DEVELOPMENT AND EVALUTION OF AN INSTALLED HYDROLOGICAL MODELLING SYSTEM

Report to the

Water Research Commission

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Page

LIST OF TABLES

DEVELOPMENT AND EVALUATION OF AN INSTALLED HYDROLOGICAL MODELLING SYSTEM

R.E. Schulze and A. Pike (Eds)

EXECUTIVE SUMMARY
(K5/1155)

OBJECTIVES AND INTENDED RESEARCH PRODUCTS

The three stated objectives of this research project were

- first, the development of a generic framework for Installed Hydrological Modelling Systems (IHMS) to be utilised by experts in the service of water authorities in South Africa
- secondly, the development of a national, regional and local hydrological data and information system for application in South Africa and in support of IHMS and the *ACRU* model and
- thirdly, the application, promotion, maintenance, development and improvement of the *ACRU* model, as required by the project and in response to appropriate and reasonable requests from users, and improvement of the *ACRU* agrohydrological modelling system within the above framework.

The intended research products were also threefold, *viz*,

- first, a more user-friendly, versatile and multi-purpose *ACRU* modelling system, linked to information bases and utilising GIS (Geographic Information Systems), where appropriate, to assist in the selection of input variables and for the display of output from the model
- secondly, applications of the IHMS to selected catchments and water management areas of South Africa and
- thirdly, in collaboration with other WRC projects, revised GIS accessible images/maps on variables and model inputs for South Africa.

OUTPUTS FROM THE PROJECT

This report presents items from the wide range of output generated by the project in three sections with, respectively, one, five and three independent chapters each. The three sections are

- **Section A** on **"*The Concept of Installed Hydrological Modelling Systems*"**
- **Section B** on **"*The ACRU Model and Enhancements to its Support Systems*"** and
- **Section C** on **"*Case Studies Using the ACRU Model as an Installed Hydrological Modelling System*".**

In regard to the project's objectives,

- Objective 1 is covered in detail in Chapter 6, with applications in Chapters 7 to 9, and by the inclusion in this report of a CD containing the framework and databases of the 1946 Quaternary Catchments of the RSA, Lesotho and Swaziland as an IHMS
- Objective 2 is encapsulated in Chapter 3 and
- Objective 3 is in Chapters 2, 4 and 5

while, similarly, with regard to the intended research products,

- Product 1 is covered in Chapters 2, 3, 4, 5 and 6
- Product 2 in Chapters 1, 7, 8 and 9 and
- Product 3 in Chapters 3 and 6
- with the CD alluded to above as an additional Product.

Section A consists of a single, short introductory chapter titled **"*Installed Hydrological Modelling Systems : Concepts and Examples*",** outlining what is understood by an IHMS and followed by a summary of catchment case studies which are not presented in this report.

Chapter 2 in Section B, ***"The ACRU Agrohydrological Modelling System : A Review up to Developments and Refinements Described in this Project"***, traces the development of the *ACRU* agrohydrological modelling system, from a distributed catchment evapotranspiration model in the mid-1970s through its various phases of enhancement, with milestone years in terms of new documentation being 1984, 1989 and 1995, to the present system, which is a multi-partnered national and international development spearheaded by funding from the Water Research Commission.

The conceptual basis of the model is outlined next. This includes discussion on the model's physical-conceptual process representation and on *ACRU* as a multi-purpose and multi-level model founded on daily multi-layered soil water budgeting procedures. The model can be operated as a lumped or distributed catchment simulator of streamflow components, with options for reservoir yield, sediment yield, irrigation demand/supply, crop yield and climate change analyses, and with a strong focus on land use impacts on hydrological responses. The model contains a dynamic input option to account for changes, either abrupt or gradual, in the catchment over time. Thereafter, the *ACRU* model's water budget is described, with emphasis on the vertical redistribution of soil water, evapotranspiration processes and runoff generation mechanisms, followed by a section on output options. The section on process representation includes those which were enhanced / refined in the course of this project, notably riparian zone processes which have now become important in the context of the National Water Act of 1998. *ACRU*'s riparian process representation is depicted schematically in Figure ES.1.

A section is devoted to the operation of *ACRU* as a distributed model, many developments of which were made in this project, as illustrated in Figure ES.2. Modelling system components and linkages are illustrated and typical minimum input requirements are presented diagrammatically before some of the main system utilities. The description is of those utilities which preceded the developments made within this project. The updated utilities are then described in Chapter 4. The chapter concludes with a summary of perceived model system strengths, what the model should *not* be used for and where the current (2003 and beyond) research focus lies.

This review updates and supersedes those of Schulze (1995) and Smithers and Schulze (1995) and is inclusive of developments and applications up to 2002. It is a shortened and slightly amended version of a full review by Schulze and Smithers (2002).

Chapter 3, ***"Determination of Baseline Land Cover Variables for Applications in Assessing Land Use Impacts on Hydrological Responses in South Africa",*** is the application which has been selected to represent Objective 2 and Products 1 and 3 in this report. Baseline land cover variables for hydrological models such as *ACRU* constitute the datum against which impacts of present land uses on hydrological responses may be assessed in light of requirements of the National Water Act (e.g. streamflow reduction activities, or the ecological reserve). Arguments are presented for the selection of Acocks' Veld Types as a suitable baseline land cover. Approaches to assigning hydrological variables to Acocks' Veld Types are described. Working rules for the determination of the water use coefficient, interception loss, root distribution, an infiltrability index and the suppression of soil water evaporation by litter are established, based *inter alia* on quantitative expressions of the moisture growing season, frost occurrence, heat units as well as rainfall seasonality and other characteristics. From climatic attributes of each of the Acocks Veld Types found in South Africa and other working rules, sets of month- by- month baseline variables for the water use coefficient, root distribution, interception per rainday, a coefficient of initial abstraction and soil water evaporation suppression are presented for each of the 70 Veld Types identified in South Africa. These baseline values are now part of the *ACRU* Decision Support System contained in a National Quaternary Catchments Database described in Chapter 6.

Chapter 4 is titled ***"New Developments in, and Refinements to, Supporting Software, Documentation, User Support and Promotion of the ACRU Agrohydrological Modelling System".*** This Chapter covers 12 separate sections of which the first is on *CalcPPTCor,* a utility to assist in the selection of rainfall stations and the adjustment of point rainfall data to an (i.e. areal catchment) representation. A utility to classify monthly rainfall and temperature values into climatic forecast categories of the above normal, near normal and below normal is presented next, followed by sections on the new Windows based *ACRU* menubuilder, *MB3*, a screenshot of the opening screen being illustrated in Figure ES.3.

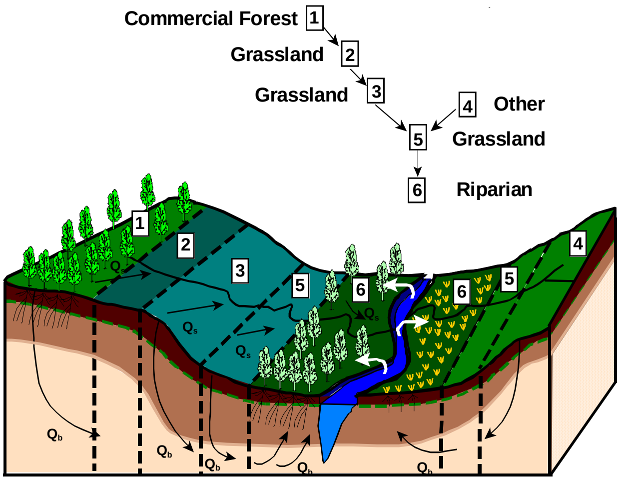

Figure ES.1 Schematic representation of riparian zone processes in *ACRU*

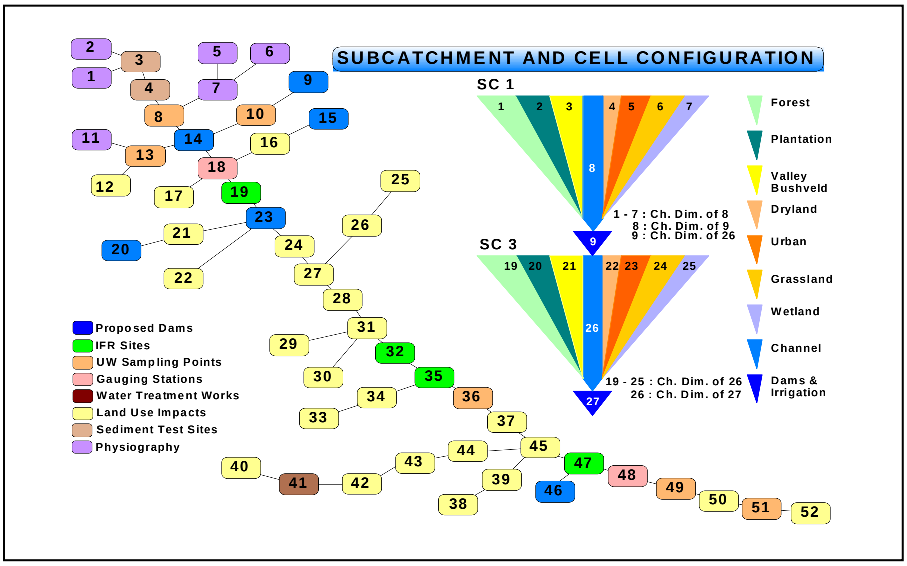

Figure ES.2 An example from the Mkomazi catchment of discretisation into management subcatchments, with further subdelimitation by land uses

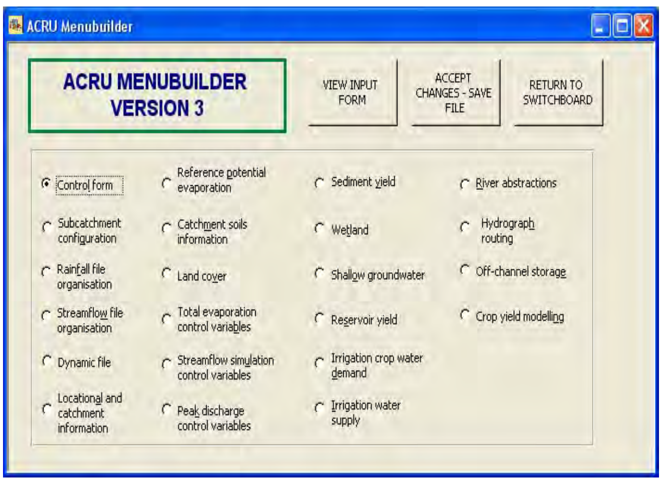

Figure ES.3 Screenshot of the Windows version of the *ACRU MenuBuilder* (V3.00)

There are sections on software developed to convert binary to database files and others on the utilities to select output variables and to convert older menus to render them compatible with the *ACRU* 2000 system.

Section 8 of Chapter 4 describes the development of the *ACRU* model website which, in addition to information on online documentation, frequently asked questions, model structure/ linkages/ decision support, and "tips and tricks" also contain an online discussion group, the opening screenshot of which is shown in Figure ES.4. This is followed by a section on the development of electronic *ACRU* theory and user manual documentation, a screenshot of former being depicted in Figure ES.5. As part of the model's promotion, a synthesis brochure on *ACRU* was published, part of which is illustrated in Figure ES.6. The chapter concludes with the section on user support, one of the most valuable functions supported by the WRC through this project.

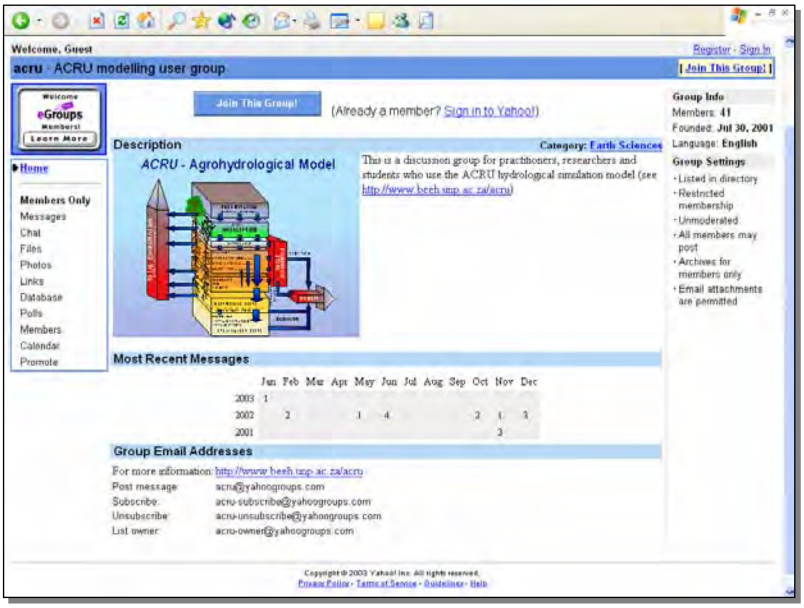

Figure ES.4 Screenshot of the *ACRU* User Group hosted by Yahoo Groups

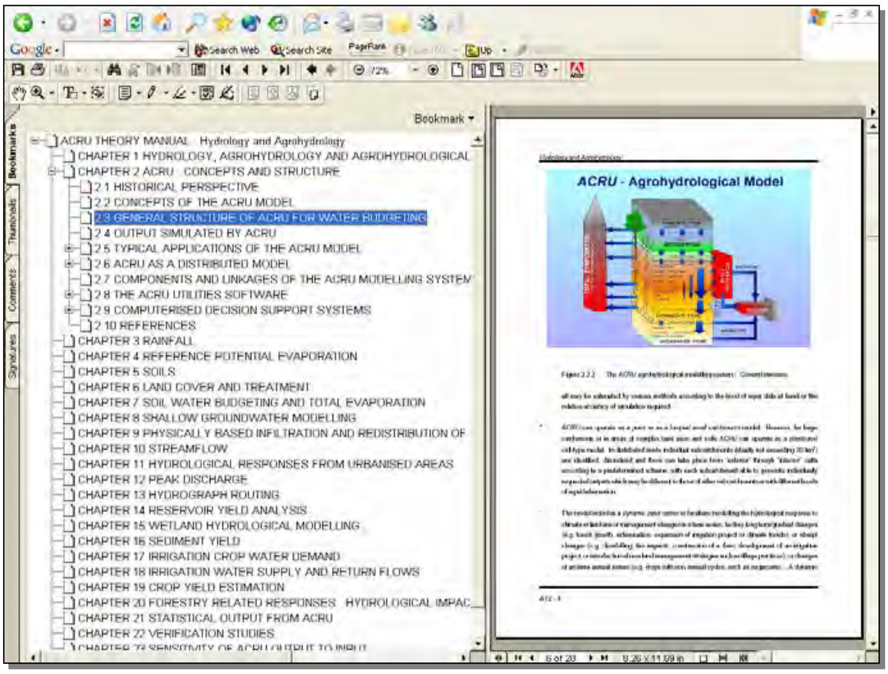

Figure ES.5 A sample page from the electronic version of the *ACRU* Theory Manual

Figure ES.6 The *ACRU* brochure : Side one

Chapter 5 on ***" ACRUView : A Visualisation and Statistical Package for Use with the ACRU Agrohydrological Modelling System"*** is a 20 page user manual on *ACRU*View, a Microsoft excel based application tool written under sub-contract by WMA Consultants and designed to analyse and view information produced by the model. This highly versatile software package, the homepage of which is shown in Figure ES.7, produces displays of statistics, comparative statistics, graphs (e.g. Figure ES.8), extreme value analyses, runlength analyses and flow duration curves.

The first and second objectives of this project are encapsulated in Chapter 6 on **"*The South African National Quaternary Catchments Database : Refinements to, and Links with, the ACRU Model as a Framework for Installed Hydrological Modelling Systems*".** As summarised in Figure ES.9, four main themes constitute this chapter. The first theme is the *ACRU* Input Database structure developed for use with the *ACRU* model. The next theme is the interface between this Input Database and the model. The third theme is the simulation of agrohydrological responses using *ACRU* with this automated system and lastly the extraction of output from the model for presentation of results.

In Section 6.2 the initial structure of the *ACRU* Input Database used to simulate agrohydrological responses of the Quaternary Catchments is outlined (*cf*. Figure ES.9). This database structure was found to be limiting and was subsequently revised, as described in Section 6.3. These revisions are continuing. The new database structure allows for greater flexibility when carrying out an *ACRU* simulation for agrohydrological simulations. In addition, this revised structure facilitates the option of subdividing the Quaternary Catchments into the next level of disaggregation, *viz*. Quinary Catchments, in those Quaternaries with a high intra-catchment variability and which, through subdivision, may result in a more realistic hydrological simulation.

Figure ES.7 The *ACRU*View homepage

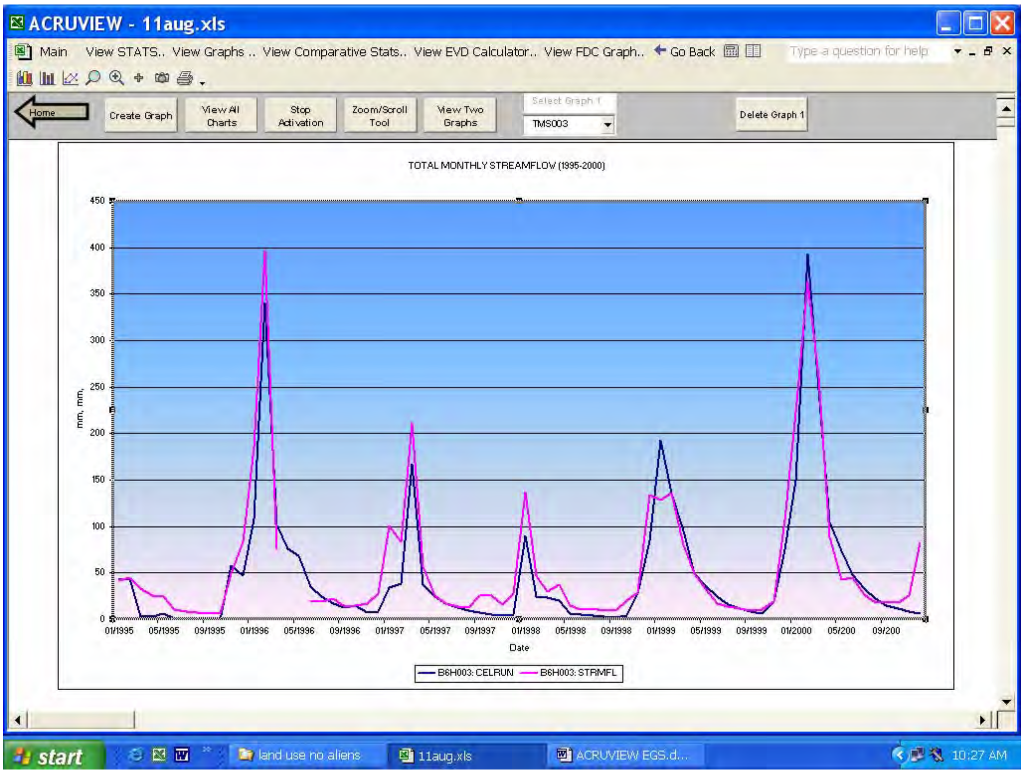

Figure ES.8 Example of a time series plot with two variables

This revised database structure was used to store the *ACRU* input parameters for the 1946 Quaternary Catchments in southern Africa as a pre-populated database which can be accessed by multiple users. However, the information stored in the *ACRU* Input Database for each Quaternary Catchment needed enhancement, as highlighted in Section 6.4.

