow of 7.6% is not surprising. The high value for parameter ST is accounting for the large moisture storage available in the weathered and fractured shale bedrock and should not be interpreted as soil moisture storage. A non-zero value for SL has also been used on the basis of the assumption that not all the stored moisture will be available to contribute to baseflow. The changes to the parameter values made to account for afforestation are similar to those made for the other catchments and suggest a runoff decrease of 7% during the first four years, 46% during the following 4 years and over 78% during the next 3 years. Table A11.9 indicates that the forestry area was slightly reduced after the end of 1979 to account for a reduction from 1370 to 650 stems ha^{-1} due to thinning. However, it would seem that other factors (expanding canopy cover, denser and deeper roots, etc.) are more than compensating for the thinning and that the actual reduction in flow over the last period is over 80%. Unfortunately, no rainfall data were provided for the post-1982 period and therefore it was not possible to assess the model's capability to simulate the complete cessation of flow that has been reported.

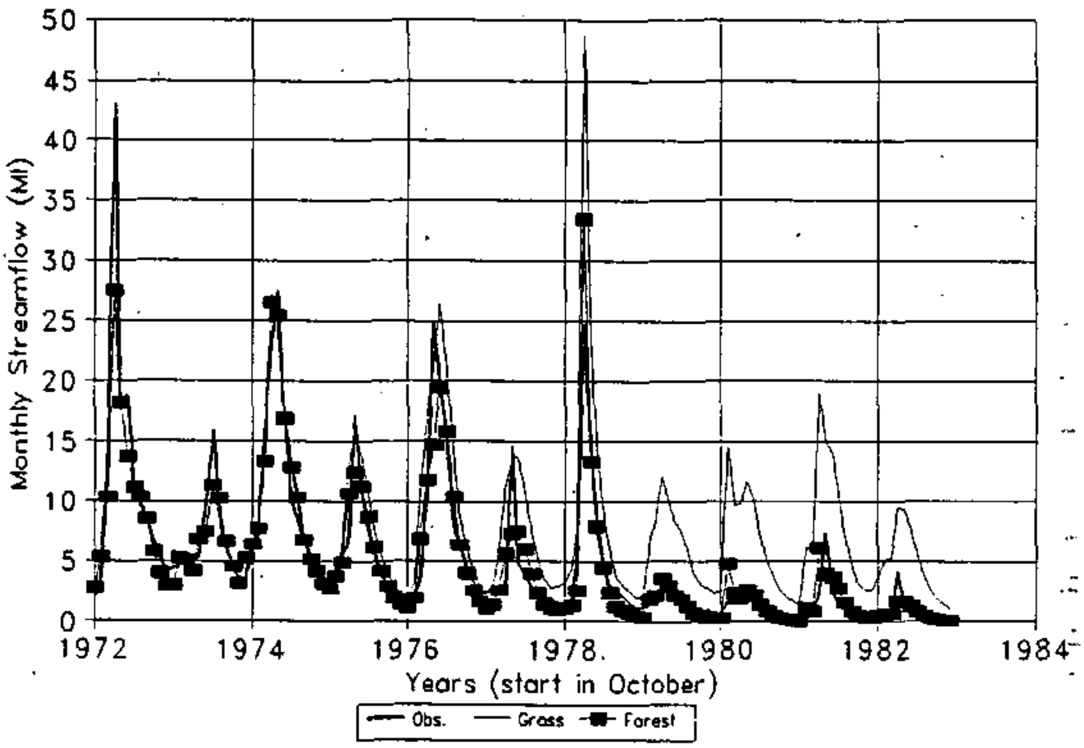


Figure A11.3 Time series of observed and simulated (using grass and modified parameter values) monthly flows for Mokobulaan.

Westfalia catchment.

The period October 1975 to September 1981 was used for calibration purposes, even though this overlaps with the initial clearance of the riparian vegetation. The parameter values used to simulate the effects of clearance and then planting of eucalypts are given in table A11.11 and it can be noted that higher forest interception and ratio of forest/veld PE ratio values have been used than for the previous examples involving pine trees. Unfortunately, this is the only catchment involving treatment with eucalypts and the different parameter value changes cannot be tested elsewhere.

Table A11.10 Simulation results, Pitman model, Mokobulaan catchment.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Grassland *parameters*	10:1972 *to*	Obs.	7.9	5.9				1.85	0.63			
	09:1975	Sim.	8.5	6.0	7.6	0.89	0.87	1.94	0.63	9.0	0.88	0.86
	10:1975 to	Obs.	4.9	6.0				1.09	1.00			
	09:1979	Sim.	8.7	8.5	79.1	0.78	0.08	1.85	0.80	69.7	0.64	0.05
	10:1979 to	Obs.	1.0	1.4				-0.46	1.29			
	09:1982	Sim.	6.3	4.5	530.0	0.55	-19.19	1.87	0.58	506.5	0.61	-2.90
Sliced parameters for afforestation	10:1972 to	Obs.	7.9	5.9				1.85	0.63			
	09:1975	Sim.	8.5	6.0	-0.8	0.91	0.91	1.84	0.67	-0.5	0.90	0.89
	10:1975 to	Obs.	4.9	6.0				1.09	1.00			
	09:1979	Sim.	4.7	6.2	-4.5	0.84	0.82	0.94	1.12	-13.8	0.84	0.77
	10:1979 to	Obs.	1.00	1.45				-0.46	1.29			
	09:1982	Sim.	1.39	1.52	39.0	0.47	0.25	0.19	0.91	141.3	0.62	0.35

Table A11.11 Pitman model parameters, Westfalia catchment (40 ha).