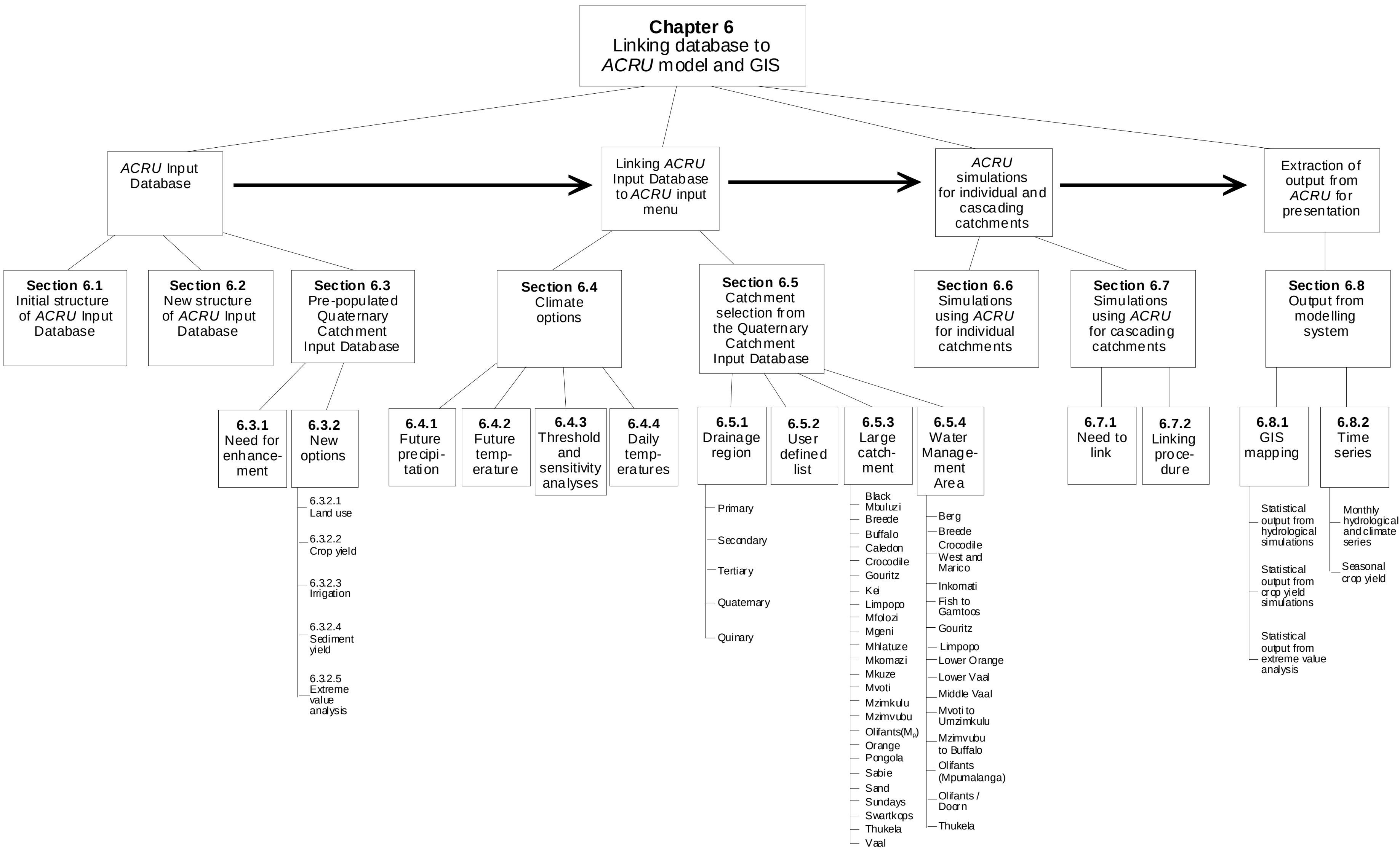

Figure ES.9 Layout plan of Chapter 6: Linking the *ACRU* Input Database to the *ACRU* model and GIS

The next objective was to develop an interface to link the *ACRU* Input Database to the *ACRU* model's input menu. This interface facilitates the incorporation of future climate scenarios, different levels of temperature input (Section 6.5) and the rapid selection of catchments whose information has been stored in the database (Section 6.6). When using this interface there is the choice of simulations methods, i.e. either simulating the hydrology of selected catchments individually or as cascading interlinked catchments. The methodology used for the simulation of catchments in *ACRU* is explained in Sections 6.7 and 6.8. Lastly, the extraction of output from *ACRU* for input into a GIS or for display as a time series is described in Section 6.9. This chapter provides an overview of the Quaternary Catchments database as of 2002.

Section C on **"Case Studies using *ACRU* as an Installed Hydrological Modelling System"** is made up of three case studies using *ACRU* as an IHMS. In Chapter 7 **"*Indicators of Hydrologic Alteration for Assessing Environmental Flows for Highly Variable Rivers*"**, the role of flow on aquatic and riparian ecosystem processes has highlighted the potential of the natural hydrograph in setting environmental flow requirements. Most studies adopt the natural flow paradigm by constructing environmental flow regimes that mimic the full range of natural intra- and inter-annual variation of hydrological regimes. Recognising that hydrological variation plays a major role in structuring the biotic diversity within river ecosystems, the US Conservancy developed the so-called Indicators of Hydrologic Alteration, IHA, a methodology to characterise the natural range of streamflow variation. The methodology analyses 33 ecologically relevant characteristics of the hydrological regime. However, it is typically applied to less variable climatic conditions than those experienced in South Africa and other semi-arid countries, where aquatic and riparian ecosystems are influenced by highly variable inter- and intra- annual climatic conditions. Longer than recommended streamflow records may be required to account for the variability associated with these climatic characteristics. The potential of this methodology is explored for its suitability to assess the environmental flows required by highly variable river systems and the identification of alternative indicators. In particular, the hydrological regime of the Mkomazi River in KwaZulu-Natal, South Africa is assessed to ascertain the likely alteration of streamflows by the construction of proposed dams.

Chapter 8 on **"*Planning for the Environmental Reserve of the Mkomazi Catchment*"** provides a second case study on environmental theme. Hydrological regimes play a major role in structuring the biotic diversity within river ecosystems and hydrological variation is recognised as a primary driving force within those ecosystems. The Range of Variability Approach, RVA (Richter *et al*., 1997), is an application of the IHA described in Chapter 8, incorporating the concepts of hydrological variability and river ecosystem integrity, and was developed to enable river managers to define and adopt preliminary flow management targets before conclusive, long-term ecosystem research results are available. This paper presents an application of the RVA to simulated streamflows at two of the four Instream Flow Requirements (IFR) Sites on the Mkomazi River in KwaZulu-Natal in order to assess the extent of alteration caused by human induced changes to the hydrological regime. The assessment was achieved by comparing the range of variation of the hydrological regime simulated under natural catchment conditions (pre-impact) with the variation resulting from catchment development (post-impact). The 25th and 75th percentile values of each of the 33 parameters were selected as the lower and upper thresholds within which streamflow management targets could be set. By setting preliminary streamflow management thresholds which can be modified and refined when ecological data and information become available, the RVA incorporates flexibility and adaptability.

The last case study, *viz*. Chapter 9 on **"*Meso-Scale Indicators of Water Poverty in the Thukela Catchment, South Africa, Under Baseline Land Cover Conditions*",** presents *ACRU* as an IHMS in research related to a Water Poverty Index. The value of the results of water resources assessments is minimal if they are not linked to, or viewed in the light of, human welfare. Since the 1992 World Summit in Rio de Janeiro, several global initiatives (e.g. The 5th Global Forum of Water Supply and Sanitation Collaboration Council, 2000; 6th Session of the Commission for Sustainable Development) have highlighted the strategic importance of the water sector in poverty alleviation and the promotion of regional stability. This has resulted in the classification of countries and regions on the basis of water stress in order to implement interventions in crisis areas. At regional and national scales, Falkenmark's (1989) water stress index) has been used with considerable success for these categorisations. However, this method is too coarse for sub-national (provincial, small catchment or community) classification programmes. Furthermore, suitable methods or indices of water stress and poverty, in addition to having to be multi-disciplinary and having to link physical water availability (supply) with requirements of human population (demand), need to accommodate the population's capacity to access water and adapt to its shortage.

The Centre for Ecology and Hydrology (CEH) at Wallingford in the UK co-ordinated a multi-phased and multi-institutional research project aimed at deriving a tool for addressing the needs highlighted above. The tool is known as a Water Poverty Index (WPI), and its utility includes:

- enabling the classification of regions on the basis of a quantifiable methodology which reflects both the physical availability of water and the human adaptive capacity to access it,
- facilitating an assessment of progress towards water related development targets,
- contributing towards prioritisation of water related needs, and
- monitoring the effectiveness of water related development projects.

The University of Natal's School of Bioresources Engineering and Environmental Hydrology (SBEEH) was one of the partner institutions in the research project. For the SBEEH, the objectives of Phase 1 of this study were:

- to provide an overview of the background hydrology of the Thukela catchment assuming baseline land cover conditions, i.e. land cover not influenced by human activities;
- in regard to water availability at the meso-scale, i.e. at the operational subcatchment level of 10s to 100s km^2 in area;
- in order to identify where, how much and how variable individual subcatchment flows as well as accumulated flows are; and furthermore
- to provide more specific detail on the background water availability at the two selected field sites within the Thukela, *viz*. at Keate's Drift and Wembezi;
- by configuring the entire Thukela into relatively homogeneous operational subcatchments in order to undertake hydrological simulations under baseline land cover conditions using the *ACRU* agrohydrological simulation model; and
- to undertake preparatory work for an envisaged Phase 2 of this WPI study.

Section 9.2 presents background information on the Thukela catchment, focusing on aspects of its hydroclimatology, but also introducing elements of human influences on the landscape by briefly assessing present land use patterns as well as discussing the general poverty status within the catchment. The configuration of the *ACRU* model for hydrological simulations is discussed in Section 9.3, while overall and site-specific results are presented in Sections 9.4 and 9.5 respectively. The case study concludes with recommendations of work proposed for Phase 2 of the project.

MEETING PROJECT OBJECTIVES

As alluded to previously already, the three project objectives and the three proposed research products have been met as follows :

- Objective 1 on the development of a generic framework for IHMS is met through Chapters 6 – 9 and by the contents of a CD-Rom which comes with this report and which includes the framework and databases (as used up to 2002) for the 1946 Quaternary Catchments of South Africa, Lesotho and Swaziland as an IHMS,
- Objective 2 on data and information systems is exemplified by the contents of Chapter 3, while
- Objective 3 on the application, promotion, maintenance, development and improvement of the *ACRU* modelling system is met through the information contained in Chapters 2, 4, and 5.
- Research Product 1 on a more user friendly and versatile *ACRU* modelling system is delivered through Chapters 2 to 6 (inclusive)
- Research Product 2 on applications of *ACRU* as an IHMS is met through the three selected case studies (out of several more completed; *cf*. Chapter 1) presented in Chapters 7-9, while
- Research Product 3 on revised model input is provided in Chapters 3 and 6.
- An additional Research Product is the CD, the contents of which is described above under Objective 1.

RECOMMENDATIONS FOR FURTHER RESEARCH

The *ACRU* model is one of the models recommended by the Department of Water Affairs and Forestry for use at Catchment Management Agency operational level to address the multitude of management issues which CMAs will face, e.g. on land use and climate change impacts, streamflow estimation, water quality simulations, water allocation including fractional allocation, demand management, dam operating rules, streamflow reduction activities, instream flow requirements or streamflow forecasting.

A follow-up project would need to address the above issues from a model development perspective and, further, consolidate the many *ACRU* process representations already researched, but not yet imbedded in the "official" publicly available version of the model. The latter includes N, P, salinity and *E.coli* routines, the Penman- Monteith equation as the estimator of reference potential evaporation and dam operating rules.

A second recommendation revolves around the development of a more comprehensive, user-friendly and seamlessly operating Hydrological Decision Support Framework (HDSF) in which models are linked with a common, flexible and extensible database fully integrated with a GIS to ensure maximum flexibility in model configurations and model interrogations by water resource managers for planning and scenarios analyses.

A final recommendation would be continuation in providing user support and up-to-date user documentation, for the *ACRU* model in particular and HDSF in general.

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  - Dr S.S. Mkize — Water Research Commission
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  - Prof J.C. Smithers — University of Natal
  - Mr M. D. Watson — Department of Water Affairs and Forestry
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CHAPTER 1

INSTALLED HYDROLOGICAL MODELLING SYSTEMS : CONCEPTS AND EXAMPLES

Roland Schulze

1.1 INSTALLED HYDROLOGICAL MODELLING SYSTEMS : THE CONCEPT

A key objective of this project was research into the development of a "generic framework for Installed Hydrological Modelling Systems (IHMSs) for applications by experts in the service of water authorities". Before such a "framework" is described, and the other project objectives and products are discussed/evaluated in the chapters which follow, the question on what is understood by an IHMS is first posed.

The concept of an IHMS is

- to configure a catchment on which operational decisions need to be made with (say) daily hydrological models at an appropriate level of spatial detail with respect to
  - delimiting relatively homogeneous response zones with regard to
  - local water related problems at hand and
  - anticipated problems of the future
- to populate the modelling system with standardised, quality controlled hydrological relevant data and information at a suitable level of detail on, for example,
  - climate variables at suitable temporal scale
  - soils
  - baseline land cover
  - land use
  - reservoirs and/or
  - irrigation demand

  and
- to link the above to an appropriate hydrological model (or models) such that once it has been set up, output may be generated with a minimum of additional effort to answer a wide range of conventional or emerging questions on, for example,
  - the intra- and inter- annual distributions of streamflows
  - water quality
  - source areas and generating mechanisms of water quality/quantity
  - potential land use/ climate change impacts
  - environmental issues
  - water poverty
  - water licensing and allocation
  - streamflow reduction activities or
  - extreme events.

There will be differences in IHMSs set up for different catchments or Catchment Management Agencies (CMAs), but the commonality is their detailed configuration which facilitates providing answers to wide ranging and often new/emerging questions of local, regional, national and/ or international significance, with relative rapidity.

What follow below are examples of IHMSs in six catchments in southern Africa. The titles of the references indicate the wide range of questions which can be addressed once an IHMS has been set up.

1.2 INSTALLED HYDROLOGICAL MODELLING SYSTEMS : EXAMPLES

1.2.1 The Mgeni Catchment

The 4 079 km^2 Mgeni catchment in KwaZulu-Natal is one of the most intensively studied catchments in South Africa. It has been configured for the *ACRU* model with ever increasing detail since the early 1990s, such that its 12 Quaternary Catchments are currently delimited into 137 relatively homogeneous cascading subcatchments. Perusal of the references below shows that specific problems addressed have revolved mainly around impacts of land use (present and anticipated future) on both water quality and quantity, effects of riparian zone clearance and analyses on extreme events, both high and low flows.

De Wet, D.L. (1993). *Assessment of Impacts of Feedlots on Water Quality in the Mgeni Catchment*. Unpublished MScEng dissertation. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering. pp 144.

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Tarboton, K.C. and Schulze, R.E. (1993). Hydrological consequences of development scenarios for the Mgeni catchment. *Proceedings, 6th South African National Hydrological Symposium*. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering. 297-304.

1.2.2 The Mkomazi Catchment

The 4 383 km^2 Mkomazi catchment was configured in detail in the late 1990s in the course of an EU funded project on the development of integrated water resources management (IWRM) systems. Within the broad realm of simulating scenarios relevant to IWRM, a focus in the Mkomazi has been on environmental issues (see especially Chapter 7 and 8 of this report), impacts of proposed reservoir construction and water allocation.

Staudenrausch, H., Flügel, W-A., Ranchin, T., Herlin, I., Rodolfi, G., Clark, M.J., Schulze, R.E., King, N., Tevera, D.S. and Matondo, J.I. (1999). The development of an innovative computer based Integrated Water Resource Management System for semi-arid catchments : Concepts and first results. *Zentralblatt für Geologie und Paläontologie*, Teil 1, Heft 3-4, 189-212.

Taylor, V. (2001). *Hydrological Modelling Applications for Water Resources Management in the Mkomazi Catchment*. Unpublished MSc dissertation (*cum laude*). University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 256.

Taylor, V., Schulze, R.E., Jewitt, G.P.W. and Pike, A. (1999). Modelling needs for integrated water resources management : Mkomazi catchment case study. *Proceedings, 9th South African National Hydrology Symposium*. NSI CapeTown, RSA. Plenary 5, Paper 2. pp 11.

Taylor, V., Jewitt, G.P.W. and Schulze, R.E. (2001). Assessing the alteration of natural flow regime of the Mkomazi River. *Proceedings, 10th South African National Hydrology Symposium*. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 11 (on CD-Rom).

Taylor, V., Schulze, R.E. and Horan, M.J.C. (2001). Streamflows available for allocation in the Mkomazi catchment, KwaZulu-Natal, South Africa. *In: Proceedings, 10th South African National Hydrology Symposium*. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA. pp 11 (on CD-Rom).

1.2.3 The Pongola Catchment

The 5 789 km^2 Pongola/ Bivane catchment upstream of Pongola town straddles the KwaZulu-Natal and Mpumalanga provinces and parts of southern Swaziland. This catchment was set up as an IHMS in response to water conflicts between the irrigation and afforestation sectors, particularly upstream of Paris Dam which has a major impact on downstream water resources, and also on dam operating rules with respect to ecological water requirements.

Butler, A.J.E. (2002). *The Development and Evaluation of an Operating Rule Framework into the ACRU 2000 Agrohydrological Modelling System*. Unpublished MScEng dissertation. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering. pp 146.

Butler, A.J.E., Smithers, J.C., Jewitt, G.P.W. and Clark, D.J. (2001). The development of an operating rule framework to satisfy the requirements of the National Water Act. *Proceedings, 10th South African National Hydrology Symposium*. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 12 (on CD-Rom).

Horan, M.J.C., Jewitt, G.P.W., Meier, K.B., Pike, A. and Schulze, R.E. (2000). The hydrological impacts of land use practices in the Pongola-Bivane Catchment Phase IV. Impacts of proposed clearance of alien invasive trees from the riparian zone and complementary afforestation on streamflows. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. *ACRUcons Report*, 31.

Jewitt, G.P.W., Horan, M.J.C., Meier, K.B. and Schulze, R.E. (2000). A hydro-economic assessment of the benefits of clearing alien vegetation from riparian zones in a South African catchment. *Proceedings, 7th British Hydrological Society Symposium*. University of Newcastle, Newcastle-Upon-Tyne, UK. 103-111.

Schulze, R.E., Horan, M.J.C., Shange, S.N., Ndlela, R.M. and Perks, L.A. (1998). Hydrological impacts of land use practices in the Pongola-Bivane catchment, Phase 3: Impacts of afforestation on streamflows and of irrigation abstractions on Paris Dam. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. *ACRUcons Report,* 26. pp 58.

Schulze, R.E., Pike, A., Lecler, N.L., Esprey, L.J., Howe, B.J. and Zammit, R.M. (1996). Hydrological impacts of land use practices in the Pongola-Bivane catchment. *ACRUcons Report*, 11. pp 49.

Schulze, R.E., Taylor, V., Matthews, G. and Hughes, G.O. (1997). Hydrological impacts of land use practices in the Pongola-Bivane catchment, Phase 2 : Re-assessment of land uses in the Bivane catchment and hydrological impacts thereof. *ACRUcons Report,* 20. pp 22.

Schulze, R.E., Taylor, V. and Pike, A. (1997). Sensitivity of hydrological responses to land use : Results from a modelling study in the Pongola-Bivane catchment. *Proceedings, 8th SA National Hydrology Symposium*. Water Research Commission, Pretoria, RSA. pp 20 (on CD-Rom).

Schulze, R.E., Taylor, V. and Pike, A. 1998. Sensitivity of hydrological responses to land use: Results from a modelling study in the Pongola-Bivane catchment, South Africa. *In*: Wheater, H. and Kirby, C. (Eds) *Hydrology in a Changing Environment, Vol 2*. Wiley & Sons, Chichester, UK. 537-552.

Taylor, V. (1997). *The Application and Simulation Modelling of Hydrological Conflict Resolution: Pongola Catchment Case Study*. Unpublished MSc dissertation. University of Natal, Pietermaritzburg, RSA, School of Environment and Development. pp 110.

1.2.4 The Sabie Catchment

The 6 260 km^2 portion of the Sabie catchment which is located within borders of South Africa, is a key catchment in the management of the waters flowing into the Kruger National Park and the waters exiting South Africa into Mozambique. It was first set up as an IHMS for the *ACRU* model in 1996 to assess source areas of sediments. The Sabie was revisited in more detail to assist in managing the delivery of the ecological reserve to the Sabie within the Kruger National Park. As a consequence of its having been configured as an IHMS, the Sabie was used in an assessment of the continuous modelling approach to design hydrology following the floods of 2000.

Jewitt, G.P.W. (1998). *Resolution of Scale Issues in an Integrated Catchment Information System for the Rivers of the Kruger National Park*. Unpublished PhD thesis. University of Stellenbosch, RSA, Department of Civil Engineering. pp 217.

Jewitt, G.P.W., Horan, M.J.C., Meier, K.B. and Schulze, R.E. (2000). A hydro-economic assessment of the benefits of clearing alien vegetation from riparian zones in a South African catchment. *Proceedings, 7th British Hydrological Society Symposium*. University of Newcastle, Newcastle-Upon-Tyne, UK. 103-111.

Pike, A. and Schulze, R.E. (2000). *Development of a Distributed Hydrological Modelling System to Assist in Managing the Delivery of the Ecological Reserve to the Sabie River System within the Kruger National Park*. Water Research Commission, Pretoria, RSA, Report 884/01/00. pp 71.

Pike, A., Schulze, R.E., Lorentz, S.A., Ballim, F., Taylor, V. and Howe, B.J. (1997). Simulation of streamflows and sediment yields in the Sand and Sabie catchments : Initial results. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering, *ACRUcons Report,* 17. pp 67.

Smithers, J.C., Schulze, R.E., Pike, A. and Jewitt, G.P.W. (2001). A hydrological perspective of the February 2000 floods : A case study in the Sabie River Catchment. *Water SA*, 27, 325-332.

1.2.5 The Thukela Catchment

The Thukela catchment constitutes one of the 19 Water Management Areas delimited in South Africa to become a Catchment Management Agency in future. Its 29 062 km^2 covers areas ranging from 3 300m in altitude to the Indian Ocean and from highly developed commercial irrigation to subsistence agriculture in semi arid zones. It was first configured as an IHMS for the *ACRU* model to undertake detailed assessments of the impacts of proposed major dams on sediment yield and environmental flows. The Thukela has subsequently been designated a UNESCO HELP (i.e. Hydrology for the Environment, Life and Policy) catchment for studies on integrated water resources management, as well as an International Dialogue on Water and Climate catchment to assess impacts of climate variability and climate change on water resources. It is, furthermore, a case study catchment for this report (*cf.* Chapter 9).

Jewitt, G.P.W., Horan, M.J.C., Meier, K.B. and Schulze, R.E. (2000). A hydro-economic assessment of the benefits of clearing alien vegetation from riparian zones in a South African catchment. *Proceedings, 7th British Hydrological Society Symposium*. University of Newcastle, Newcastle-Upon-Tyne, UK. 103-111.

Jewitt, G.P.W., Taylor, V., Hallowes, J.S. and Horan, M.J.C. (1999). Thukela Water Project: Hydrology Specialist Study. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. Report to Institute of Natural Resources, Pietermaritzburg, RSA. pp 26 plus Appendices

Schulze, R.E., Horan, M.J.C. and Perks, L.A. (1997). Water resources assessment in the Nadi catchment for community requirements at Ehlanzeni. *ACRUcons Report,* 22. pp 26.

Taylor, V., Schulze, R.E., Jewitt, G.P.W., Pike, A. and Horan, M.J.C. (2001). Practical issues of HELP: Examples from the Thukela Basin in South Africa. *Proceedings of the AWRA/University of Dundee International Specialty Conference on Globalisation and Water Management*. pp 7. (Available at http://www.awra.org or on CD-Rom).

1.2.6 The Mbuluzi Catchment

Like the Mkomazi, the 2 958 km^2 Mbuluzi catchment within the borders of Swaziland was initially configured as part of an EU project on IWRMS. Foci in IWRM have been on the simulation of impacts of veld degradation and rehabilitation, impacts of irrigation water demand on reservoir yield and meeting water obligations to downstream Mozambique.

Dlamini, D.J.M. (2001). *Integrated Water Resources Management Studies in the Mbuluzi Catchment, Swaziland*. Unpublished MSc dissertation. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 147.

Dlamini, D., Schulze, R.E. and Matondo, J.I. (2001). Simulation of sediment yields under different land uses and states of degradation/rehabilitation in the Mbuluzi catchment in Swaziland. *Proceedings, 10th South African National Hydrology Symposium*. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA. pp 12 (on CD-Rom).

Märker, M., Dlamini, D., Matondo, J.I., Rodolfi, G. and Schulze, R.E. 2001. Soil erosion modelling in the Mbuluzi river catchment : Part II Sediment yield analysis. *Geografia Fisica e Dinamica Quaternaria*, 24, 189-198.

Staudenrausch, H., Flügel, W-A., Ranchin, T., Herlin, I., Rodolfi, G., Clark, M.J., Schulze, R.E., King, N., Tevera, D.S. And Matondo, J.I. (1999). The development of an innovative computer based Integrated Water Resource Management System for semi-arid catchments : Concepts and first results. *Zentralblatt für Geologie und Paläontologie*, Teil 1, Heft 3-4, 189-212.

1.3 CONCLUSIONS

Many other catchments have been configured for the *ACRU* model − some large, some small. Not all qualify as IHMSs, however, because they may have been used on a one-off basis. What concludes this report in Chapters 7 to 9, after descriptions of the other components of this research project, will be three detailed case studies in which an IHMS has been used to address very specific questions of the type which catchment managers may face in the future.

CHAPTER 2

THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM : A REVIEW UP TO DEVELOPMENTS AND REFINEMENTS DESCRIBED IN THIS PROJECT

Roland Schulze

ABSTRACT

This chapter commences by tracing the development of the *ACRU* agrohydrological modelling system, from a distributed catchment evapotranspiration model in the mid-1970s through its various phases of enhancement, with milestone years in terms of new documentation being 1984, 1989 and 1995, to the present system, which is a multi-partnered national and international development spearheaded by funding from the Water Research Commission.

The conceptual basis of the model is outlined next. This includes discussion on the model's physical-conceptual process representation and on *ACRU* as a multi-purpose and multi-level model founded on daily multi-layered soil water budgeting procedures. The model can be operated as a lumped or distributed catchment simulator of streamflow components, with options for reservoir yield, sediment yield, irrigation demand/supply, crop yield and climate change analyses, and with a strong focus on land use impacts on hydrological responses. The model contains a dynamic input option to account for changes, either abrupt or gradual, in the catchment over time. Thereafter, the *ACRU* model's water budget is described, with emphasis on the vertical redistribution of soil water, evapotranspiration processes and runoff generation mechanisms, followed by a section on output options.

A section is devoted to the operation of *ACRU* as a distributed model. Modelling system components and linkages are illustrated and typical minimum input requirements are presented diagrammatically before some of the main system utilities, such as the *ACRU Menubuilder*, its *Outputbuilder* and the option for use of a stochastic daily rainfall generator are discussed. The chapter concludes with a summary of perceived model system strengths, what the model should *not* be used for and where the current (2002 and beyond) research focus lies.

This review updates and supersedes those of Schulze (1995) and Smithers and Schulze (1995) and is inclusive of developments and applications up to of 2002. It is a shortened and slightly amended version of a full review by Schulze and Smithers (2002).

2.1 HOW DID THE *ACRU* MODEL COME ABOUT? . . . WHAT IS ITS PRESENT STATUS?

The *ACRU* model has its *hydrological* origins in a distributed catchment evapotranspiration based study carried out in the Natal Drakensberg in the early 1970s (Schulze, 1975). Although the acronym *ACRU* now represents a generic model name, it was initially derived from the ***A***gricultural ***C***atchments ***R***esearch ***U***nit within the erstwhile Department of Agricultural Engineering, now School of Bioresources Engineering and Environmental Hydrology, at the University of Natal in Pietermaritzburg, South Africa. The *agro*hydrological component of *ACRU* first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1983). Since then the model has developed, through co-operation with many colleagues and graduate students, and with funding provided primarily from the Water Research Commission (WRC), to its present status. Other partners in the development of *ACRU* have been the forest industry, the SA Sugar Association's Experiment Station, the University of Natal Research Fund, the National Research Foundation, US Country Studies for Climate Change Programme, the European Union, the Department of Water Affairs & Forestry, Universities of the Free State and Stellenbosch in South Africa, Universities of Bonn and Jena in Germany, of Cornell and Florida in the USA, the Department for International Development of the UK, Environmentek of the CSIR and Water Management Area Consultants (WMAC).

User documentation on *ACRU* was first published in 1984 (Schulze, 1984) and updated in 1989 (Schulze, 1989a; 1989b; Schulze, George, Angus and Lynch, 1990). A series of papers and reports applying continually updated and more sophisticated versions of the model has been published in the international and southern African literature, the major papers on developmental aspects being an overview by Schulze (1986), a paper on its application as a dynamic simulator of afforestation effects on runoff (Schulze and George, 1987a), a synthesis on its status as of 1988 by Schulze (1988a) and an unpublished report to the WRC in 1992 on new development to the model up to that time, mainly in regard to flow routing, wetlands, shallow groundwater routines, a forest Decision Support System and model linkage to a Geographic Information System (GIS). There are two major current references to the *ACRU* model. The 552 page *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* under the editorship of Schulze (1995) and also popularly referred to as *ACRU Theory*, contains background, concepts and theory in 24 chapters. Accompanying this text is the 371 page *ACRU User Manual Version 3.00* by Smithers and Schulze (1995), which includes operating instructions, input requirements and information, interpretation and graded exercises. Both the *ACRU Theory* and *User Manual* are now available on line at www.beeh.unp.ac.za/acru, through which medium they are currently also updated. A restructured version of the *ACRU* system using an object-oriented design methodology has been described in detail by, for example, Lynch and Kiker (2001) and Clark, Kiker and Schulze (2001).

Other than in southern Africa (South Africa, Botswana, Namibia, Lesotho, Malawi and Swaziland), the model has been presented via courses, lectures or symposium presentations in Australia, Austria, Benin, Canada, Chile, Costa Rica, Czech Republic, France, Germany, Hungary, Japan, Kenya, Morocco, Nepal, Netherlands, Portugal, Spain, Sweden, Switzerland, Tanzania, the UK and the USA. The model has been verified widely on data from South Africa, Swaziland, Zimbabwe, Germany and the USA. Schulze (1995) in his Chapter 22, presents 11 verification studies on various components of *ACRU*, both of outputs and internal state variables; other output verifications are included in Herpertz, 1994; New and Schulze, 1996; Schulze, Pike, Lecler, Esprey, Howe and Zammit, 1996; Kienzle, Lorentz and Schulze, 1997; Jewitt and Schulze, 1999; Taylor, Schulze, Jewitt and Pike, 1999; Lumsden, Schulze, Lecler and Schmidt, 1999; Pike and Schulze, 2000 and Dlamini, 2001; Gush, Scott, Jewitt, Schulze, Hallowes and Görgens, 2001). *ACRU* has also been used extensively as an aid to decision making in South Africa and by 2001 the model had been applied internationally in hydrological design, the simulation of water resources and research in Botswana, Chile, Germany, Lesotho, Mozambique, Namibia, Swaziland, the USA and Zimbabwe.

2.2 ON WHAT CONCEPTS IS THE *ACRU* MODEL BASED?

Fundamental concepts, basic premises and requirements around which sound operational models should be developed, if they are to be used as decision aids at a time of major paradigm shifts in water resources, have been discussed in detail by Schulze (1998a; 1998b; 2000a; 2001a). The *ACRU* agrohydrological modelling system (Schulze, 1995) complies with many of those premises and principles and is centred around the following aims (Figures 2.1 and 2.2) :

- It is a *physical conceptual* model, i.e. it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly (Eagleson, 1983).
- *ACRU* is not a parameter fitting or optimising model. Variables (rather than optimised parameters values) are, as a rule, estimated from physically based characteristics of the catchment.
- It is a *multi-purpose* model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system. It can be applied as a versatile model for design hydrology, crop yield modelling, reservoir yield simulation, ecological requirements, irrigation water demand/supply, water resources assessment, planning optimum water resource utilisation/allocation, conflict management in water resources, climate change impacts and land use impacts - in each case with associated risk analyses.
- The model uses *daily time steps* and thus daily climate input data, thereby making optimal use of available data (Schulze, 2001a). Certain more cyclic, conservative and less sensitive variables (e.g. temperature, reference potential evaporation), for which values may have to be input at monthly level (if daily values are not available) are transformed internally in *ACRU* to daily values by Fourier Analysis. More sensitive intra-daily information (e.g. of rainfall distribution) is obtained by synthetic disaggregation of daily values into shorter duration time steps within the model.
- The *ACRU* model revolves around daily *multi-layer soil water budgeting* and the model has been developed essentially into a versatile total evaporation model (Figure 2.2). It has, therefore,

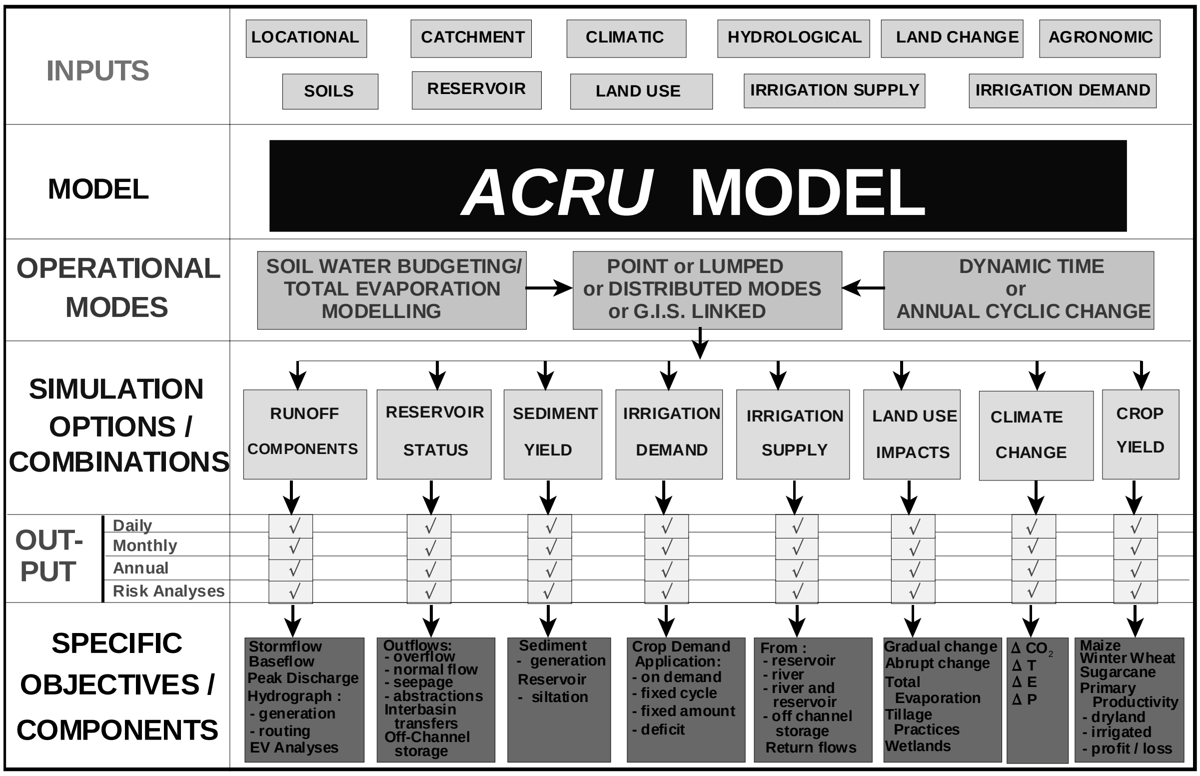

Figure 2.1 The *ACRU* agrohydrological modelling system: Concepts (after Schulze, 1995)

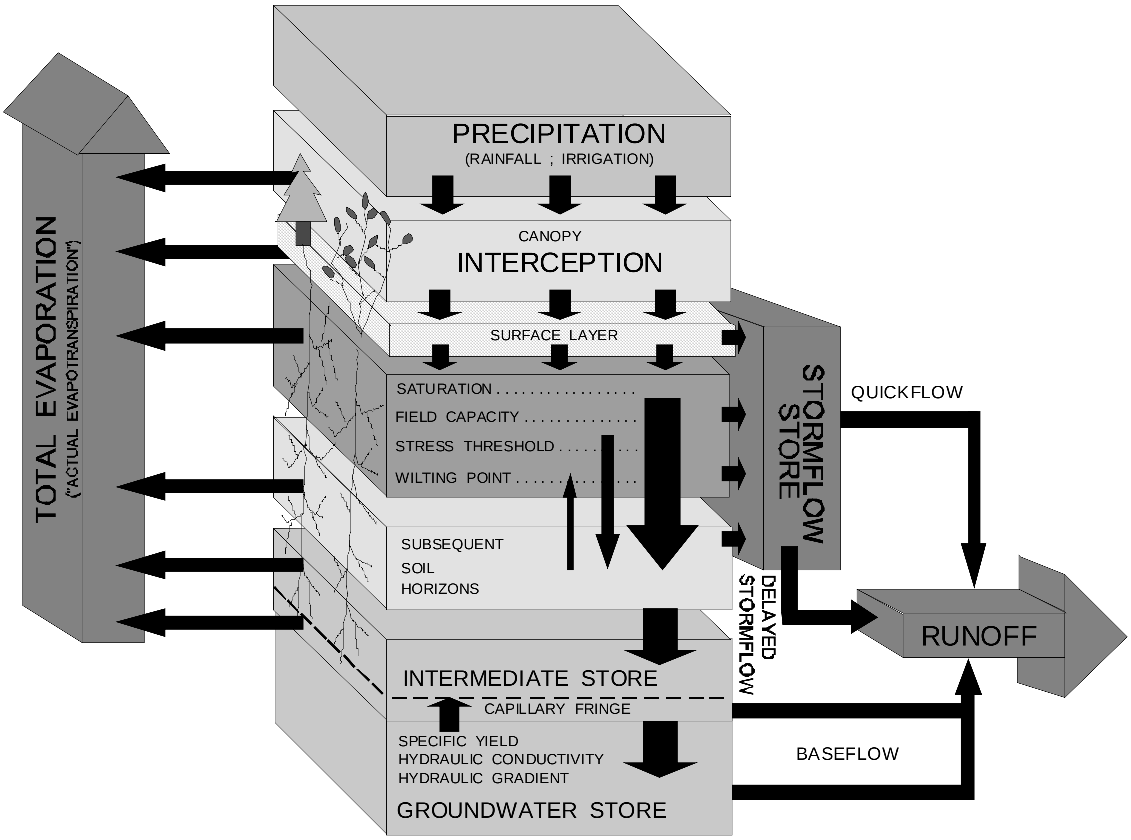

Figure 2.2 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995)

been structured to be highly sensitive to climate and to land cover, land use and management changes on the soil water and runoff regimes, and its water budget is responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO_2 concentrations or to the onset and degree of plant stress.