Parameter name	Parameter values				
	Before Feb. 1981	Feb. 1981 for 1 month	Dec. 1982 for 1 month	Mar. 1983 for 40 months	Oct. 1986 for 60 months
Storage-Runoff (POW)	1.5	1.5	1.5	1.5	1.5
Max. storage (ST)	1300.0	1300.0	1300.0	1300.0	1300.0
No runoff below storage (SL)	400.0	400.0	400.0	400.0	400.0
Runoff at ST (FT)	110.0	110.0	110.0	110.0	110.0
Min. abs. rate (ZMIN)	80.0	80.0	60.0	80.0	100.0
Max. abs. rate (ZMAX)	1600.0	1600.0	1600.0	1600.0	1600.0
Veld interception (PIV)	1.5	1.5	1.5	1.5	1.5
Forest interception (PIF)	5.0	5.0	5.0	5.0	5.0
Evap-storage coeff. (R)	0.3	0.32	0.4	0.1	0.0
Forest area (%)	0.0	0.0	0.0	100.0	75.0
Forest/veld PE ratio (FF)	1.6	1.6	1.6	1.6	1.6
Surface runoff lag (TL)	0.15	0.15	0.15	0.15	0.15

The results are listed in table A11.12 for three periods; the initial period including the first stage of clearance, the period up to when the trees are nearly three years old, and the final period up to the end of the record (trees aged almost 9 years). The low flow period, over hydrological years 1981 to 1983, was difficult to simulate and implies that the model tends to over-simulate during drought periods. In general terms, however, the impact of afforestation appears to have been reasonably well simulated and suggests that a reduction in streamflow volume of about 20% occurred during the first 3 to 4 years, while this increased to over 60% when the trees were between 4 and 9 years old.

General comments about the Pitman model simulations.

The results demonstrate that, in general terms, the model is able to simulate the impacts of afforestation with either pine or eucalypt trees and clearfelling of pine trees. There is a reasonably high degree of stability in the nature of the parameter value changes that are necessary to achieve this. The model did not seem to be very sensitive to the effects of wildfires on two of the catchments and the results were not examined in sufficient detail to determine whether or not the model is capable of correctly simulating the shorter term effects during different stages of growth. It is very difficult to make firm conclusions about the model's abilities in this regard as it involves assessing the simulation results for individual years, when other factors (rainfall and PE input accuracy, for example) also influence the results.

Table A11.12 Simulation results, Pitman model, Westfalia catchment.

Catchment	Period		Mean (Ml)	SD (Ml)	Mean % Error	R^2	CE	Mean ln	SD ln	Mean ln % Error	R^2 ln	CE ln
Grassland parameters	10:1975 to 09:1981	Obs.	25.3	21.3				2.93	0.77			
		Sim.	24.0	21.5	-4.9	0.78	0.76	2.93	0.67	0.0	0.82	0.82
	10:1981 to 09:1985	Obs.	7.4	5.2				1.82	0.60			
		Sim.	11.1	6.2	49.9	0.71	0.07	2.27	0.53	24.7	0.67	0.08
	10:1985 to 09:1991	Obs.	6.9	9.9				1.31	1.29			
		Sim.	17.4	12.0	152.2	0.87	-0.34	2.72	0.51	107.6	0.64	-0.74
Sliced parameters for afforestation	10:1975 to 09:1981	Obs.	25.3	21.3				2.93	0.77			
		Sim.	24.0	21.5	-4.9	0.78	0.76	2.93	0.67	0.0	0.82	0.82
	10:1981 to 09:1985	Obs.	7.4	5.2				1.82	0.60			
		Sim.	9.1	4.5	21.9	0.73	0.63	2.09	0.49	14.8	0.69	0.48
	10:1985 to 09:1991	Obs.	6.9	9.9				1.31	1.29			
		Sim.	6.9	6.5	0.3	0.70	0.66	1.53	1.05	16.8	0.61	0.57

A11.5 Calibration procedure, VTI model.

Effectively, the same approach that was used for the Pitman model was applied to the VTI model. The parameter estimation procedures within HYMAS were used to establish some of the values and the other parameters calibrated against the control catchment (where present) and/or the period of the observed data that occurs prior to the landuse change on the treated catchment. The estimation procedure was then repeated for the changed conditions and the 'time-slices' established in the same way as the Pitman model to simulate gradual, or abrupt changes as appropriate. In those cases where no estimation procedure is available for a parameter, but it is considered to be an important parameter (as in the case of the crop factor), guidelines were established using the Erin catchment data and applied to the other areas for testing and (where necessary) re-appraisal. Estimation procedures are available for the vegetation (and hence interception) and the surface condition (and hence infiltration) parameters and these were considered the most important together with the crop factor.

A11.6 Simulation results, VTI model.