- *ACRU* has been designed as a *multi-level* model, with either multiple options or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of input data available, or the detail of output required. Thus, for example, reference potential evaporation, interception losses, values of soil water retention constants, maximum (i.e. 'potential') as well as total evaporation ('actual evapotranspiration'), leaf area index, components of peak discharge estimation, hydrograph routing, reservoir storage : area relationships or the length of phenological periods in crop growth, may all be estimated by different methods according to the level of input data at hand or the relative accuracy of simulation required.
- *ACRU* can operate as a *point* model, as a *lumped* small catchments model, on large catchments or at national scale. In areas of complex land uses and soils, over large catchments or at national scale *ACRU* operates as a *distributed* cell-type model. In distributed mode individual subcatchments which ideally should not exceed 50 km^2, but which are often at the level of Quaternary or sub-Quaternary (Quinery) Catchments in South Africa, are identified . Once discretised into subcatchments, flows can take place from 'exterior' through 'interior' cells according to a predetermined scheme, with each subcatchment able to generate individually requested outputs which may be different to those of other subcatchments or with different levels of input/information.
- The model includes a *dynamic input option* to facilitate modelling the hydrological response to climate or land use or management changes in a time series, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of an irrigation project or climate trends), or abrupt changes (e.g. clearfelling, fire impacts, construction of a dam, development of an irrigation project, or introduction of new land management strategies such as tillage practices), or changes of an intra-annual nature (e.g. crops with non-annual cycles, such as sugarcane). A dynamic input file is then accessed each year, with the new variable inputs to be used from that year onwards, e.g. water use coefficients, root mass distributions, planting dates or soils properties (e.g. for new tillage practices).
- *ACRU* operates in conjunction with the interactive *ACRU Menubuilder* and *Outputbuilder* and the associated *ACRU Input Utilities*. The latter are suites of software programs to aid in the preparation of input data and information. The *ACRU Menubuilder* prompts the user with unambiguous questions, leading the user into inputing, for example, complex distributed catchment information easily. The *Menubuilder* contains alternative decision paths with pre-programmed *Decision Support* values. Furthermore, the *Menubuilder* includes a *HELP* facility, built-in *default values* as well as warning and error messages. The *Outbuilder* allows the user to select, from a predefined list, which variables are to be stored during a simulation for subsequent output and analysis.
- The *ACRU Output Utilities* enable the user to print out, and to analyse, any observed as well as simulated results. The types of analyses include frequency analysis, extreme value analysis and comparative statistics in order to determine the goodness of fit between simulated and observed data.

2.3 HOW DO THE *ACRU* MODEL'S WATER BUDGETING PROCESSES OPERATE?

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in Figure 2.2 That rainfall and/or irrigation application not abstracted as interception or as stormflow (either rapid response or delayed), first enters through the surface layer and 'resides' in the topsoil horizon. When the topsoil is 'filled' to beyond its drained upper limit (field capacity), the 'excess' water percolates into the subsoil horizon(s) as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed the drained upper limit, saturated vertical drainage/recharge into the intermediate and eventually groundwater stores occurs, from which baseflow may be generated. Unsaturated soil water redistribution, both upwards and downwards, also occurs but at a rate considerably slower than the water movement under saturated conditions, and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone.

Evaporation takes place from previously intercepted water as well as simultaneously from the various soil horizons, either separately as soil water evaporation (from the topsoil horizon only) and as plant transpiration (from all horizons in the root zone), or combined, as total evaporation (i.e. 'actual evapotranspiration'). Evaporative demand from the plant is estimated, *inter alia*, according to atmospheric demand (through a reference potential evaporation, E_r) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density of the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in land use and crop yield modelling to determine at which point in the depletion of the plant available water reservoir any plant stress actually sets in, since stress implies a soil water content below the optimum for evaporation, hence the necessity to irrigate (if irrigation is applied). It also implies a reduction in crop yield. In modelling terms, this problem may be expressed as the critical soil water content, ψ^{cr}_l, at which total evaporation, E, is reduced to below the vegetation's maximum evaporation, E_m (formerly termed 'potential evapotranspiration'). Experimental evidence points to E equalling E_m until a certain fraction, f_s (Figure 2.3), of maximum (profile) available soil water to the plant, *PAW*, is depleted. Maximum available water to the plant is the difference in soil water content between that at the soil's drained upper limit, *DUL*, and its lower limit, *PWP* (Figure 2.3). Research results show that the critical soil water fraction at which stress commences varies according to atmospheric demand, $E_{r,}$ and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. The implications of stress setting in at such different levels of soil water content are significant in terms of total crop evaporation, crop production modelling and irrigation scheduling. Total evaporation also reduces when the soil is too wet, as a result of anoxia, with a linear decline assumed when soil water content is above *DUL*, but below saturation, indicated by *PO* in Figure 2.3.

The generation of stormflow in *ACRU* is based on the premise that, after initial abstractions (through interception, depression storage and that infiltration which occurs before runoff commences), the runoff produced is a function of the magnitude of the rainfall and the soil water deficit from a critical response depth of the soil, D_{sc}(m). The soil water deficit which is antecedent to a rainfall event is simulated by *ACRU*'s multi-layer soil water budgeting routines on a daily basis. The critical response depth has been found to depend, *inter alia*, on the dominant runoff-producing mechanism. This depth is, therefore, generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, while it is generally deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and 'push-through' runoff generating mechanisms predominate (Figure 2.4). Not all the stormflow generated by a rainfall event responds at the catchment outlet on the same day; stormflow is therefore separated into quickflow (i.e. same day response) and delayed stormflow (Figure 2.2), with the 'lag' (which may be conceptualised as a surrogate for simulating interflow) dependent, *inter alia*, on soil properties, catchment size, slope and the drainage density.

Baseflow in *ACRU* is modelled explicitly, with the baseflow contribution deriving from soil water which has percolated out of the base of the subsoil horizon (hence the importance of soil depth and the saturation redistribution fraction) into a baseflow store. The baseflow store is assumed to be 'connected' to the stream's channel system and releases water into the stream through an input decay coefficient which is then varied within the model according to the previous day's ground water store. The stormflow contribution on a given day plus its baseflow, constitute the catchment's total runoff for the day, with both assumed to discharge directly into the stream's channel system.

When riparian zone processes are simulated (for example, when assessing influences of alien invasive infestation in the riparian zone and effects of its clearance), it is assumed that the baseflow contributions from their contributing areas within a catchment, are routed to a defined riparian zone subcatchment as subsurface flows, as illustrated schematically in Figure 2.5. These subsurface flows fill the riparian zone's soil profile from the bottom upwards, thereby increasing the soil water availability to deeper rooted plants. Should the total soil profile become saturated right to the soil surface, any excess water is added to the stormflow contribution. In the riparian zone the main channel has a maximum capacity and when that is exceeded, water spills onto the riparian zone, wetting it from the top downwards.

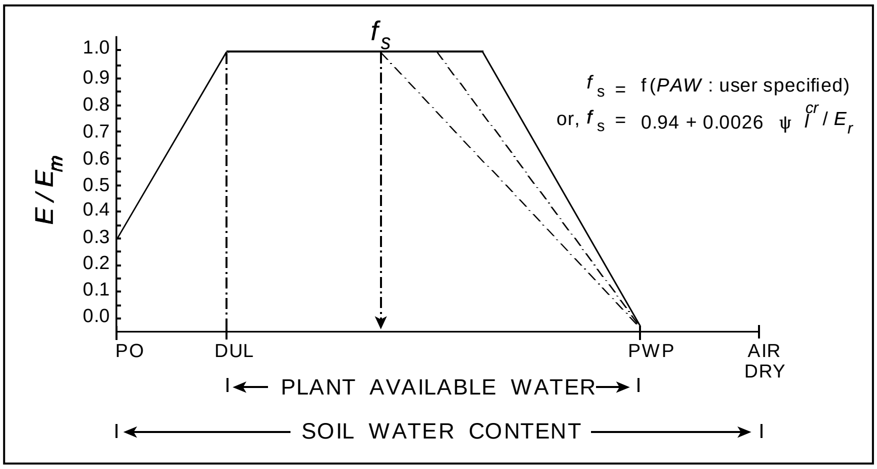

Figure 2.3 Interrelationships used in *ACRU* between soil water content and the ratio of E : E_m (after Schulze, 1995)

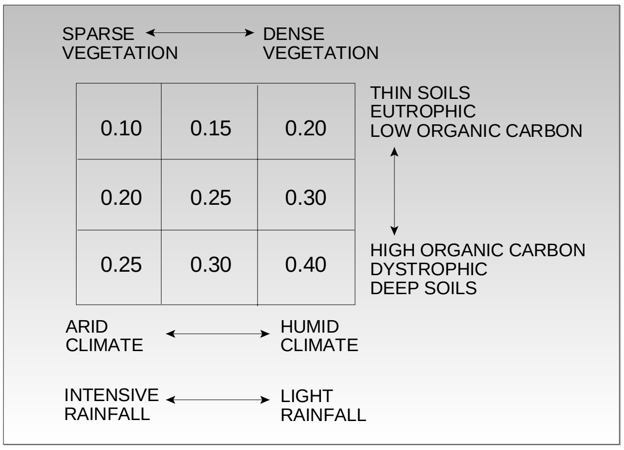

Figure 2.4 Suggested default values of the critical stormflow response soil depth, D_{sc}(m), according to climatic, vegetation and soils characteristics (after Schulze, 1995)

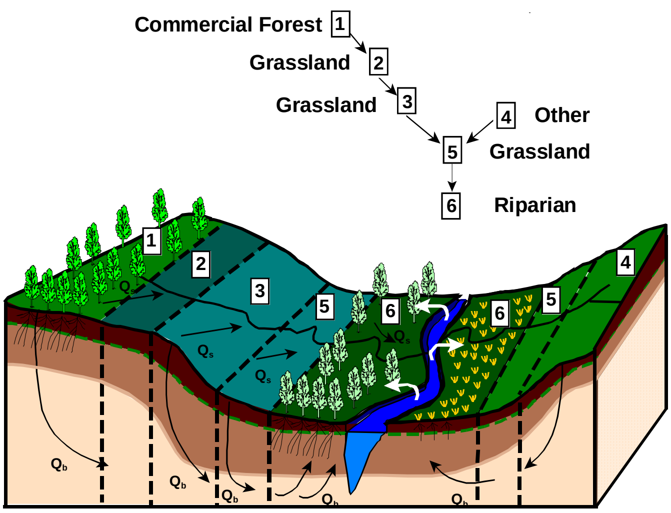

Figure 2.5 Schematic representation of riparian zone processes in *ACRU* (after Meier *et al.*, 1997; Schulze, 2000b)

2.4 WHAT OUTPUT CAN BE GENERATED BY *ACRU*?

The ‘heart’ of the *ACRU* model is a daily multi-layer soil water budget, and hence the model simulates the components of the hydrological cycle affecting this soil water budget, including :

- canopy interception of rainfall by vegetation
- net rainfall reaching the ground surface
- infiltration of net rainfall into the soil
- total evaporation (transpiration as well as soil water evaporation) from the various horizons of the soil profile to root depth
- suppression of soil water evaporation by litter or mulch
- the redistribution of soil water in the soil profile, both saturated and unsaturated, and
- percolation of soil water into the intermediate/groundwater zone.

The model can output any of the above components. In the output routines the user may select which components to output from a predefined list of variables. Thus for example, output on a daily basis, or summations as monthly or annual totals of the daily values, may be made of:

- gross rainfall, i.e. the input daily rainfall, adjusted (if necessary) for systematic differences between station and catchment representative rainfall
- canopy interception
- effective rainfall
- reference potential evaporation, i.e. the input E_r , adjusted (if necessary) for differences between station and catchment representative E_r
- maximum evaporation, i.e. ‘potential evapotranspiration’, from the vegetation under conditions of freely available soil water
- total evaporation, i.e. ‘actual evapotranspiration’, in the form of transpiration and soil water evaporation from top- and subsoil horizons respectively
- soil water content of top- and subsoil layers, also in relation to the horizons' drained upper limits and
- drainage from the various soil zones to the next lower zone.

From the soil water budget, the model is capable of outputing simulated elements of streamflow on a daily time step, or as monthly or annual totals of daily values. These include :

- stormflow depth (or volume)
- baseflow depth (or volume)
- total runoff
- accumulated streamflow from all upstream catchments when simulating distributed, multiple subcatchments and
- peak discharge (including hydrograph routing when simulating distributed multiple subcatchments).

The components of the water budget are integrated with modules embedded within the *ACRU* system to enable modelling of:

- effects of land use change and alien vegetation clearance on the riparian zone (Figure 2.5)
- reservoir yield analysis (overflow, reservoir status, abstractions, transfers; including routing of flows through reservoirs; using processes of the reservoir water budget as conceptualised schematically in Figure 2.6)
- sediment yield analysis (daily, monthly, annual; reservoir sedimentation)
- irrigation water demand (for different crops, application efficiencies, modes of scheduling; with processes as illustrated schematically in Figure 2.7)
- irrigation water supply (from streams, reservoirs and combinations thereof; alternatively, pumped off-channel reservoir storage; with processes as illustrated schematically in Figure 2.8)
- wetlands hydrological responses (based on processes as illustrated schematically in Figure 2.9)
- effects of abstractions from the stream (e.g. for domestic purposes) on catchment water yield
- fluctuations of shallow groundwater under certain conditions
- hydrological impacts of afforestation
- effects of other land cover, land use and management (e.g. tillage) changes (gradual or abrupt)

- seasonal crop yields (maize, sugarcane, winter wheat - either dryland or irrigated, as well as for non-crop specific net above ground primary production) and
- the effects of enhanced atmospheric CO_2 levels on transpiration suppression and hence on crop yield and water resources.

2.5 WHAT HAS THE *ACRU* MODEL TYPICALLY BEEN APPLIED FOR?

Since the mid-1980s the *ACRU* model has been used extensively to provide assessments to a range of water resources related problems associated with the modules listed above. A number of references are cited in the following subsections, which refer to the various capabilities of *ACRU*. The integrating nature of the model is highlighted by the appearance of the same reference under a number of the subheadings. A full reference list of applications of *ACRU* is given in Schulze and Smithers (2002).

2.5.1 Water Resources Assessments

It is the multi-purpose structure and versatility of the *ACRU* system, in integrating land use sensitive and daily time step catchment hydrological processes with channel hydraulics in a (usually) semi-distributed hydrologically cascading (upstream to downstream) system, with facilities to simulate reservoir yield (Figure 2.6), sediment yield, wetlands processes, irrigation water demand/supply, crop yield and climate change feedbacks, that has made this widely verified model an ever increasingly applied tool in a range of water resources assessments in South Africa and elsewhere. While ensuing sections review more specific applications, five general types of water resources assessments may be identified, *viz*.

- general water resources assessments on catchments of 10 to ~1000 km^2
- specialised evaluations on off-channel storage
- water resources assessments associated with rural development
- comprehensive basin studies with *ACRU* as an installed hydrological modelling system and
- national scale studies.

Schulze and Smithers (2002) cite 59 applications of the *ACRU* model in the water resources assessments category.

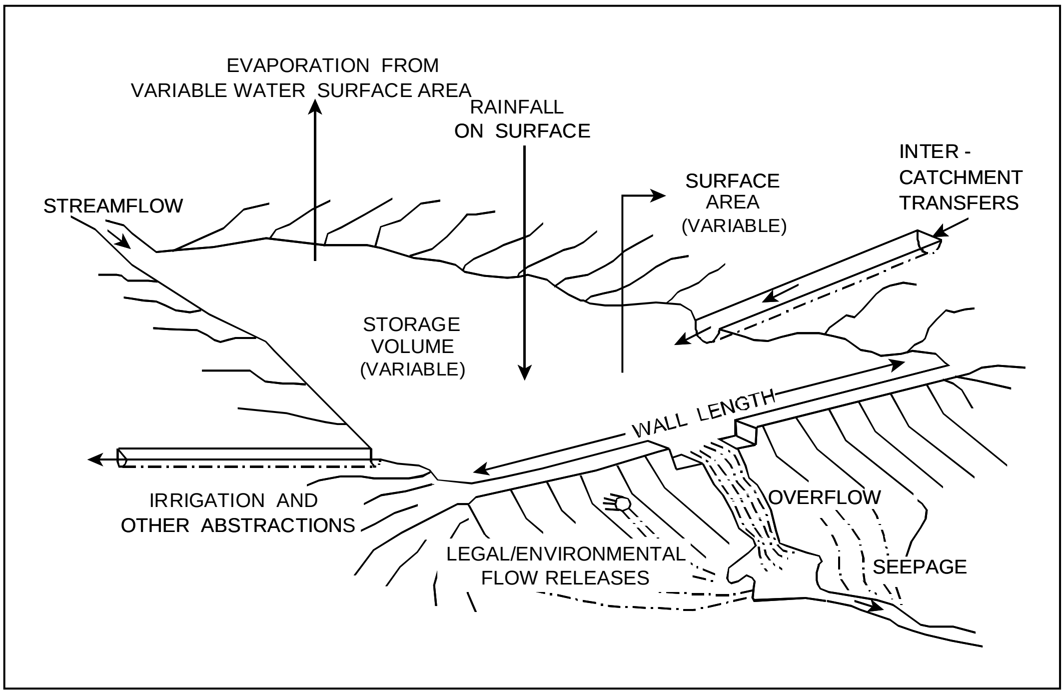

Figure 2.6 Schematic depiction of the reservoir water budget in *ACRU* (after Schulze, 1995)

2.5.2 Design Hydrology

Verified stormflows simulated by the *ACRU* model from research catchments in the USA, representing a range of climates and catchment areas, were used in the development of SCS design flood estimation techniques for southern Africa by Schulze (1982), Dunsmore, Schulze and Schmidt (1986) and Schmidt and Schulze (1987a). In the latter study, the *ACRU* model was used to integrate risk analysis with simulated soil water changes antecedent to design events, and was also used to estimate design streamflow by considering the joint association between rainfall and antecedent soil moisture conditions. The culmination of this work was the PC-based *SCS-SA* design manual for practitioners published by Schulze, Schmidt and Smithers in 1993, and currently under revision with more up-to-date databases. A series of background papers associated with this design hydrology approach appeared in the scientific literature (e.g. Schmidt and Schulze, 1984; Schmidt, Schulze and Dunsmore, 1986; Haan and Schulze, 1987; Schmidt and Schulze, 1987b; 1987c; 1989). A plea for an *ACRU*-type continuous modelling approach to estimating design runoff as a consequence of the non-stationarity of catchment responses over time, made by Schulze (1989c), has been followed up in a current WRC project (Smithers and Schulze, 2001). Schulze and Smithers (2002) cite a further 9 references on applications of *ACRU*'s capabilities in design hydrology.

2.5.3 Irrigation Water Demand and Supply

One of the *ACRU* model's strengths is the integration of water demand and supply on a catchment scale. The basic processes involved are illustrated schematically in Figures 2.7 and 2.8. This integration has been used extensively in reconciling and optimising irrigation water demand and supply. Schulze and Smithers (2002) summarise 35 reports/papers on applications of *ACRU*'s irrigation capabilities under themes of simulating crop water requirements, irrigation strategies, optimum utilisation of limited water, economic analyses, water use efficiency, downstream impacts and national scale studies.