The VTI model simulation results are presented in a similar group of tables as used for the Pitman model. The parameter value tables include a sub-set of the full list of parameters and concentrate on those that are changed to reflect the landuse changes, as well as a few others that the model results are sensitive to and can be related in some way to some of the Pitman model parameters (i.e. those related to total storage and drainage from storage).

Erin catchments.

Table A11.13 lists the main model parameters and the changes that were included to simulate the impacts on the afforested (76 ha) catchment. The initial changes are related to the removal of the natural cover, while the later ones are an attempt to simulate the forest growth. The change to the standard deviation of soil moisture content parameter was included on the assumption of more evenly distributed soil moisture under a forest canopy.

The results are presented in table A11.14 using flow units of $l\ s^{-1}$ for the untransformed data and it is clear that they are comparable to those generated using the Pitman model, except that the simulated effect of afforestation is somewhat lower (10% less runoff for the first 5 years and 35% for the last four years from the treated part of the catchment). The crop factor was increased to 1.4 during the final time-slice as the forest was assumed to be still less than mature. However, it would appear that a crop factor of 1.5 would have been better, which increases the impact in the last four years to just over 38%.

The daily flow comparison (observed versus simulated) statistics are extremely good and almost as high as the monthly values listed for the Pitman model and it is not surprising therefore that the statistics based on monthly values for the VTI model are slightly better than for the Pitman model.

Table A11.13 VTI model parameters (see table 2.2 for explanations of parameter meanings), Erin catchments.

Parameter name	Parameter values				
	Control (21 ha)	Afforested (76 ha)			
		Before Nov. 1980	Nov. 1980 for 1 month	Feb. 1981 for 43 months	Oct. 1984 for 36 months
Crop factor	0.8	0.8	0.6	0.8	1.4
Proportion veg. cover	0.36	0.36	0.26	0.40	0.85
Leaf Area Index	1.3	1.3	0.9	1.3	4.2
Canopy capacity (mm)	0.33	0.33	0.16	0.33	1.85
Infil. curve k parameter	0.63	0.63	0.63	0.63	0.63
Infil. curve C parameter	175.0	175.0	175.0	175.0	200.0
Total soil store (mm)	540.0	540.0	540.0	540.0	540.0
FC/Porosity ratio (PIV)	0.57	0.54	0.54	0.54	0.54
Soil hydraulic cond. (mm h^{-1})	18.5	18.0	18.0	18.0	18.0
G'water hydr. cond. (mm h^{-1})	1.8	2.0	2.0	2.0	2.0
Texture distr. factor	0.5	0.5	0.5	0.5	0.5
St. Dev. soil moist. distr.	0.11	0.16	0.16	0.16	0.14

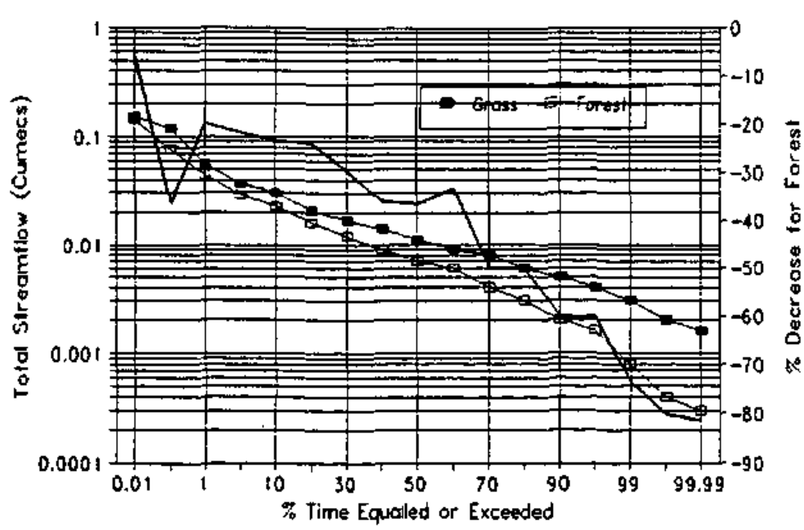


Figure A11.4 Simulated 1-day flow duration curves for fixed grassland and forest parameters (on the treated Erin catchment) applied to the period October 1977 to September 1991 (the bold line represents the % decrease in flow for the total catchment).

Table A11.14 Simulation results, VTI model, Erin catchments.

Catchment	Period		Mean ($l\ s^{-1}$)	SD ($l\ s^{-1}$)	Mean % Error	R^2	CE	Mean ln ($m^3\ s^{-1}$)	SD ln ($m^3\ s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Control 21 ha	10:1977 to 09:1982	Obs.	2.49	2.5				-6.29	0.72			
		Sim.	2.31	2.8	-7.1	0.87	0.85	-6.46	0.82	-2.7	0.88	0.78
	10:1982 to 09:1987	Obs.	1.64	2.2				-6.84	0.83			
		Sim.	1.64	2.1	0.0	0.64	0.63	-6.81	0.81	0.4	0.74	0.73
	10:1987 to 09:1991	Obs.	1.50	1.6				-6.82	0.81			
		Sim.	1.65	1.6	10.0	0.77	0.75	-6.75	0.74	1.0	0.79	0.78
Total 97 ha (Fixed grass parameters for 76 ha)	10:1977 to 09:1982	Obs.	18.6	19.8				-4.26	0.67			
		Sim.	17.8	14.5	-4.3	0.76	0.74	-4.27	0.64	-0.2	0.89	0.89
	10:1982 to 09:1987	Obs.	11.0	11.3				-4.80	0.68			
		Sim.	13.2	12.2	20.0	0.65	0.52	-4.63	0.74	3.5	0.71	0.58
	10:1987 to 09:1991	Obs.	8.2	7.2				-5.12	0.79			
		Sim.	13.7	10.0	67.0	0.82	0.08	-4.52	0.65	11.7	0.86	0.27
Total 97 ha (Time-sliced parameters for 76 ha)	10:1977 to 09:1982	Obs.	18.6	19.8				-4.26	0.67			
		Sim.	18.4	15.8	-1.1	0.77	0.75	-4.24	0.66	-0.5	0.90	0.89
	10:1982 to 09:1987	Obs.	11.0	11.3				-4.80	0.68			
		Sim.	12.0	11.2	9.1	0.69	0.67	-4.70	0.70	2.0	0.80	0.76
	10:1987 to 09:1991	Obs.	8.2	7.2				-5.12	0.79			
		Sim.	9.4	7.2	14.6	0.83	0.80	-4.95	0.76	3.3	0.86	0.81

Jonkershoek catchments, Bosboukloof.

Tables A11.15 and A11.16 list the parameter values and results statistics, respectively, for the Bosboukloof catchment (57% of catchment afforested then clear felled). As with the Erin catchments, the VTI model suggests a smaller landuse effect largely due to lower simulated volumes for the afforested situation. The streamflow increases vary from 21% after initial clearing and 32% for the later period which includes the wildfire effect. The values for R^2 and CE suggest, however, that the daily simulations are more than adequate. The relatively high value for the crop factor, for this catchment having 57% cover initially, compared to a similar value for the less mature, but denser cover, on the Erin catchment may be related to differences in soil type and evaporative demand. However, it may also suggest that a non-linear relationship between the value of this parameter and cover density and maturity is applicable, such that the value increases more slowly as cover density and tree maturity increase beyond certain levels. The changes to the channel depression storage parameter are designed to simulate evaporative losses from the channel and may reflect riparian zone water uses.

Table A11.15 VTI model parameters (see table 2.2 for explanations of parameter meanings), Bosboukloof catchment (200.9 ha).

Parameter name	Parameter values				
	Before Feb. 1981	Feb. 1981 for 2 months	Feb. 1982 for 2 months	Feb. 1986 for 1 month	May 1986 for 36 months
Crop factor	1.4	1.0	0.8	0.5	0.8
Proportion veg. cover	0.88	0.7	0.5	0.2	0.5
Leaf Area Index	4.1	3.1	2.1	0.8	2.1
Canopy capacity (mm)	1.92	1.5	0.8	0.2	0.8
Infil. curve k parameter	0.67	0.67	0.67	0.61	0.67
Infil. curve C parameter	196.6	185.0	175.0	125.0	175.0
Total soil store (mm)	440.0	440.0	440.0	440.0	440.0
FC/Porosity ratio (PIV)	0.5	0.5	0.5	0.5	0.5
Soil hydraulic cond. (mm h^{-1})	23.0	23.0	23.0	23.0	23.0
G'water hydr. cond. (mm h^{-1})	0.25	0.25	0.25	0.25	0.25
Texture distr. factor	0.82	0.82	0.82	0.82	0.82
St. Dev. soil moist. distr.	0.11	0.11	0.11	0.11	0.11
Max. channel depression store (mm).	0.04	0.04	0.03	0.00	0.03

Table A11.16 Simulation results, VTI model, Bosboukloof catchment.

Catchment	Period		Mean (l s⁻¹)	SD (l s⁻¹)	Mean % Error	R^2	CE	Mean ln ($m^3 s^{-1}$)	SD ln ($m^3 s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Fixed forest parameters	01:1979 to	Obs.	20.3	16.9				-4.08	0.57			
	12:1980	Sim.	22.1	18.1	8.9	0.88	0.86	-4.01	0.63	2.2	0.83	0.79
	01:1981 to	Obs.	34.0	27.2				-3.61	0.65			
	12:1985	Sim.	29.9	26.8	-12.1	0.83	0.80	-3.78	0.71	-4.7	0.91	0.82
	01:1986 to	Obs.	37.4	30.8				-3.54	0.68			
	12:1990	Sim.	28.3	20.2	-24.3	0.81	0.66	-3.78	0.65	-6.8	0.82	0.69
Sliced parameters for clearance	01:1981 to	Obs.	34.0	27.2				-3.61	0.65			
	12:1985	Sim.	36.1	31.3	6.2	0.82	0.76	-3.58	0.69	0.8	0.91	0.89
	01:1986 to	Obs.	37.4	30.8				-3.54	0.68			
	12:1990	Sim.	37.4	25.7	0.0	0.86	0.85	-3.49	0.63	1.4	0.89	0.88

Jonkershoek catchments, Lambrechtbos.