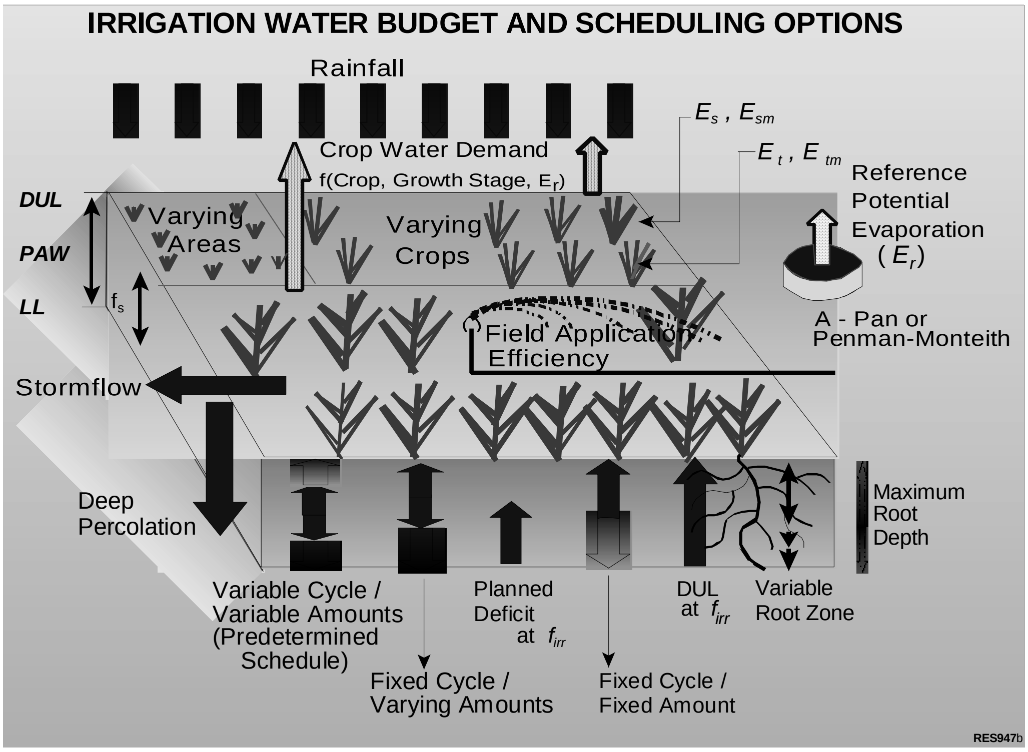

Figure 2.7 Schematic of irrigation water demand and scheduling options available in *ACRU* (after Schulze, 1995 and updates)

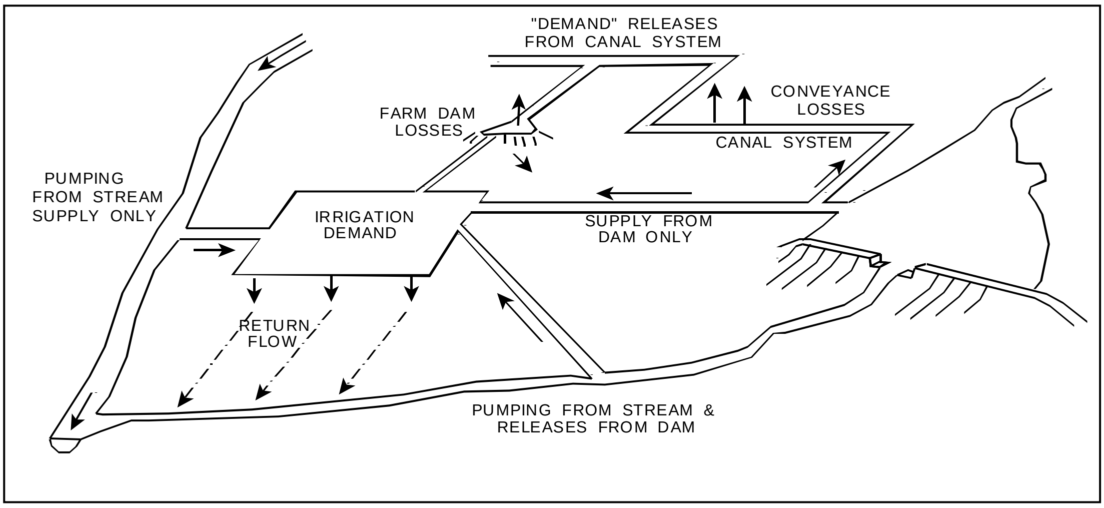

Figure 2.8 Schematic of irrigation water supply options available in *ACRU* (after Schulze, 1995)

2.5.4 Crop Yield and Primary Production Modelling

The *ACRU* model has options to simulate seasonal yields of

- maize (with the original *ACRU* maize model refined by Domleo, 1990),
- winter wheat (Domleo, 1990),
- sugarcane (using the Thompson, 1976; 1977 concepts; refined by Lumsden, Schulze, Lecler and Schmidt, 1999), as well as
- primary production (Schulze, 1984).

Over 25 reports/papers/dissertations on crop yield applications using *ACRU* are presented by Schulze and Smithers (2002).

2.5.5 Assessments of Impacts of Land Use and Land Use Change on Hydrological Responses

The *ACRU* model's conceptual representations render it particularly suitable to simulating hydrological responses to land use and management impacts and changes thereof. Important background papers in that regard include those by Schulze in 1987, 2000a and 2001a. Impacts of land use on both water quantity and quality (selected determinants) can be simulated with *ACRU*. Examples of these studies, which exclude specific afforestation related impacts which are reviewed separately, fall under four broad subheadings, with the respective number of applications cited by Schulze ad Smithers (2002) given in parentheses, *viz*.

- general land use impact studies (13)
- impacts of sugarcane (6)
- land use impacts on water quality (7) and
- impacts in the riparian zone (4).

2.5.6 Forest Hydrological Impacts

With the impacts of commercial plantation afforestation to exotic tree species in South Africa under the spotlight as a streamflow reduction activity for the past 50 years, the *ACRU* model, by virtue of its physical-conceptual structure, has frequently been applied to provide answers to a range of forest hydrological questions. Some 46 forest hydrological applications using *ACRU* are given in the review by Schulze and Smithers (2002). The current "official" technique to estimate the streamflow reduction by afforestation uses the *ACRU* model in its computations.

2.5.7 Assessment of Hydrological Impacts of Wetlands

A wetland module for the *ACRU* model was initially developed by Schulze, Chapman, Angus and Schmidt (1987) and used to assess the potential hydrological impacts of proposed reservoirs up-upstream of wetlands in East Griqualand. A schematic depiction of concepts, processes and assumptions involved is given in Figure 2.9. Four further applications of *ACRU* to wetlands problems are described in Schulze and Smithers (2002).

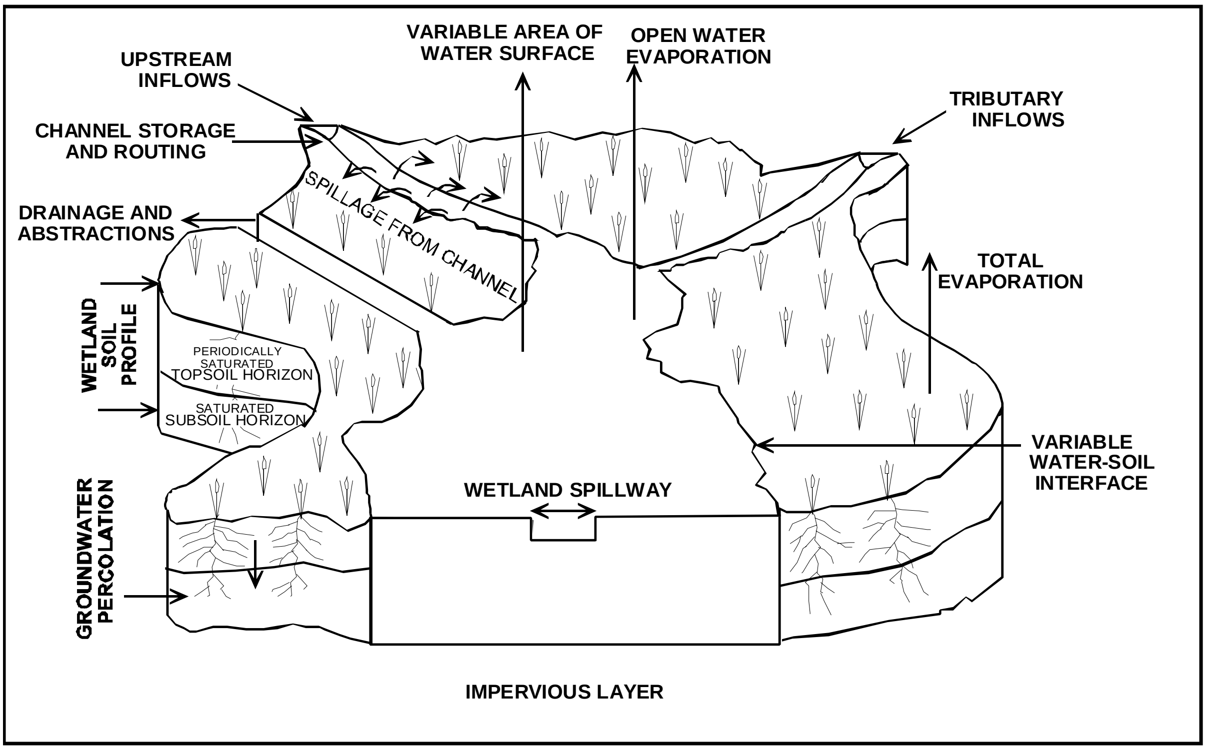

Figure 2.9 Concepts, processes and assumptions involved in the *ACRU* wetlands module (after Schulze *et al*., 1987; with modifications by Schulze, 2001b)

2.5.8 Groundwater Modelling

The use of *ACRU*'s shallow groundwater module to simulate likely long term consequences of afforestation on fluctuations in groundwater was demonstrated and verified for deep sandy soils in northeastern KwaZulu-Natal by Kienzle and Schulze (1992). Schulze and Smithers (2002) cite 7 further applications of *ACRU* in groundwater modelling.

2.5.9 Hydro-Economic Analyses

With water becoming a tradable commodity and the value of water being realised, in terms of monetary value per m^3 used, yield (tonnage) per m^3 of water utilised and allocation to competing crops under irrigation, the *ACRU* model is being used more and more frequently in hydro-economic analyses. Ten applications on hydro-economic analyses performed with *ACRU* are cited in Schulze and Smithers (2002).

2.5.10 Assessment of Potential Impacts of Global Climate Change on Crop Production and Hydrological Responses

A number of studies utilising the *ACRU* model have been conducted to assess the potential impact of elevated CO_2 and temperature levels and possible resultant changes in precipitation and potential evaporation on crop and runoff production in southern Africa. Amongst them is the US Country Study on Climate Change Impacts on South Africa. Schulze and Smithers (2002) summarise 21 reports/papers/theses in which *ACRU* was used in climate change impact studies. A new WRC funded national scale study on climate change impacts on South Africa's water resources, using *ACRU* as its simulation model, has recently (2003) commenced.

2.5.11 Agrohydrological Forecasting

The high inter-annual variability of South Africa's climate, the effects of which are amplified by the hydrological system, render seasonal forecasts of crop yields and streamflows vital for a range of operational decisions. In Schulze and Smithers (2002) 9 examples of forecast applications with *ACRU* are described.

2.5.12 Simulations with *ACRU* in the Service of the National Water Act of 1998

A change in water supply priorities since 1994 and promulgation of the National Water Act of 1998 (NWA, 1998) have ushered in a series of new simulation opportunities for daily hydrological models in Integrated Water Resources Management. These include streamflow reduction activities, rural water supplies, environmental flow computations, risk analysis, reservoir operating rules for the human and ecological reserves and impacts of alien riparian vegetation clearance ('Working for Water' programme). In this context Schulze and Smithers (2002) cite 12 studies which have applied the *ACRU* model.

2.5.13 International Applications of *ACRU*

ACRU is increasingly being used internationally and Schulze and Smithers (2002) list 13 applications from Namibia, Botswana, Swaziland, Mozambique, Germany and Zimbabwe.

2.5.14 Other Applications of *ACRU*

ACRU has, in recent years, been applied to diverse other agrohydrologically related problems, *inter alia*, assessing

- potential impacts of cloud seeding on streamflow production (Howard and Görgens, 1993)
- water quality under urban conditions (Schmitz, De Villiers and Schulze, 1993)
- hydrological effects of a wildfire in a forest plantation (Scott, Schulze and Kunz, 1991)
- soil forming factors (Donkin and Schulze, 1990)
- the palaeo-rainfall history over South Africa by relating wetting cycles to percentage finer of the soil in granitic parent material (Partridge, Demenocal, Lorentz, Paiker and Vogel, 1997) and
- sediment yield using contributing area techniques (Howe and Lorentz, 1995).

Furthermore, the model has been used in the adjustments of stormflow responses to antecedent soil moisture conditions in the PC based SCS-SA package, now in standard use by practitioners in southern Africa, on design hydrographs from small catchments (Schmidt and Schulze, 1987a; Schulze, Schmidt and Smithers, 1993).

2.6 HOW DOES *ACRU* OPERATE AS A DISTRIBUTED MODEL?

Being a daily time step model, *ACRU* does not, in most of its standard routines, account for the temporal variability within individual storm events. However, the distributed version of the *ACRU* model has the ability to take account of the spatial variability not only of rainfall, but also of land uses and soils to provide a more accurate representation of where, within the catchments, the hydrological responses are occurring and with what magnitude.

2.6.1 Catchment Discretisation

Characteristics, advantages and disadvantages and methods of catchment discretisation are given in Schulze (1998a) and Schulze (2001a). *ACRU* generally makes use of a 'cell' type discretisation to subdivide the catchment, where each cell may be regarded as a subcatchment, or management unit. Cell boundaries are defined from large scale orthophotos or topographical maps. In southern Africa the current standard management unit is the DWAF Quaternary Catchment (QC), of which 1 946 have been delineated within the borders of South Africa, Lesotho and Swaziland. Generally, the more complex a region is physiographically or developmentally, the finer the spatial resolution of

QCs. The QCs may, nevertheless, be too diverse physiographically and climatically to act as a basic and relatively homogeneous hydrological unit (*cf*. Schulze, 2001a) and may therefore require further discretisation into Quinery level catchments.

Criteria considered in the finer delineation of QCs are classed as either

- *natural*, e.g. based on
  - rainfall range
  - altitude range (and associated temperature/evaporation change)
  - breaks in terrain morphometry, e.g. an escarpment
  - natural vegetation zones, e.g. Acocks' (1988) Veld Types
  - soil groups with similar hydrological response properties or
  - major tributaries joining a mainstem river; or
- *anthropogenic* in origin, e.g. based on present and/or future
  - land uses with different hydrological responses
  - inflow or outflow points, on a reservoir
  - water abstraction or return flow points
  - monitoring sites, such as
    - streamflow gauging weirs
    - water quality monitoring sites
    - instream flow requirement locations on a stream, or the
    - raingauge network.

The level of subcatchment discretisation is highly dependent on the particular purpose for which the model is being put to use and remains subjective up to a point. Two illustrations of discretisation into management units are presented below (Figures 2.10 and 2.11). These two figures show that in cell-type distributed models such as *ACRU*, the catchment is depicted as an assembly of interconnected, i.e. cascading, units of area, each considered a lumped (averaged) representation of that area.

Two types of cells can be identified from Figures 2.10 and 2.11, *viz*. exterior and interior cells. An exterior cell has a portion of its boundary as a common boundary with the main catchment and the outflow from an exterior cell is assumed to be independent of that of all the other cells. An interior cell has one or more upstream cells (i.e. subcatchments or management units), and the outflow from an interior cell may include contributions from upstream cells.

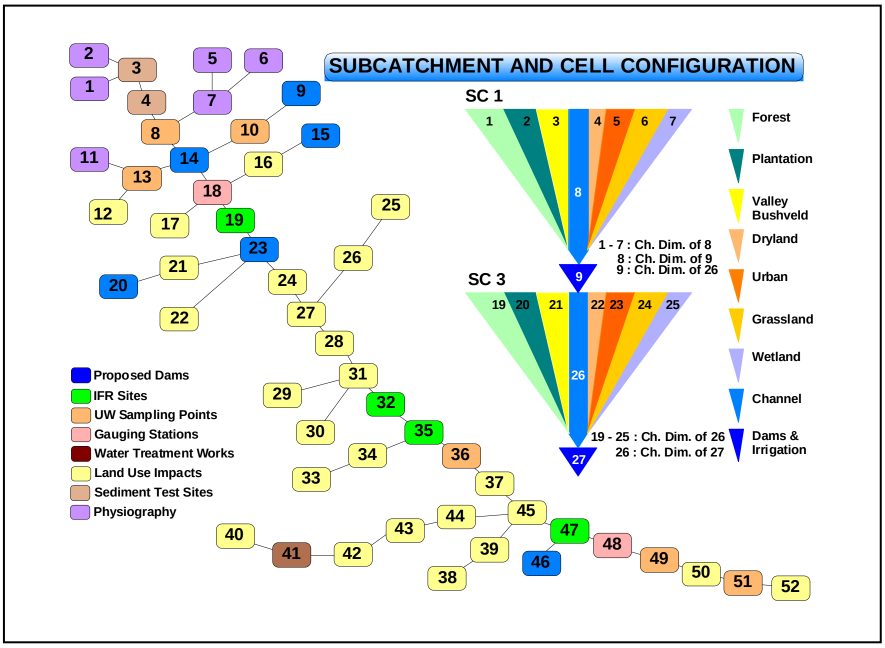

Figure 2.10 An example from the Mkomazi catchment of discretisation into management units by watershed boundaries and with further subdelimitation by land use (after Taylor *et al*., 2001)

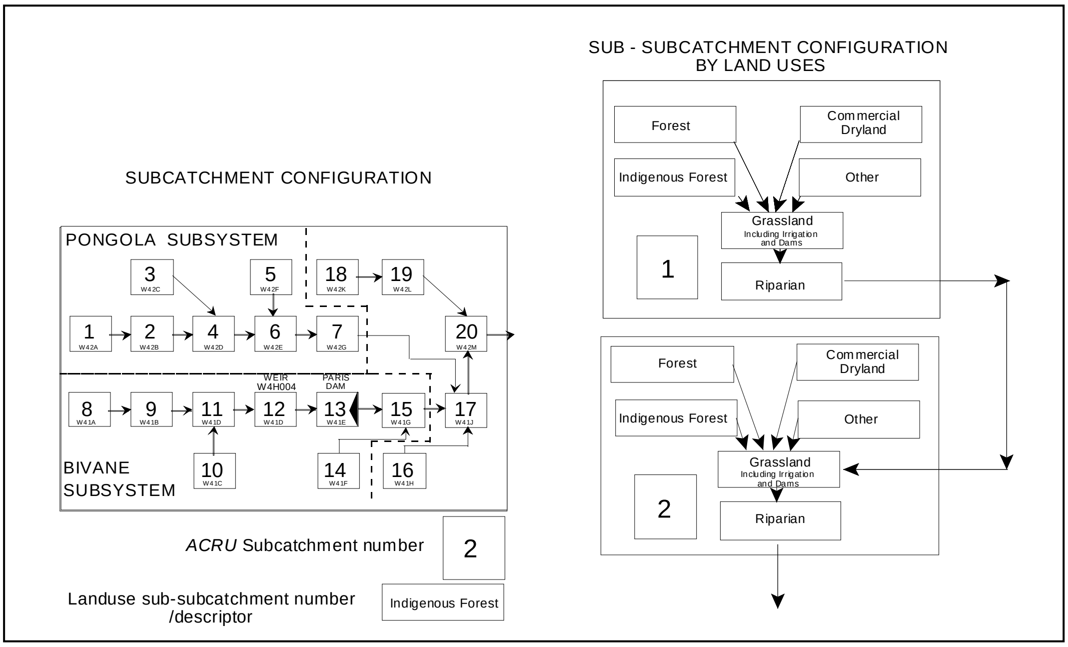

Figure 2.11 Subcatchment configuration: Pongola-Bivane study area (after Schulze *et al*., 1996)

2.6.2 Inter-Subcatchment Streamflows

The lumped model's soil water budgeting routine is performed assuming a point scale with all units expressed in mm. Stormflow and baseflow, which together make up streamflow, are thus also expressed in mm. In order to direct outflow to downstream cells, the streamflow depth calculated by the model is converted to a volume (m^3) to account for the different areas of each subcatchment.

2.6.3 Other Features of *ACRU* as a Distributed Model

A feature of the *ACRU* distributed model is that each subcatchment, while nested within other up- and downstream subcatchments in transmitting water, also operates as a unique, individual catchment.