Tables A11.17 and A11.18 present the parameter values and simulation results for the Lambrechtbos catchments where the treatment is confined to thinning during normal growth. As with the Pitman model simulations, the results are less than clear and not very easy to interpret. Part of the problem lies in the fact that there is no stable landuse cover period to use for calibration and therefore some of the results could possibly include effects that are more related to generally inadequate parameter values, rather than inadequate changes to parameter values. It should also be emphasised that the meteorological inputs to these Jonkershoek catchments are difficult to define and the raingauge records used may be adequately representing the catchment inputs over some periods, but not others. The simulations do serve to illustrate the impact of modifying the main vegetation parameters.

Table A11.17 VTI model parameters (see table 2.2 for explanations of parameter meanings), Lambrechtbos catchment (65.5 ha).

Parameter name	Parameter values			
	Before Oct. 1972	Oct. 1972 for 62 months	Jan. 1978 for 3 months	Jan. 1983 for 3 months
Crop factor	1.4	1.4	1.3	1.1
Proportion veg. cover	0.92	0.95	0.82	0.73
Leaf Area Index	4.4	4.5	3.8	3.3
Canopy capacity (mm)	2.0	2.3	1.8	1.5
Infil. curve k parameter	0.67	0.67	0.67	0.67
Infil. curve C parameter	196.6	196.6	190.0	185.0
Total soil store (mm)	665.0	665.0	665.0	665.0
FC/Porosity ratio (PIV)	0.5	0.5	0.5	0.5
Soil hydraulic cond. (mm h^{-1})	23.0	23.0	23.0	23.0
G'water hydr. cond. (mm h^{-1})	0.4	0.4	0.4	0.4
Texture distr. factor	0.82	0.82	0.82	0.82
St. Dev. soil moist. distr.	0.14	0.14	0.14	0.14
Max. channel depression store (mm).	0.05	0.05	0.05	0.04

Table A11.18 Simulation results, VTI model, Lambrechtbos catchment.

Catchment	Period		Mean (l s⁻¹)	SD (l s⁻¹)	Mean % Error	R^2	CE	Mean ln ($m^3 s^{-1}$)	SD ln ($m^3 s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Forest parameters (col. 2 in table A11.17)	10:1972 to 09:1978	Obs.	7.0	9.3				-5.42	0.89			
		Sim.	7.8	12.2	11.4	0.67	0.41	-5.39	0.85	0.6	0.76	0.75
	10:1978 to 09:1983	Obs.	3.1	3.5				-6.13	0.80			
		Sim.	3.5	2.3	12.9	0.38	0.36	-5.75	0.50	6.1	0.67	0.41
	10:1983 to 09:1995	Obs.	6.6	7.2				-5.34	0.74			
		Sim.	5.1	7.5	-22.7	0.40	0.14	-5.56	0.68	-4.1	0.64	0.53
Sliced parameters for growth and thinning	10:1972 to 09:1978	Obs.	7.0	9.3				-5.42	0.89			
		Sim.	7.8	12.2	11.4	0.67	0.41	-5.38	0.85	0.8	0.76	0.75
	10:1978 to 09:1983	Obs.	3.1	3.5				-6.13	0.80			
			3.6	2.3	16.1	0.41	0.38	-5.71	0.50	6.8	0.71	0.38
	10:1973 to 09:1995	Obs.	6.6	7.2				-5.34	0.74			
		Sim.	5.6	8.0	-15.1	0.41	0.15	-5.46	0.67	-2.2	0.65	0.61

Jonkershoek catchments, Langrivier.

The results for the VTI model (parameter values given in table A11.19, results in table A11.20) using Langrivier data are very similar to the Pitman model results, in that the model was difficult to calibrate satisfactorily, despite having over 10 years of data with a stable landuse. This serves to illustrate the problems of trying to make use of any type of rainfall-runoff model when there are serious doubts about the representativeness of the rainfall input data. The impacts of the wildfire suggested by the VTI model are similar to those for the Pitman model (< 10% over the 8 years following the fire) and would seem to be less than the impacts that actually occurred. There is little doubt that the model calibration requires further refinement before any conclusions can be reached about the model's capabilities of simulating the effects of the wildfire.

Table A11.19 VTI model parameters (see table 2.2 for explanations of parameter meanings), Langrivier catchment (245.8 ha).

Parameter name	Parameter values		
	Before Oct. 1987	Oct. 1987 for 1 month	Oct. 1988 for 60 months
Crop factor	0.8	0.5	0.8
Proportion veg. cover	0.57	0.2	0.57
Leaf Area Index	2.3	0.8	2.3
Canopy capacity (mm)	0.82	0.2	0.82
Infil. curve k parameter	0.63	0.60	0.63
Infil. curve C parameter	180.6	125.0	180.0
Total soil store (mm)	216.0	216.0	216.0
FC/Porosity ratio (PIV)	0.5	0.5	0.5
Soil hydraulic cond. (mm h^{-1})	23.0	23.0	23.0
G'water hydr. cond. (mm h^{-1})	0.45	0.45	0.45
Texture distr. factor	0.82	0.82	0.82
St. Dev. soil moist. distr.	0.13	0.13	0.13
Max. channel depression store (mm).	0.03	0.03	0.03

Table A11.20 Simulation results, VTI model, Langrivier catchment.