- Therefore, individually requested input information pathways can be used on different subcatchments and individual and different output can be requested for each subcatchment. Thus, for example, one could request crop yield and sediment yield together with a risk analysis of only monthly streamflow from Cell 1, whilst requesting an irrigation requirement analysis, reservoir yield risk analysis and daily water budget printout from the next subcatchment.
- In, for example, a series of complex multi-irrigated subcatchments, irrigation water from the river may all have been abstracted by upstream users, requiring downstream irrigation users to request water releases from an upstream reservoir as draft - a 'fact' which the simulation only 'finds out' after having cascaded through a number of subcatchments downstream. For such cases, a so-called 'loopback' option can be operated in *ACRU*, by which complex transfers of water (other than natural streamflow) between subcatchments are accounted for.

2.7 HOW ARE THE COMPONENTS OF THE *ACRU* MODELLING SYSTEM LINKED?

The *ACRU* modelling system is made up of a number of discrete, but interlinked components. As shown in Figure 2.12, the *ACRU* model requires both an input menu file and a file containing hydrometeorological data, and may contain an optional dynamic file.

2.8 WHAT ARE TYPICAL MINIMUM DATA AND INFORMATION REQUIREMENTS TO OPERATE *ACRU*?

ACRU has been designed as a *multi-level* model, with either multiple options or alternative pathways

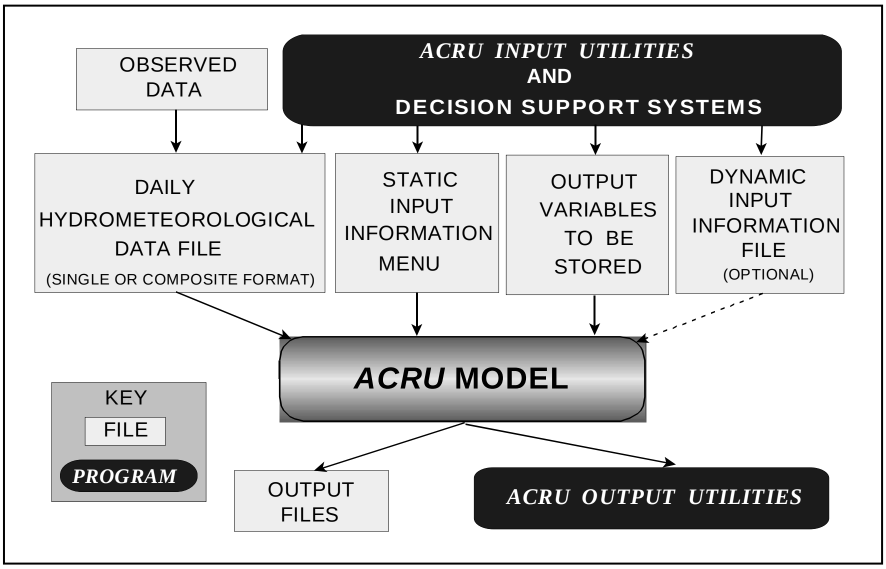

Figure 2.12 Components and linkages of the *ACRU* modelling system (after Schulze, 1995)

(or a hierarchy of pathways) available in many of its routines, depending on the level of available input data/information or the type and detail of output required. The minimum data and information required to run the model is, therefore, not unique and depends on the options chosen and on the availability of data/information to a particular user. Typical minimum data and information requirements which are compulsory input into the model and which are readily obtainable for southern Africa, are summarised schematically in Figure 2.13. The optional inputs to the model, which are required to simulate specific processes (e.g. peak discharge or sediment yield), are also included in Figure 2.13.

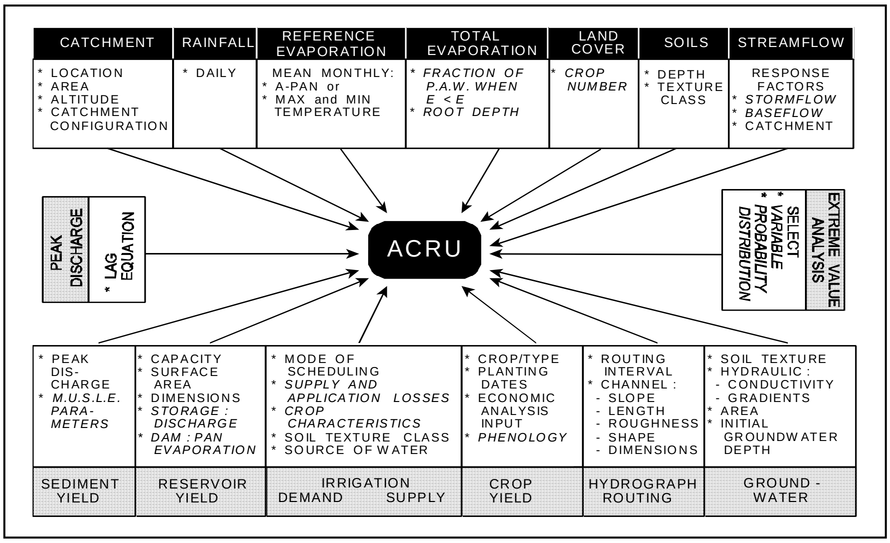

Figure 2.13 Schematic of the *ACRU Utilities*' linkages with the *ACRU* model (after Schulze, 1995)

2.9 WHAT UTILITIES COME WITH THE *ACRU* SYSTEM?

Deterministic hydrological models, particularly when operating in distributed mode, require detailed soils, land use and climatic information and the collection and inputing of this information can be both time consuming and laborious. It is to this end that a suite of software programs, the *ACRU Utilities*, has been developed to aid users in preparing input information for, and output information from, the *ACRU* agrohydrological simulation model. A schematic overview of the way in which the *Utilities* link with the *ACRU* model is given in Figure 2.14 and brief descriptions of just a few of key individual

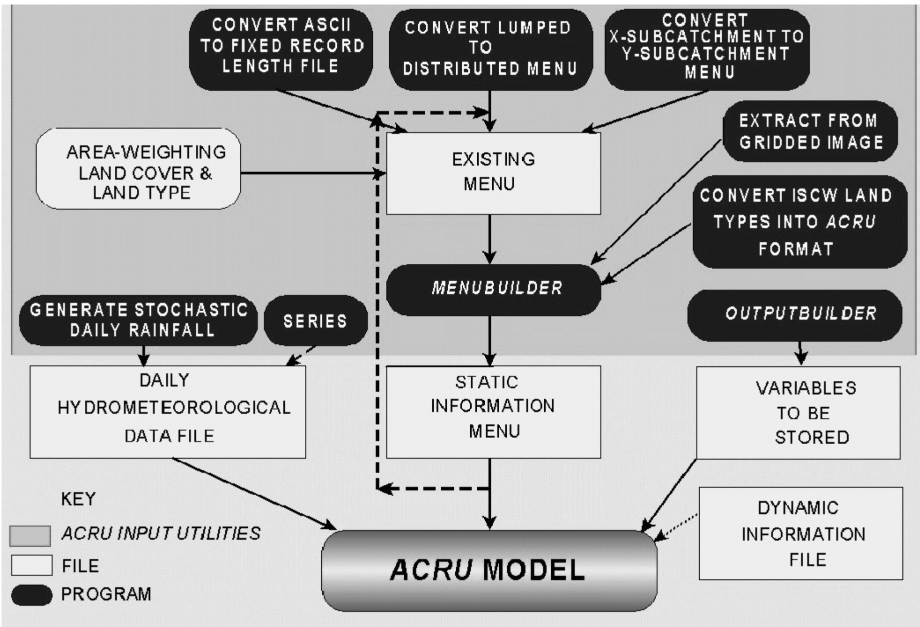

Figure 2.14 Schematic diagram of the *ACRU Utilities'* linkages with the *ACRU* modelling system as of 2001 (after Schulze, 1995)

programs making up the *Utilities* follow. Details on the other *Utilities* are found in the *ACRU* User Manual (Smithers and Schulze, 1995).

2.9.1 The *ACRU* Menubuilder

The *ACRU Menubuilder* is an interactive, user friendly program of over 250 subroutines which prompts the user with questions for information, also guides (with internal help and error checking facilities) the user through the various options available and facilitates rapid information input through a MENU file (Figure 2.13). It contains pre-programmed *Decision Support tools*. Technical details on the *Menubuilder* are given in Chapter 5 of the *ACRU* User Manual (Smithers and Schulze, 1995) and updates are given in ensuing chapters of this report.

Information is input into the *Menubuilder* in a sequential mode, dealing with individual processes one at a time. A feature of the *Menubuilder*, which can assist in editing a previously created MENU, is the facility to proceed to any selected section of the MENU, and skip over previously input information. In addition, the user can end the session at any time and all information will be written to the user selected output MENU file name.

ACRU caters for several levels of information availability. Detailed information is often not available and the user can then resort to the 'experience' that has built into *ACRU* and the *Menubuilder* through *Decision Support* tools by way of default values and pre-programmed information.

The two areas where this facility is particularly useful are in inputing soils and land use information. In each case, if catchment information is limited or considered 'inadequate', the user can select from a range of classes of input and the program assigns realistic default values to the variables.

2.9.2 The *ACRU* Outputbuilder

As illustrated in Figure 2.14, the *ACRU* model requires an input file containing details on which variables to store during a simulation, for which output and analysis at the completion of the simulation are then required. Users may select to store only those variables relevant to their problem. The *Outputbuilder* lists all the variables available for storage during the simulation (with descriptions of the variables) and the user may click on either a subset of all the variables or the entire set for graphical or statistical analysis. In Chapter 4 of this report updates are presented.

2.9.3 Generation of Stochastic Time Series of Daily Rainfall

Often, for planning purposes, a stochastic time series of daily rainfall values is used in preference to historical data, which may be difficult to obtain or which may contain missing data. A routine may be called to generate a stochastic time series of daily rainfall, for any one of over 3 000 station locations in South Africa, based on an original study by Zucchini and Adamson (1984), and subsequent updates of that research. The user inputs latitude and longitude co-ordinates for the location of interest, and then selects any one of the 10 computer selected rainfall stations closest to the location and appearing on screen, before selecting any length of record desirable. The generated daily rainfall series can be automatically formatted to an *ACRU* format, ready for use; alternatively the user can request that the stochastic series be output in any one of a number of other formats.

2.9.4 Extraction of Gridded Images

The School of Bioresources Engineering and Environmental Hydrology at the University of Natal has developed gridded images of altitudes, median monthly rainfall, mean monthly A-pan equivalent evaporation, monthly means of daily solar radiation and of relative humidity as well as monthly means of daily maximum and minimum temperatures, at a resolution of one minute by one minute (1' x 1') of a degree latitude/longitude covering southern Africa (Schulze, 1997). A routine is included which will extract values from the gridded image for a rectangular catchment boundary which the user has to specify.

2.10 CONCLUDING THOUGHTS ON THE *ACRU* MODELLING SYSTEM : WHY TO USE; WHEN NOT TO USE; WHERE DOES THE FUTURE LIE?

2.10.1 Perceived Advantages and Strengths of the *ACRU* Agrohydrological Modelling System

From descriptions of the model's structure and its varied applications, *ACRU*'s perceived modelling strengths are its

- physical-conceptual process representation, mimicked at a
- daily time step resolution, its
- multi-purposeness, which includes the
  - landscape
  - riparian and
  - channel phases

  of the natural hydrological system, on to which are juxtaposed routines to simulate
  - land use/management influences on water and sediment flows
  - reservoir performance
  - irrigation demand/supply and/or
  - crop yields,

  all combined into a single system,
- thus making it an *agrohydrological* rather than only a *hydrological* model; furthermore, it contains
- multi-level input facilities which are determined, *inter alia*, by data availability, the
- ability to model in distributed cell-type mode,
- dynamic input options and extensive
- pre- and post-processing facilities,
- all together making it a modelling *system* rather than only a *model*.
- Further major perceived strengths are the *ACRU* model's comprehensive documentation. Both the *ACRU* Theory and the *ACRU* User Manual are now continually updated via the *ACRU* home page at www.beeh.unp.ac.za/acru and are downloadable
- the model's continual enhancement and refinement, driven by user needs, in particular through requirements from the National Water Act of 1998 and, with that, the advent of Catchment Management Agencies
- the availability of a dedicated *ACRU* User Consultant and
- model support from other WRC projects on databases and decision support.

2.10.2 What Not to Use the *ACRU* Model For

Model developers should document clearly for what purposes *not* to use their model. In *ACRU*'s case

- the model should ideally not be used to simulate catchment hydrology on areas less than 1-2 km^2 because of the type of stormflow and baseflow equations used, nor should spatial units exceed 50 km^2 (ideally)
- the model does not yet, in its present state, simulate
  - channel transmission losses
  - aquifer related processes
  - subsurface tile drainage
  - rate functions of infiltration and soil water redistribution
  - 2-dimensional hillslope hydrological processes
  - vegetation dynamics explicitly
  - snowmelt processes (although snowmelt routines have recently been developed and verified by Herpertz, 2001) or
  - salinity processes (which are currently, i.e. 2003, being completed).
- Furthermore, it should be stressed that while *ACRU* is a *modelling system* (i.e. a model with pre-processors, decision support tools and post-processors), it is *not a systems model*.

2.10.3 Where to . . . the Future?

Research on the model is currently (2003) focusing on

- reservoir operating rules
- environmental flows
- further refinements to land management strategies
- nitrate and phosphate modelling (through partnership with the University of Florida, USA)
- salinity modelling
- sediment routing
- transmission losses and
- adding socio-economic and demographic components to the model.

In regard to model support, Chapter 6 provides an update on work recently completed in this regard.

All of the above will render the *ACRU* model more versatile and easier to use as an installed modelling system.

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CHAPTER 3

DETERMINATION OF BASELINE LAND COVER VARIABLES FOR APPLICATIONS IN ASSESSING LAND USE IMPACTS ON HYDROLOGICAL RESPONSES IN SOUTH AFRICA

Roland Schulze

3.1 THE CONCEPT OF A BASELINE HYDROLOGY

For purposes of assessing reference flows in ecological reserve determination, or for evaluating possible impacts of certain land uses, or the influences of different levels of management within a given land use, on a catchment's or landscape unit's water resources, acceptable "baseline" or "benchmark" or "reference" land cover attributes are required for hydrological models against which critical hydrological response changes from a catchment or landscape unit can be estimated. These responses include changes in

- mean (or median) monthly and annual streamflows, as well as
- monthly and annual streamflows at certain levels of risk (e.g. the wettest or driest year in 5 or 10 or 50)
- flow duration curves at monthly, seasonal or annual time scales
- different components of runoff, such as stormflow as distinct from baseflow
- flow sequences in the dry season
- the generation of sediment yield, or
- the estimation of extreme flow volumes and/or peak discharges at specified recurrence intervals (e.g. 5 or 20 or 100 years).

The need for a "baseline" hydrology in South Africa is not new. For example, the concept and application of "naturalised" flows in South African catchment studies, even if believed by this author to contain some conceptual hydrological flaws in its derivation, is indirectly an expression of a hydrology under "baseline" conditions, against which responses of catchment development can be assessed. The whole question of a baseline land cover for use as a datum against which to evaluate hydrological impacts of current or anticipated future land uses has, however, been given new impetus and has become a major issue following the passing of South Africa's National Water Act, Act No. 36 of 1998 (NWA, 1998). This is so because this Act places a heavy emphasis

- on land use induced "stream flow reduction activities", whereby the imposition of levies is viewed as a means of managing water resources, with levies on certain land use activities based in part on the additional water use by the respective land uses over and above that of a baseline land cover it replaces, as well as
- on an ecological reserve of water, including Instream Flow Requirements for aquatic habitats which have to be met in the event of catchment development through land use change and/or the construction of an impoundment and its downstream environmental impacts, or by inter-basin water transfers.

For both these above examples, as well as in the case of managing other upstream-downstream conflicts resulting from land use manipulation, a baseline hydrology, against which impacts of subsequent land uses can be evaluated, is required. In its broadest sense such a baseline hydrology requires, *inter alia*, a baseline historical climate period, a baseline spatial scale of analysis and a baseline land cover. This chapter evaluates the last- named of the three baselines.

3.2 PROBLEMS IN SELECTING A BASELINE LAND COVER FOR HYDROLOGICAL PURPOSES

There is no "perfect" baseline land cover applicable to South Africa against which to make comparisons of hydrological responses, let alone have any substantial measurements of hydrological attributes of baseline land covers been made. Nevertheless, baseline land cover conditions have to be defined and their attributes quantified for hydrological purposes. In doing that, there is little scientific merit in arguing for the status of land use at a given point in time in the recent history of South Africa to be representative of the baseline, e.g. the status as at mid-century in 1950, or just prior to implementation of the forest permit system in the early 1970s, or in 1996 because that was the year for which satellite images were selected for the CSIR's first national land cover map of South Africa, or in 1998 when the National Water Act came into effect. The reasoning for this is that at national and regional levels land cover and its management levels at any given point in recent time would have strongly reflected both the economic and political development histories of South Africa, while at the local scale social pressures and/or agricultural market forces would also have left their mark on land use patterns.

On the other hand, the use of one common or "standard" land cover as a baseline, e.g. grassland in a hydrological "fair" management condition, as defined in Schulze *et al*. (1993), is too simplistic a concept because grasslands are not found everywhere and, where found, they can vary considerably in their influence on runoff and sediment generation because of differences in tuft density, photosynthetically active biomass, height, litter, rooting patterns or duration of the dry season period of senescence.

There is also no perfect "natural" vegetation baseline, because climates over southern Africa have undergone considerable inter-decadal and intra-decadal changes over the past few recent centuries (Tyson, 1986) and with that, natural vegetation has also been dynamic, with favoured vegetation migration routes being the east coast, the mountain ranges of the west, south and eastern margins of South Africa as well as the hot, moist river valleys (Acocks, 1988).

What is required by the hydrological community working in a relatively large country of 1.22 million km^2 in which hydrological responses reflect clearly

- the diversity of mean annual precipitations (MAPs) ranging from < 80 mm to > 3 000 mm
- altitudes varying from sea level to over 3 300 m
- rainfall seasonalities varying from dominantly summer to winter to all year rainfall regions and
- strong oceanic as well as continental influences on the hydroclimate,

is a categorisation of baseline land covers

- which captures the physiographic diversity described above
- at a spatial scale which is compatible with the hydrological delineation of South Africa into Quaternary catchments
- which is hydrologically neither too simplistic (e.g. if it operated only at the coarse level of the 12 biomes identified in the country)
- nor too complex (e.g. if it were to use mappable units which reflect highly localised and often very small scale influences on vegetation patterns such as aspect, soils or toposequence position) and
- which enjoys overall acceptance amongst both the botanical/ecological as well as the hydrological communities.

3.3 ACOCKS' VELD TYPES AS A BASELINE LAND COVER FOR HYDROLOGICAL IMPACTS STUDIES

There have been several attempts at mapping "natural" vegetation and biomes over southern Africa, including recent ones. Despite being somewhat dated, Acocks' (1988) vegetation classification into so-called "Veld Types" (Figure 3.1) nevertheless remains a scientifically respected and generally accepted seminal work on the "natural" vegetation ecology of South Africa.

While vegetation is made up of individual plants, usually of different species often in competition with one another such that a balance is maintained in a given environment, the concept of the Veld Type was reached by Acocks from a perspective of both botanical composition as well as practical utilisation. Veld Types are defined by Acocks (1988) as

> *A unit of vegetation whose range of variation is small enough to permit the whole of it to have the same farming potentialities.*

Important in its acceptance as a baseline land cover categorisation for hydrological response analyses are the following factors stressed by Acocks (1988), *viz*. that a Veld Type

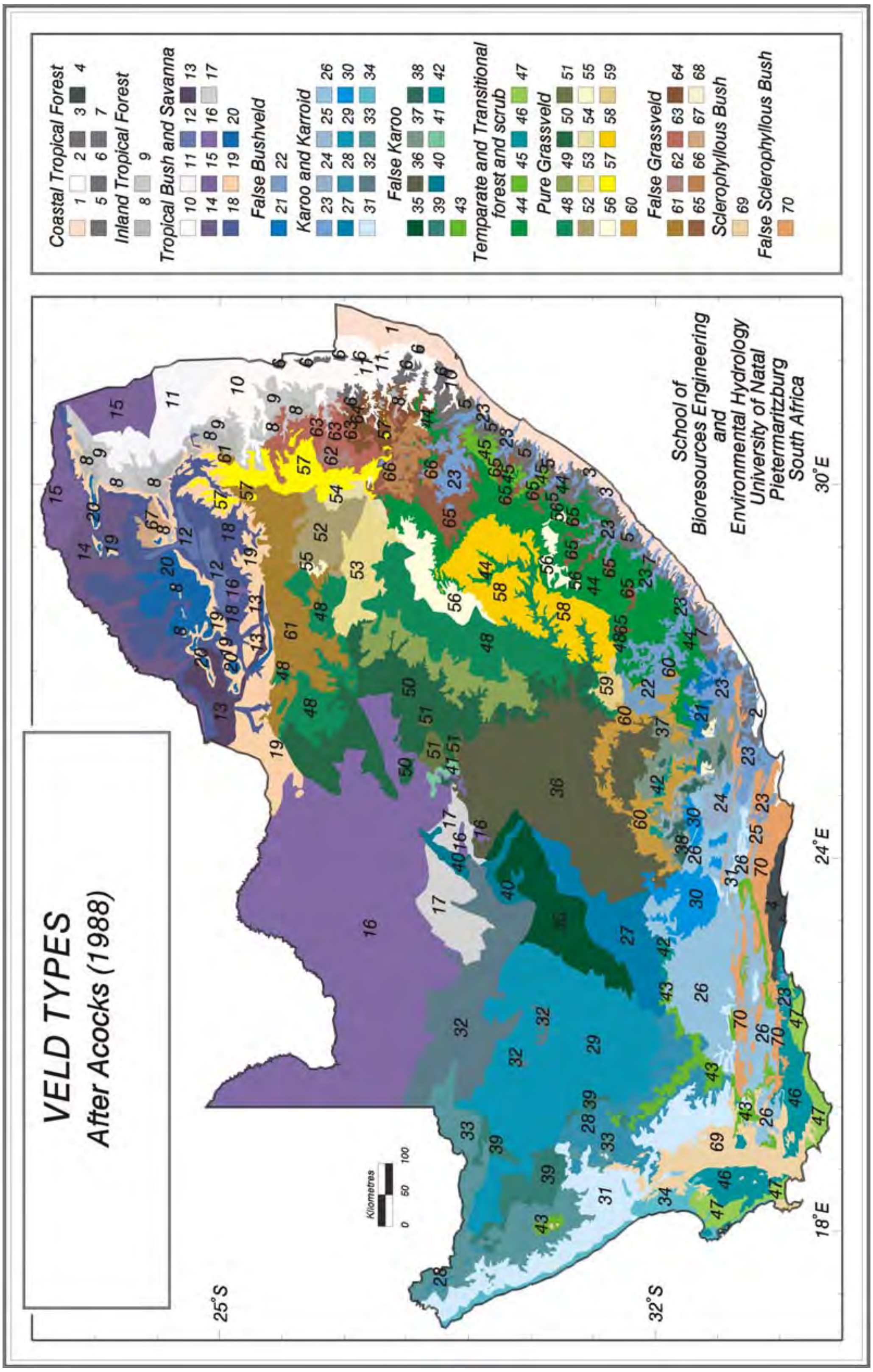

Figure 3.1 Acocks' (1988) Veld Types

- is based on a major indicator species within it
- is a manageable unit at local, regional and national scale and
- is based on the separation of natural variation of vegetation types from variations induced by human influences.

Equally significant to remember, however, is that Veld Types do not necessarily constitute climax vegetation.

3.4 AN APPROACH TO ASSIGNING HYDROLOGICAL VARIABLES TO LAND COVER

A natural land cover influences hydrological responses by virtue of its

- *above- ground attributes*, for example
  - *biomass*, expressed through a leaf area index or a water use (i.e. crop) coefficient, which varies with vegetation type and intra-annual seasonality and is influenced by factors such as water availability, heat units and frost duration, and which determines largely the potential transpiration rates and canopy interception of rainfall
  - *structure*, which can influence erodibility of rainfall through consideration of drop fall height and associated terminal velocities, and
  - *physiological factors*, which affect the level of available soil water at which plant water stress sets in; by
- *ground- surface attributes*, such as the intrinsic infiltrability into the soil which is one of the controls of initial abstractions of rainfall before stormflow commences, as well as litter and/or mulch, which can protect soil against erosion and can reduce evaporation losses from the soil surface; and by
- *below- surface attributes*, such as the seasonal distribution of effective root distribution in the various soil horizons and the degree of root colonisation within the horizons, which affect soil water extraction patterns.

In the daily time step conceptual-physical *ACRU* model (Schulze, 1995), for example, and in many similarly structured hydrological models, land cover related input variables expressing the above attributes have been defined. These are discussed in Section 3.5.2.2.

3.5 ASSIGNING VALUES TO HYDROLOGICAL VARIABLES FROM ACOCKS' VELD TYPES

3.5.1 Background

In assigning values to hydrological model variables from Acocks' (1988) Veld Types, a combination of qualitative and quantitative approaches was adopted.

- *Qualitatively* the descriptions by Acocks of his individual Veld Types were used with respect to
  - dominant vegetation structure, density and other descriptive attributes, as were his
  - comparisons of one Veld Type with adjacent ones in regard to the concept of transition, and his
  - broad climatic descriptions in terms of ranges of annual rainfall, temperature distributions, humidity or duration of, and sensitivity to, frost occurrence.
  - The photographs in Acocks (1988) proved to be of further qualitative value.
- *Quantitatively* the climate descriptions given by Acocks (1988) were evaluated from superimposing gridded information contained in the "South African Atlas of Agrohydrology and
  - Climatology" (Schulze, 1997) over the vector image of Acocks' Veld Types with respect to
  - the length of the active growing season, based on water budgeting considerations,
  - the seasonality as well as concentration of rainfall,
  - available energy, expressed through the heat unit concept, and
  - the typical dates of onset and end of the frost period, and hence its duration.

A first attempt at assigning values to hydrological model variables to Acocks' Veld Types in South Africa was made in the early 1990s (Schulze and Hohls, 1993), and these values were "imbedded" in a decision support system for land cover in the *ACRU* model Version 3.0, with procedures described in the model's documentation of the mid-1990s (Schulze, 1995; Smithers and Schulze, 1995). The variables have now, however, been re-determined with greater scientific rigour, and inconsistencies which had been noted removed, as more detailed regional and national catchment hydrological studies have been undertaken in the interim in which the necessity for a consistent methodology for determining baseline hydrological attributes has become imperative.

3.5.2 Working Rules for Determining Hydrological Attributes for Acocks' Land Types

3.5.2.1 Why Working Rules?

Unlike most agricultural and horticultural crops, or commercially grown tree species, where scientific research with lysimeters, soil moisture probes, heat pulse and Bowen ratio techniques or paired catchments experiments, as well as other direct measurement techniques in the field, has provided a reasonably sound database nationally and internationally from which to derive relatively reliable simulation model input variables for use in South Africa, the same cannot be said for natural vegetation types such as Acocks' Veld Types. Hence the need arose for developing consistent and scientifically credible experience-based and literature-based "working rules" for the estimation of hydrological model input variables for the 70 Veld Types which Acocks' identified for South Africa, Lesotho and Swaziland.

3.5.2.2 Assumptions and Premises

For daily conceptual physical hydrological models such as *ACRU*, and many other models, the most important above-ground, surface and below-ground land cover variables are as follows:

- ***Water Use Coefficient, K_{cm}***

  This expresses transpiration and soil water evaporation losses to the atmosphere under conditions of sufficient soil moisture as a fraction of atmospheric demand, i.e. maximum evaporation/ reference potential evaporation. K_{cm} is a plant attribute and is a function largely of actively photosynthesising biomass. It is thus influenced, *inter alia*, by the vegetation's
  - cover and spacing
  - active growing season
  - structure
  - reflectivity of solar radiation and
  - aerodynamic roughness.

  For natural vegetation K_{cm} would thus need to be quantified by consideration of the triggers which "drive" the onset of growth at the beginning of a season, the sustainability of actively photosynthesising biomass, and the cessation of growth at the end of a season. These drivers are essentially energy and water, singly or in combination with one another.

  Hence, factors determining K_{cm} include
  - the active moisture growing period and its inter-annual variation, and hence also the seasonality and concentration of rainfall
  - frost onset and duration of the frost season, which can induce senescence and
  - available energy during the active moisture growing season, and particularly in the early growing season, which can be expressed by, for example, the heat unit (i.e. degree day) concept.

  Note that the estimation of K_{cm} does not consider its temporary decline with in-season soil water stress conditions, or a recovery following rains, as these are simulated internally in models such as *ACRU* by daily soil water budgeting which includes feedforwards and feedbacks of plant water stress processes.

  Typical starting values for K_{cm} in the active moisture growing season were assigned as follows:
  - forests : 0.85, but reduced where/when there was a moisture deficiency
  - bushveld : 0.75, but increasing to 0.80 if heat units in the moisture growing season exceed 400 for a given month
  - grassveld : 0.65 when heat units exceed 300
    0.60 when heat units are between 200 and 300 for a given month
    0.50 when heat units are below 200 for the month.

- For Veld Types such as grasslands which senesce, K_{cm} declines to 0.20 for the average duration of the frost period.

- ***Interception Loss, I_l***

  Maximum canopy and litter interception losses on a rainday depend on above-ground and surface biomass. Interception loss thus frequently displays a slight decline in the dry season, but not to the same extent as K_{cm} because, while active photosynthesis and transpiration may cease, there usually remains biomass which can intercept rainfall. The basis of starting values of maximum I_l were De Villiers' (1975) values from his seminal work on interception losses in South Africa, which included estimates of interception by Acocks' Veld Types.

- ***Root Distribution, R_A***

  For a 2-layer soil horizonation the root distribution may be expressed as the fraction of active roots in the critical topsoil (or A) horizon (R_A) compared with those in the total active soil profile. As starting working rules, R_A was assigned to be

  - 0.75 throughout the year for natural forests with their deeper rooting systems, but still with a dominance of active roots in the nutrient rich topsoil
  - 0.80 throughout the year for bushveld/thornveld as well as karroo/macchia type vegetations and
  - 0.90 for shallower rooted grasses in their moisture growing season, but increasing gradually when moisture availability declines, to 1.00 during the frost season when roots are assumed to die off and any evaporative activity would be from soil water evaporation from the topsoil only (hence R_A of 1.0).

- ***Coefficient of Initial Abstractions, cI_a***

  This expresses the abstraction of rainfall on a given rainy day before stormflow commences. Initial abstractions are influenced by the soil surface's inherent infiltrability which, in conjunction with soil moisture content of the topsoil horizon, determines I_a through daily soil water budgeting. The coefficient '*c*' of I_a depends, *inter alia*, on typically expected rainfall intensities, which can vary with season. The internationally used default value of cI_a = 0.2 of the soil water deficit in the topsoil has, therefore, been changed as follows, based on South African research by Arnold (1981), Schulze (1984), Jewitt (1991) and Topping (1993). Thus cI_a for:

  - winter and all year rainfall regions, associated with low intensity rainfalls:
    0.30 for all months of the year
  - summer rainfall region : 0.15 in the mid-summer convective period, depending on the rainfall concentration, and increasing to
    0.30 in the winter frontal rainfall season, but with
    0.25 replacing 0.15 along coastal zones where rainfall intensities are lower than in the inland
  - dense natural forests : 0.35 throughout the year, because the deep litter layer enhances initial infiltration before stormflow commences.

- ***Soil Surface Cover by Litter, $C_{s\%}$***

  On the basis of observations in a range of grasslands, bushveld and natural forests, and in consultation with the National Botanical Institute (Rutherford, 2001, pers. com.) a first approximation of $C_{s\%}$ for natural vegetation was made using a sigmoidal relationship between $C_{s\%}$ and K_{cm}. In simplified multi-linear form this relationship is

$$C_{s\%} = 100(Kcm - 0.20) \quad \text{for } K_{cm} \text{ between 0.20 and 0.40}$$
$$C_{s\%} = 20 + 177.8(Kcm - 0.40) \quad \text{for } K_{cm} \text{ between 0.40 and 0.85}$$
$$C_{s\%} = 100 \quad \text{for } K_{cm} \text{ greater than 0.85}$$

  By implication, the greater the above-ground biomass the higher the litter cover. Litter cover was computed from the highest monthly value of K_{cm} and litter decomposition was not accounted for.

3.5.2.3 Climatic Attributes of Acocks' Veld Types

The vector image of Acocks' 70 Veld Types (*cf.* Figure 3.1) was superimposed onto the following 1'x1' of a degree latitude/longitude raster images taken from the "South African Atlas of Agrohydrology and –Climatology" (Schulze, 1997):

- mean annual precipitation (MAP, mm) from Dent, Lynch and Schulze (1989)
- average first date of heavy frost
- average last date of heavy frost, and hence frost duration
- month-by-month values of heat units, i.e. growing degree days (base 10^{o}C)
  rainfall concentration, which reflects the effective duration of the rainfall season, based on Markham's technique as used in Schulze (1997) and the
- onset and end of the moisture growing season as determined by Schulze (1997) using the FAO (1978) technique.

The means of all the 1'x1' gridded values falling within each respective Veld Type, as well as the 10th and 90th percentile values were computed. A summary of the above climatic attributes for the Acocks Veld Types is given in Table 3.1.

3.5.2.4 Derived Hydrological Attributes for Acocks' Veld Types

Using the climatic attributes from Table 3.1 and the working rules established above in Section 3.5.2.2, sets of month-by-month hydrological attributes for input into models such as *ACRU* were derived. These are given in Table 3.2 for the water use coefficient, vegetation interception loss per rainday, root fraction in the topsoil and the coefficient of initial abstractions.

3.6 DISCUSSION AND CONCLUDING REMARKS

With the implementation phase of the National Water Act (1998) now in full operation, it has become necessary to assess and compare the water uses and hence hydrological responses of different natural and man-made land covers and associated land use management scenarios. With that, the necessity has arisen to determine a baseline against which hydrological response comparisons can be made with some objectivity.

There appears to be no perfect vegetation or land use related baseline for hydrological purposes, with certain approaches, which have been highlighted in the introductory sections, being either too complex, too simplistic or too dynamic. This paper makes a case for using Acocks' (1988) Veld Types as the baseline for use in hydrological impact studies in South Africa. While not the most current vegetation classification of South Africa, it remains a respected, credible and accepted division of the vegetation ecology of this region and is based on painstaking, in-depth and highly quantified field observations which are still being analysed some 25 years after John Acocks' death in 1979, as testified by the recent (March 2003) special edition of the South African Journal of Botany devoted entirely to re-analysis of Acocks' work.

This paper has outlined procedures by which hydrological variables used in models such as *ACRU* have been assigned to Acocks Veld Types in a rigorous and consistent manner. Examples have been presented and reasons for assigning hydrological values have been given.

A problem with the Acocks classification, and any other natural vegetation classification in South Africa for that matter, remains that no absolute or measured values of hydrological attributes are available. The limited lysimeter data reported in Snyman *et al*.(1978) on grasslands at various successional stages have been used as a basis, but for the rest, hydrological values have been assigned using a set of working rules moderated by Acocks' descriptions as well as being guided by the photographs in Acocks (1988) and by eliciting expert opinion of vegetation ecologists.

Above, all the quest has been for consistency in the methodology of deriving and assigning values of hydrological variables to baseline land covers, and for compatibility in approach with the methodologies also applied when values of variables are assigned to agricultural crops and other land uses.

Table 3.1 Acocks' (1988) Veld Types : Climatic attributes

Moisture Growing Season , MGS (days) : Lowest 10% Median Highest 10%
Frost Duration (only if > 10 days) :
Heat Units (base 10ºC) per month : 201

Number	Acocks' Veld Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	FROST (days)	MGS (days)	MAP (mm)	CONC %
	COASTAL TROPICAL FOREST TYPES																
1	Coastal Forest and Thornveld	428	392	412	338	278	201	200	231	270	313	340	405		256	929	37
2	Alexandria Forest	361	336	341	272	223	153	141	162	188	229	267	324		277	666	9
3	Pondoland Coastal Plateau Sourveld	366	337	352	285	239	171	169	197	221	253	276	336		269	1235	39
4	Knysna Forest	341	314	305	230	163	93	76	96	130	186	243	307	32	316	864	6
5	Ngongoni Veld - Zululand	349	322	330	257	195	120	122	164	203	239	266	327	10	236	901	46
6	Zululand Thornveld	434	388	406	329	264	177	184	236	285	327	353	414		205	790	47
7	Eastern Province Thornveld	350	326	329	257	206	126	119	153	180	219	252	315	10	237	683	28
	INLAND TROPICAL FOREST TYPES																
8	North-Eastern Mountain Sourveld	330	291	296	230	158	74	79	135	200	256	278	316	26	194	991	59
9	Lowveld Sour Bushveld	431	384	394	312	234	146	150	212	281	341	365	415		192	862	59
	TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)																
10	Lowveld	474	424	442	359	282	194	320	257	317	369	393	454		177	692	53
11	Arid Lowveld	487	433	446	366	285	191	195	257	324	386	419	470		114	533	63
12	Springbok Flats Turf Thornveld	419	367	367	272	175	78	81	160	260	340	362	400	46	136	556	63
13	Other Turf Thornveld	473	407	403	288	171	60	60	160	290	397	419	451	68	116	565	64
14	Arid Sweet Thornveld	478	417	420	321	216	111	112	197	305	395	426	460	25	48	418	68
15	Mopani Veld	504	442	460	380	298	201	205	265	332	406	441	487		103	421	68
16	Kalahari Thornveld	477	416	389	258	138	21	20	99	207	322	383	464	89	25	313	65
17	Kalahari Thornveld invaded by Karoo	453	384	347	209	93	0	0	54	154	274	342	422	110	9	321	60
18	Mixed Bushveld	433	378	380	284	184	83	85	167	270	353	378	415	42	132	524	65
19	Sourish Mixed Bushveld	417	360	350	248	141	41	42	126	233	329	359	398	63	142	591	63
20	Sour Bushveld	384	332	330	240	143	45	43	124	228	305	338	367	60	145	630	65
21	False Thornveld of Eastern Cape	361	332	322	231	157	69	62	110	158	211	258	327	50	60	521	30
22	Invasion of Grassveld by Acacia Karoo	329	291	270	167	81	0	0	49.6	113	175	227	296	114	95	523	45
23	Valley Bushveld	372	342	343	264	203	116	113	153	192	239	278	343	23	221	629	35
24	Noorsveld	423	384	366	255	178	83	71	121	180	251	314	388	54	0	262	31
25	Succulent Mountain Scrub	392	354	333	224	135	42	31	76	137	214	281	357	84	0	306	20
26	Karroid Broken Veld	392	353	327	212	118	26	14	57	123	209	279	355	94	110	203	32
27	Central Upper Karoo	374	328	291	155	48	0	0	0	78	177	252	335	138	20	231	49
28	Western Mountain Scrub	388	365	343	215	119	14	0	39	108	202	278	349	109	11	210	42
29	Arid Karoo	422	381	355	224	115	12	1.6	54	138	237	311	383	105	23	141	54
30	Central Lower Karoo	394	351	324	206	110	20	8	56	126	212	281	358	101		208	37
31	Succulent Karoo	403	375	364	272	192	107	78	110	164	242	309	366	37	48	140	53
32	Orange River Broken Veld	465	406	380	251	138	30	23	87	180	291	360	431	87	4	180	63
33	Namaqualand Broken Veld	403	378	367	261	163	72	54	88	158	242	309	364	52	40	122	58
34	Strandveld	360	337	338	272	197	123	95	116	153	226	284	326	3	112	184	56

Table 3.1 Acocks' (1988) Veld Types: Climatic attributes (continued)