Catchment	Period		Mean ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Mean % Error	R^2	CE	Mean ln ($m^3 s^{-1}$)	SD ln ($m^3 s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Normal parameters	01:1972 to 12:1987	Obs.	0.13	0.35				-2.77	1.01			
		Sim.	0.12	0.26	-7.7	0.37	0.36	-2.81	1.01	-1.4	0.76	0.74
	01:1988 to 09:1995	Obs.	0.13	0.27				-2.78	1.07			
		Sim.	0.10	0.20	-23.1	0.40	0.38	-2.94	0.99	-5.7	0.76	0.73
Sliced parameters for wildfire	01:1988 to 09:1995	Obs.	0.13	0.27				-2.78	1.07			
		Sim.	0.11	0.20	-15.4	0.41	0.39	-2.90	0.99	-4.3	0.76	0.75

Mokobulaan catchment.

The VTI model parameters used to simulate the effects of planting 100% of this catchment to pines are given in table A11.21, while table A11.22 and figure A11.5 illustrate the results. The effects are quite dramatic and illustrate the enormous impact that afforestation has had on the runoff from this catchment. The value for the total moisture storage is related to the apparently high available storage in the weathered and fractured shale bedrock, which has been treated as a 'soil' in the VTI model, largely because it seems to react in terms of drainage characteristics more like a soil than a typical ground water storage. The main reason for this is that a large part of the baseflow occurs quite rapidly, rather than as a slower and more sustained seasonal response. In fact the observed ground water drainage response lies somewhere between the type of response that would normally be modelled as soil baseflow and that which would normally be treated as ground water baseflow. The final reason for simulating the baseflows as drainage from a 'soil' is to allow that storage to be depleted by evapotranspiration. If the storage had been treated as ground water, less water would have been lost through this mechanism and the impacts would not have been reproduced as well. This clearly points to the need for an improved ground water - evapotranspiration routine that is required under certain situations.

Table A11.21 VTI model parameters (see table 2.2 for explanations of parameter meanings), Mokobulaan catchment (34.6 ha).

Parameter name	Parameter values		
	Before Oct. 1973	Oct. 1973 for 72 months	Nov. 1979 for 1 month
Crop factor	0.8	1.5	1.4
Proportion veg. cover	0.44	0.97	0.80
Leaf Area Index	1.5	4.8	4.0
Canopy capacity (mm)	0.51	2.3	1.9
Infil. curve k parameter	0.63	0.63	0.63
Infil. curve C parameter	200.0	210.0	210.0
Total soil store (mm)	1068.0	1068.0	1068.0
FC/Porosity ratio (PIV)	0.58	0.58	0.58
Soil hydraulic cond. (mm h^{-1})	19.0	19.0	19.0
G'water hydr. cond. (mm h^{-1})	0.2	0.2	0.2
Texture distr. factor	0.6	0.6	0.6
St. Dev. soil moist. distr.	0.17	0.15	0.15
Max. channel depression store (mm).	0.03	0.03	0.03

Table A11.22 Simulation results, VTI model, Mokobulaan catchment.

Catchment	Period		Mean ($l\ s^{-1}$)	SD ($l\ s^{-1}$)	Mean % Error	R^2	CE	Mean ln ($m^3\ s^{-1}$)	SD ln ($m^3\ s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Grassland parameters	10:1972 to 09:1975	Obs.	3.0	2.7				-6.06	0.65			
		Sim.	3.4	2.8	13.3	0.64	0.57	-5.97	0.74	1.5	0.80	0.73
	10:1975 to 09:1979	Obs.	1.9	2.6				-6.85	1.03			
		Sim.	3.5	4.0	84.2	0.48	-0.58	-6.05	0.86	11.7	0.62	0.01
	10:1979 to 09:1982	Obs.	0.4	0.8				-7.99	0.97			
		Sim.	2.5	2.5	525.0	0.66	-11.6	-5.94	0.70	25.6	0.73	-3.80
Sliced parameters for afforestation	10:1972 to 09:1975	Obs.	3.0	3.1				-6.06	0.65			
		Sim.	2.7	2.7	3.3	0.66	0.62	-6.08	0.79	-0.3	0.81	0.72
	10:1975 to 09:1979	Obs.	1.9	2.6				-6.82	1.00			
			2.0	2.9	5.3	0.58	0.45	-6.85	1.18	-0.4	0.82	0.74
	10:1979 to 09:1982	Obs.	0.4	0.8				-7.90	0.95			
		Sim.	0.4	0.6	0.0	0.69	0.69	-7.98	1.04	-1.0	0.71	0.64

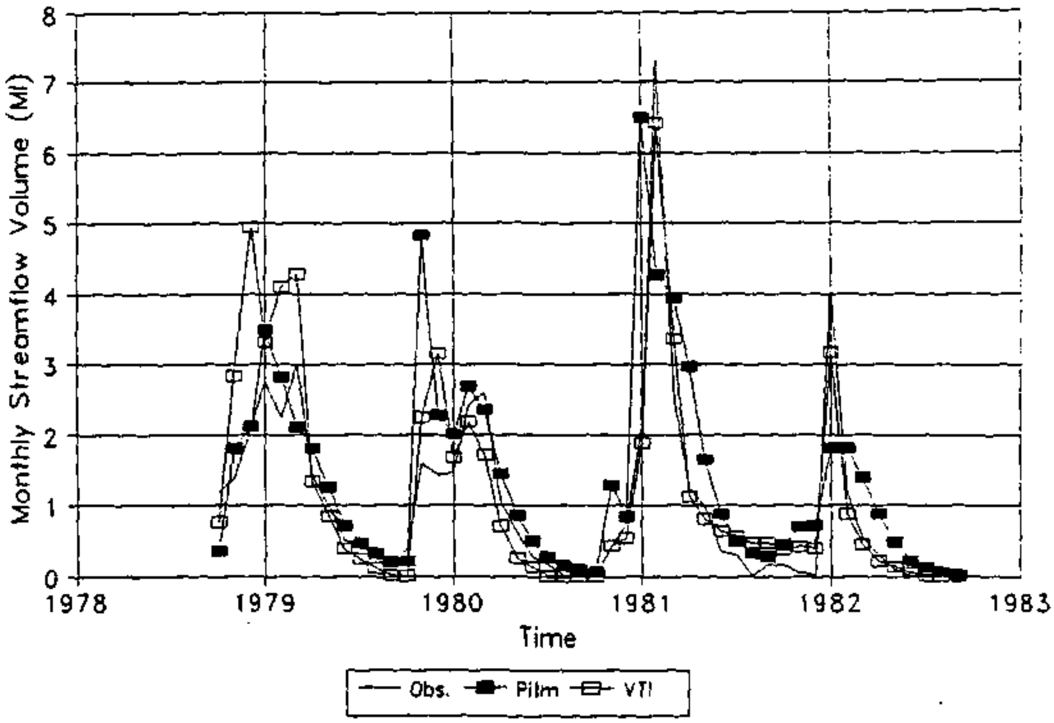


Figure A11.5 Mokobulaan catchment, observed and simulated (Pitman and VTI models) monthly streamflow volumes for October 1979 to September 1982 using the afforestation parameters.

Comparing the monthly hydrographs given in figure A11.5 for the two models with the observed data suggests that the daily model has been somewhat more successful and has reproduced the general seasonal response better. However, there is still some doubt about whether the VTI model will reproduce the post-1982 cessation of surface flow that is supposed to have occurred (but for which no data were provided). The relatively higher values for the crop factor and the vegetation cover parameters is a reflection of the complete coverage of this catchment (including the riparian strip) and only partial thinning during the record period.

Westfalia catchment.

The results for Westfalia are presented in table A11.23 (parameter values) and table A11.24 (simulation statistics). Table A11.23 indicates that higher parameter values have been used to represent afforestation with eucalypts (see also table A11.11 for the Pitman model). For example a maximum crop factor of 1.7 has been used on the basis of other reports of greater water use by this type of tree compared to pine species. Despite this, table A11.24 suggests that the observed effect in the final period has been under-simulated. Most of this under-simulation seems to be due to excessive (too sustained) ground water outflow simulated by the model, which may be a result of too little drying out of the soil by the trees and consequently too much recharge. It may also be that the trees are using more of the ground water moisture storage than is allowed for in the model. Unfortunately, no other catchment data sets were available that repeated the experience of afforestation with eucalypts and therefore the very high crop factor used (1.7 compared to 1.5 for full cover pine plantations) could not be tested.

Table A11.23 VTI model parameters (see table 2.2 for explanations of parameter meanings), Westfalia catchment (40 ha).

Parameter name	Parameter values				
	Before Feb. 1981	Feb. 1981 for 1 month	Dec. 1982 for 1 month	Mar. 1983 for 40 months	Oct. 1986 for 60 months
Crop factor	0.9	0.9	0.9	1.55	1.7
Proportion veg. cover	0.64	0.57	0.47	0.81	0.92
Leaf Area Index	2.65	2.2	1.7	3.7	4.5
Canopy capacity (mm)	1.03	0.82	0.57	1.62	2.1
Infil. curve k parameter	0.61	0.61	0.61	0.61	0.61
Infil. curve C parameter	160.6	160.6	160.6	180.6	190.6
Total soil store (mm)	1268.0	1268.0	1268.0	1268.0	1268.0
FC/Porosity ratio (PIV)	0.6	0.6	0.6	0.6	0.6
Soil hydraulic cond. (mm h^{-1})	18.5	18.5	18.5	18.5	18.5
G'water hydr. cond. (mm h^{-1})	0.5	0.5	0.5	0.5	0.5
Texture distr. factor	0.7	0.7	0.7	0.7	0.7
St. Dev. soil moist. distr.	0.15	0.15	0.15	0.13	0.12
Max. channel depression store (mm).	0.03	0.03	0.03	0.035	0.04

General comments about the VTI model simulations.

In general terms the VTI model applications can be considered a success. The model appears to be sensitive to most of the landuse changes and the parameter value modifications used to generate the effects are reasonably consistent and, where relevant, fit in with the parameter estimation procedures used with the model. The two parameters that were changed that have no parameter estimation procedures associated with them are the crop factor and the standard deviation of soil moisture distribution. The changes made to these parameters, for the various catchments used, do certainly fit a pattern that should be applicable to other areas. While it would clearly be useful to test this issue using more well documented changes, unfortunately, such information does not seem to be readily available.

Table A11.24 Simulation results, VTI model, Westfalia catchment.

Catchment	Period		Mean ($l\ s^{-1}$)	SD ($l\ s^{-1}$)	Mean % Error	R^2	CE	Mean ln ($m^3\ s^{-1}$)	SD ln ($m^3\ s^{-1}$)	Mean ln % Error	R^2 ln	CE ln
Fixed forest parameters	10:1976 to 09:1981	Obs.	9.4	11.0				-5.09	0.86			
		Sim.	9.3	13.9	-1.1	0.66	0.46	-5.09	0.80	0.0	0.87	0.87
	10:1981 to 09:1985	Obs.	2.8	3.1				-6.17	0.71			
		Sim.	3.7	4.1	32.1	0.79	0.52	-5.93	0.78	3.9	0.69	0.50
	10:1985 to 09:1991	Obs.	2.6	6.3				-6.69	1.19			
		Sim.	6.2	8.3	138.5	0.55	-0.12	-5.32	0.66	20.5	0.60	-0.75
Sliced parameters for clearance	10:1975 to 09:1981	Obs.	9.4	11.0				-5.09	0.87			
		Sim.	9.3	13.9	-1.1	0.66	0.46	-5.09	0.87	0.0	0.87	0.87
	10:1981 to 09:1985	Obs.	2.8	3.1				-6.17	0.71			
		Sim.	3.0	3.4	7.1	0.82	0.80	-6.14	0.78	0.5	0.74	0.68
	10:1985 to 09:1991	Obs.	2.6	6.3				-6.68	1.19			
		Sim.	3.1	6.1	19.2	0.57	0.54	-6.22	0.88	6.9	0.61	0.45

A11.7 General conclusions

Table A11.25 summarises the parameter value changes for the two models that have been used to simulate the main landuse effects represented by the limited data set that was made available. The table represents an attempt to integrate the results for all the catchments and provide approximate guidelines for future use of the models in similar situations. Caution should be exercised in applying these guidelines too literally as they are developed on the basis of a small sample of small sized catchments.

The models certainly seem to be capable of simulating the general response of catchments to afforestation and clear felling, but it is not clear to what extent the models are suitable for simulating the effects of thinning and the responses at certain stages of growth. The implication is that the experience of the models in not sufficient to allow their application to simulating the different responses brought about by different planting and management practices. The fact that the models have been able to reproduce the responses during the growth of a plantation forest, without even really attempting to relate the parameters to actual stages of growth, suggests that there is some potential for applying both models to more detailed studies. However, the likely success (or failure) of such an exercise cannot be concluded from the results of the present study.

With respect to a comparison of the volumes of the different components of the two models it is interesting to note what proportions are lost from canopy evaporation and soil or ground water evapotranspiration. For the Erin catchment under grassland conditions, the Pitman model suggests 16% and 84% for losses from the canopy and soil, respectively. Under forest conditions the overall evaporative losses increase by 31% and the distribution changes to 35% (canopy) and 65% (soil). The grassland figures for the VTI model are similar, except that 4% is simulated as being lost from ground water. For the forested condition (26% increase in total losses), 29% is lost as canopy evaporation, 67% from the soil and 4% from ground water. The other catchments indicate broadly similar trends, given the differences in the landuse changes and the parameter values used to represent them. Apart from the additional ground water component, the two models give broadly similar results using the Pitman model parameters recommended in this report. It is clear that if the commonly recommended standard value of 10.0 for forest interception were to be used, the balance between soil and canopy losses would be very different.

Table A11.25 Approximate summary of the parameter changes used for the two models to reproduce the landuse effects represented by the example catchments (the question marks suggest either unclear changes or small changes to which the results may be relatively insensitive).

	Pitman Model					VTI Model			
Main Landuse effect	Forest Int. Parameter (PIF)	Forest/veld PE ratio	Forest area	ZMIN	Evap-storage coeff.	Crop factor	Other Veg. parameters	Infil. curve C param.	St. Dev. soil moist.
Mature pine tree coverage	4.0	1.5	Used to control proportion of cover and growth.	10 - 30% increase	<0.1 for 100% cover	1.5 for 100% cover	Set % cover characteristics using the physiographic variable input facility and allow estimation procedures to calculate	10-15% Increase for 100% cover	10% Decrease for 100% cover
Thinning effects in pine plantations	4.0	1.5	Used to control cover density.	Reduced for thinning	Increased	Reduce to allow for thinning (?)		Decrease (?)	Small increase (?)
Clear felling of pine plantations	4.0	1.5	Reduced to zero	Can be quite large decrease	Increased	0.8 (?)		Decrease by about 10-15%	10-20% Increase
Burning of fynbos cover	N/A	N/A	N/A	Decreased to low value	1.0	0.5		Decrease by >30%	?
Mature eucalypt coverage	5.0	1.6	Used to control proportion of cover and growth.	Increase (?)	0.0 for 100% cover	1.7 for 100% cover		15-20% Increase for 100% cover	20% decrease for 100% cover
Thinning effects in eucalypt plantations	5.0	1.6	Used to control cover density.	Decrease slightly	Remains at 0.0	Reduce slightly (1.6 ?)		Decrease (?)	Small increase