	FALSE KAROO TYPES															
35	False Arid Karoo	426	367	333	200	91	0	0	48	140	245	314	394	117	6	239	55
36	False Upper Karoo	386	326	291	161	51	0	0	17	111	208	272	350	128	25	355	49
37	False Karroid Broken Veld	371	332	312	201	110	23	14	67	135	208	264	336	89	18	362	35
38	False Central Lower Karoo	392	353	332	224	133	44	34	82	152	228	287	361	80	11	323	33
39	False Succulent Karoo	400	372	352	230	119		8	50	129	219	294	360	95	11	99	47
40	False Orange River Broken Veld	457	389	357	222	112	3	0	71	168	281	348	426	101	7	297	59
41	Pan Turf Veld invaded by Karoo	426	363	333	207	96	0	0	67	171	276	332	400	105	9	405	58
42	Karroid Merxmuellera Mountain Veld replaced by Karoo	329	290	254	128	26	0	0	0	69	150	215	291	151	12	316	36
43	Mountain Renosterveld	352	321	288	164	67	0	0	0	65	155	237	312	121	51	308	34
	TEMPERATE AND TRANSITIONAL FOREST AND SCRUB TYPES															
44	Highland Sourveld and Döhne Sourveld	296	265	254	164	84	3	2	59	126	174	209	270	96	216	815	50
45	Natal Mist Belt Ngongoni Veld	316	290	291	216	144	63	68	118	171	212	239	299	42	230	920	50
46	Coastal Rhenosterveld	358	333	324	242	163	95	67	85	123	200	263	322	14	138	434	34
47	Coastal Macchia	338	312	309	239	163	104	78	88	122	189	245	304	10	142	430	36
	PURE GRASSVELD TYPES															
48	Cymbopogon-Themeda Veld	335	281	257	143	34	0	0	17	120	203	246	307	123	171	629	54
49	Transitional Cymbopogon Themeda Veld	358	301	276	159	47	0	0	25	134	225	269	330	122	102	546	54
50	Dry Cymbopogon-Themeda Veld	395	336	313	197	84	0	0	60	173	268	311	371	111	107	506	57
51	Pan Turf Veld	414	351	322	201	90	0	0	60	167	268	320	386	107	26	436	58
52	Themeda Veld or Turf Highveld	302	2602	250	150	48	0	0	39	144	217	240	284	111	173	662	59
53	Patchy Highveld to Cymbopogon-Themeda Veld Transition	316	270	256	150	45	0	0	34	140	217	246	295	116	170	639	57
54	Turf Highveld to Highland Sourveld Veld Transition	281	239	229	138	43	0	0	34	131	189	215	262	115	184	697	59
55	Bankenveld to Turf Highveld Transition	310	267	256	155	54	0	0	42	150	226	249	291	110	170	675	59
56	Highland Sourveld to Cymbopogon-Themeda Veld Transition	293	249	229	125	22	0	0	9	107	175	210	267	128	197	716	54
57	North-Eastern Sandy Highveld	267	230	223	140	51	0	0	45	135	188	209	251	91	192	769	59
58	Themeda-Festuca Alpine Veld	166	136	101	9	0	0	0	0	0	47	83	135	209	216	728	50
59	Stormberg Plateau Sweetvelt	290	241	200	84	0	0	0	0	45	126	179	253	158	108	539	43
60	Karroid Merxmuellera Mountain Veld	316	274	239	117	14	0	0	0	63	143	203	279	153	17	413	40
	FALSE GRASSVELD TYPES															
61	Bankenveld	337	293	281	182	78	0	0	64	176	256	278	321	96	167	658	60
62	Bankenveld to Sour Sandveld Transition	319	277	278	192	105	20	25	98	182	234	258	305	76	206	848	58
63	Piet Retief Sourveld	317	280	284	204	124	41	47	115	189	237	258	305	57	213	918	57
64	Northen Tall Grassveld	371	325	336	252	177	90	98	160	227	274	300	355	31	210	839	54
65	Southern Tall Grassveld	333	297	293	206	124	41	43	105	174	225	257	313	74	200	812	56
66	Natal Sour Sandveld	347	305	309	221	136	50	56	122	198	247	276	332	69	191	746	58
67	Pietersburg Plateau False Grassveld	355	308	307	230	143	50	50	118	206	281	309	341	55	122	477	64
68	Eastern Province Grassveld	357	326	309	218	138	53	42	93	144	202	252	322	78	12	388	28
69	Macchia	319	302	284	195	113	35	14	36	83	160	228	284	63	149	625	50
70	False Macchia	330	304	295	206	127	45	31	62	110	175	230	293	75	218	532	12

Table 3.2 Acocks' (1988) Veld Types: Derived hydrological attributes

CAY : WATER USE (CROP) COEFFICIENT   COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
VEGINT : INTERCEPTION (mm) per RAINDAY   ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SURFACE COVER	VARIABLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
	COASTAL TROPICAL FOREST TYPES															
1	Coastal Forest and Thornveld	100.00	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85	0.80
			VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10	2.82
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
2	Alexandria Forest	100.00	CAY	0.60	0.85	0.85	0.85	0.75	0.75	0.70	0.70	0.70	0.65	0.60	0.60	0.72
			VEGINT	2.00	2.50	2.50	2.50	2.00	2.00	1.90	1.90	1.90	1.90	1.90	1.90	2.08
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
3	Pondoland Coastal Plateau Sourveld	91.20	CAY	0.80	0.80	0.80	0.70	0.60	0.55	0.50	0.60	0.70	0.75	0.75	0.80	0.70
			VEGINT	2.50	2.50	2.50	2.30	2.00	2.00	2.00	2.00	2.20	2.30	2.40	2.50	2.27
			ROOTA	0.80	0.80	0.80	0.80	0.85	0.90	0.90	0.85	0.80	0.80	0.80	0.80	0.83
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25	0.28
4	Knysna Forest	100.00	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.80	0.85	0.85	0.85	0.85	0.85	0.85
			VEGINT	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
5	Ngongoni Veld - Zululand	73.40	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70	0.62
			VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40	1.35
			ROOTA	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.92
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
6	Zululand Thornveld	91.20	CAY	0.80	0.80	0.80	0.70	0.65	0.50	0.50	0.60	0.75	0.80	0.80	0.80	0.71
			VEGINT	2.40	2.40	2.40	2.10	1.80	1.80	1.80	1.80	2.20	2.40	2.40	2.40	2.16
			ROOTA	0.80	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.80	0.83
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
7	Eastern Province Thornveld	82.30	CAY	0.75	0.75	0.75	0.65	0.50	0.40	0.40	0.40	0.60	0.70	0.75	0.75	0.62
			VEGINT	1.60	1.60	1.60	1.50	1.40	1.30	1.30	1.40	1.60	1.60	1.60	1.60	1.51
			ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.85	0.82	0.80	0.80	0.80	0.84
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.28
	INLAND TROPICAL FORESTS															
8	North-Eastern Mountain Sourveld	82.30	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75	0.56
			VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60	2.37
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80	0.87
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
9	Lowveld Sour Bushveld	82.30	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75	0.68
			VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50	2.35
			ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
	TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)															
10	Lowveld	91.20	CAY	0.80	0.80	0.80	0.65	0.55	0.40	0.40	0.40	0.60	0.75	0.75	0.80	0.64
			VEGINT	2.50	2.50	2.50	2.10	1.90	1.90	1.90	1.90	2.10	2.50	2.50	2.50	2.23
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
11	Arid Lowveld	91.20	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80	0.56
			VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10	1.98
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
12	Springbok Flats Turf Thornveld	82.30	CAY	0.70	0.70	0.60	0.50	0.45	0.30	0.20	0.20	0.40	0.50	0.70	0.75	0.50
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
13	Other Turf Thornveld	82.30	CAY	0.75	0.70	0.60	0.50	0.45	0.20	0.20	0.20	0.40	0.50	0.60	0.70	0.48
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.85	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
14	Arid Sweet Thornveld	82.30	CAY	0.75	0.60	0.50	0.45	0.35	0.30	0.20	0.20	0.40	0.55	0.65	0.75	0.48
			VEGINT	1.60	1.60	1.60	1.50	1.30	1.20	1.10	1.10	1.20	1.40	1.60	1.60	1.40
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
15	Mopani Veld	82.30	CAY	0.75	0.55	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.75	0.50
			VEGINT	1.80	1.60	1.50	1.50	1.50	1.40	1.30	1.30	1.30	1.50	1.70	1.80	1.52
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
16	Kalahari Thornveld	82.30	CAY	0.65	0.75	0.70	0.60	0.45	0.20	0.20	0.20	0.40	0.50	0.55	0.65	0.49
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.80	0.80	0.80	0.90	1.00	1.10	0.98
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	0.90	0.88	0.85	0.80	0.89
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
17	Kalahari Thornveld invaded by Karoo	64.50	CAY	0.60	0.65	0.60	0.45	0.30	0.20	0.20	0.20	0.20	0.40	0.50	0.60	0.41
			VEGINT	1.50	1.60	1.60	1.50	1.30	1.10	1.10	1.10	1.20	1.30	1.40	1.50	1.35
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	1.00	0.95	0.90	0.80	0.90
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
18	Mixed Bushveld	82.30	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75	0.54
			VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60	2.33
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
19	Sourish Mixed Bushveld	82.30	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70	2.36
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80	0.86
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
20	Sour Bushveld	82.30	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70	2.36
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80	0.86
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15	0.24

Table 3.2 Acocks' (1988) Veld Types: Derived hydrological Attributes (continued)

21	False Thornveld of Eastern Cape	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.35	0.30	0.30	0.40	0.45	0.50	0.55	0.50
			VEGINT	1.70	1.70	1.70	1.60	1.40	1.30	1.30	1.30	1.30	1.40	1.40	1.50	1.47
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.85	0.80	0.89
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
22	Invasion of Grassveld by Acacia Karoo	64.50	CAY	0.63	0.65	0.65	0.55	0.40	0.20	0.20	0.20	0.20	0.40	0.50	0.60	0.43
			VEGINT	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.00	1.00	1.10	1.20	1.08
			ROOTA	0.80	0.80	0.80	0.90	0.90	1.00	1.00	1.00	1.00	0.90	0.85	0.80	0.90
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
23	Valley Bushveld	82.30	CAY	0.75	0.75	0.75	0.65	0.55	0.20	0.20	0.40	0.60	0.75	0.75	0.75	0.59
			VEGINT	2.50	2.50	2.50	2.20	2.00	2.00	1.90	1.90	2.20	2.50	2.50	2.50	2.27
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80	0.87
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20	0.26
24	Noorsveld	20.00	CAY	0.40	0.40	0.40	0.40	0.35	0.25	0.20	0.25	0.35	0.40	0.40	0.40	0.35
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.87	0.93	1.00	1.00	0.95	0.90	0.80	0.80	0.87
			COIAM	0.15	0.15	0.15	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15	0.24
25	Succulent Mountain Scrub	20.00	CAY	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.35
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
26	Karroid Broken Veld	37.80	CAY	0.30	0.30	0.40	0.50	0.50	0.40	0.35	0.35	0.40	0.30	0.30	0.30	0.37
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25	0.28
27	Central Upper Karoo	37.80	CAY	0.50	0.50	0.50	0.40	0.30	0.20	0.20	0.20	0.20	0.30	0.40	0.50	0.35
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.90
			COIAM	0.15	0.15	0.15	0.15	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.24
28	Western Mountain Scrub	20.00	CAY	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.33
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.80	0.80	0.89
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
29	Arid Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			VEGINT	0.20	0.20	0.20	0.20	0.25	0.30	0.25	0.20	0.20	0.20	0.20	0.20	0.22
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.26
30	Central Lower Karoo	15.00	CAY	0.30	0.30	0.35	0.35	0.30	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00	0.95	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
31	Succulent Karoo	20.00	CAY	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.32
			VEGINT	0.20	0.20	0.20	0.25	0.35	0.40	0.35	0.30	0.20	0.20	0.20	0.20	0.25
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	0.95	0.90	0.90	0.90	0.90	0.93
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.28
32	Orange River Broken Veld	10.00	CAY	0.25	0.30	0.30	0.25	0.25	0.20	0.20	0.20	0.25	0.30	0.30	0.30	0.26
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.88
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.28
33	Namaqualand Broken Veld	15.00	CAY	0.25	0.25	0.25	0.30	0.35	0.35	0.35	0.30	0.25	0.25	0.25	0.25	0.28
			VEGINT	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.20	0.20	0.20	0.20	0.23
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
34	Strandveld	20.00	CAY	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.34
			VEGINT	0.50	0.50	0.50	0.50	0.60	0.60	0.60	0.50	0.50	0.50	0.50	0.50	0.53
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
				FALSE KAROO TYPES												
35	False Arid Karoo	20.00	CAY	0.30	0.40	0.40	0.30	0.25	0.20	0.20	0.20	0.25	0.30	0.30	0.30	0.28
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.36
			ROOTA	0.80	0.80	0.80	0.80	0.95	1.00	1.00	1.00	0.95	0.80	0.80	0.80	0.88
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
36	False Upper Karoo	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24
37	False Karroid Broken Veld	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24
38	False Central Lower Karoo	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24
39	False Succulent Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
40	False Orange River Broken Veld	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

Table 3.2 Acock's (1988) Veld Types: Derived hydrological attributes (continued)

41	Pan Turf Veld invaded by Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
42	Karroid Merxmuellera Mountain Veld replaced by Karoo	37.80	CAY	0.30	0.50	0.50	0.40	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30
			VEGINT	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.90
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
43	Mountain Renosterveld	37.80	CAY	0.30	0.30	0.30	0.30	0.50	0.40	0.30	0.30	0.30	0.30	0.30	0.30	0.33
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	TEMPERATE AND TRANSITIONAL FOREST AND SCRUB TYPES															
44	Highland Sourveld and Döhne Sourveld	73.40	CAY	0.70	0.70	0.70	0.50	0.30	0.20	0.20	0.20	0.50	0.65	0.70	0.70	0.50
			VEGINT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.30	1.60	1.60	1.60	1.38
			ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
45	Natal Mist Belt Ngongoni Veld	73.40	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	0.70	0.52
			VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50	1.34
			ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
46	Coastal Rhenosterveld	37.80	CAY	0.40	0.40	0.40	0.45	0.50	0.50	0.50	0.50	0.50	0.45	0.40	0.40	0.45
			VEGINT	0.80	0.80	0.80	1.00	1.20	1.20	1.20	1.20	1.00	0.80	0.80	0.80	0.97
			ROOTA	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.93
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
47	Coastal Macchia	55.60	CAY	0.35	0.40	0.42	0.50	0.60	0.60	0.60	0.60	0.55	0.50	0.40	0.35	0.49
			VEGINT	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.89
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PURE GRASSVELD TYPES															
48	Cymbopogon-Themeda Veld	64.50	CAY	0.65	0.65	0.65	0.55	0.40	0.20	0.20	0.20	0.40	0.50	0.65	0.65	0.48
			VEGINT	1.20	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.12
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
49	Transitional Cymbopogon Themeda Veld	64.50	CAY	0.65	0.65	0.65	0.50	0.25	0.20	0.20	0.20	0.30	0.45	0.50	0.60	0.43
			VEGINT	1.10	1.10	1.10	1.10	0.90	0.80	0.80	0.80	0.90	1.00	1.10	1.10	0.98
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
50	Dry Cymbopogon-Themeda Veld	64.50	CAY	0.60	0.65	0.65	0.50	0.30	0.20	0.20	0.20	0.30	0.40	0.50	0.55	0.42
			VEGINT	1.00	1.00	1.00	0.90	0.90	0.90	0.80	0.80	0.80	0.90	1.00	1.00	0.92
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
51	Pan Turf Veld	64.50	CAY	0.58	0.65	0.60	0.50	0.35	0.20	0.20	0.20	0.30	0.40	0.50	0.55	0.42
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.80	0.80	0.80	0.90	1.00	1.10	0.98
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
52	Themeda Veld or Turf Highveld	64.50	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.09
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
53	Patchy Highveld to Cymbopogon-Themeda Veld Transition	64.50	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.09
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
54	Turf Highveld to Highland Sourveld Veld Transition	55.60	CAY	0.60	0.60	0.60	0.52	0.40	0.20	0.20	0.20	0.35	0.50	0.60	0.60	0.45
			VEGINT	1.30	1.30	1.30	1.20	1.00	0.90	0.90	0.90	1.10	1.20	1.30	1.30	1.14
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
55	Bankenveld to Turf Highveld Transition	64.50	CAY	0.65	0.65	0.65	0.50	0.35	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.20	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.10
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
56	Highland Sourveld to Cymbopogen-Themeda Veld Transition	59.16	CAY	0.62	0.62	0.62	0.50	0.30	0.20	0.20	0.20	0.25	0.50	0.62	0.62	0.44
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.10	1.10	1.03
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
57	North-Eastern Sandy Highveld	59.16	CAY	0.62	0.62	0.60	0.50	0.35	0.20	0.20	0.20	0.35	0.50	0.62	0.62	0.45
			VEGINT	1.30	1.30	1.30	1.20	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.30	1.19
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
58	Themeda-Festuca Alpine Veld	37.80	CAY	0.50	0.50	0.45	0.35	0.20	0.20	0.20	0.20	0.30	0.35	0.45	0.50	0.35
			VEGINT	1.30	1.30	1.30	1.10	0.90	0.90	0.90	0.90	1.10	1.20	1.30	1.30	1.13
			ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.95
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
59	Stormberg Plateau Sweetvelt	55.60	CAY	0.60	0.60	0.60	0.55	0.40	0.20	0.20	0.20	0.20	0.35	0.45	0.55	0.41
			VEGINT	1.30	1.30	1.30	1.20	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.20	1.10
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
60	Karroid Merxmuellera Mountain Veld	55.60	CAY	0.40	0.60	0.60	0.40	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.35	0.33
			VEGINT	0.60	0.60	0.60	0.60	0.50	0.40	0.40	0.40	0.40	0.40	0.50	0.50	0.49
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.80	0.91
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25

Table 3.2 Acocks' (1988) Veld Types: Derived hydrological attributes (continued)

FALSE GRASSVELD TYPES																
61	Bankenveld	64.50	CAY	0.65	0.65	0.65	0.50	0.35	0.20	0.20	0.20	0.25	0.50	0.65	0.65	0.45
			VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.18
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
62	Bankenveld to Sour Sandveld Transition	73.40	CAY	0.70	0.70	0.70	0.50	0.40	0.20	0.20	0.20	0.50	0.60	0.65	0.70	0.50
			VEGINT	1.20	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.10	1.20	1.20	1.20	1.13
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
63	Piet Retief Sourveld	73.40	CAY	0.70	0.70	0.70	0.55	0.45	0.20	0.20	0.20	0.50	0.60	0.70	0.70	0.52
			VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.20	1.30	1.30	1.30	1.20
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
64	Northen Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.30	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	1.70	1.70	1.70	1.60	1.50	1.40	1.40	1.50	1.60	1.70	1.70	1.70	1.60
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
65	Southern Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.54
			VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60	1.53
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
66	Natal Sour Sandveld	82.30	CAY	0.75	0.75	0.70	0.50	0.35	0.20	0.20	0.20	0.50	0.65	0.70	0.75	0.52
			VEGINT	1.80	1.80	1.80	1.80	1.60	1.40	1.40	1.40	1.50	1.70	1.80	1.80	1.65
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
67	Pietersburg Plateau False Grassveld	64.50	CAY	0.65	0.65	0.50	0.40	0.35	0.20	0.20	0.30	0.50	0.55	0.65	0.65	0.47
			VEGINT	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.92
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
68	Eastern Province Grassveld	55.60	CAY	0.50	0.60	0.50	0.40	0.30	0.20	0.20	0.20	0.30	0.40	0.50	0.50	0.38
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.20	1.20	1.08
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
69	Macchia	55.60	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45	0.54
			VEGINT	1.00	1.00	1.10	1.20	1.20	1.20	1.20	1.20	1.10	1.10	1.00	1.00	1.11
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
70	False Macchia	55.60	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45	0.54
			VEGINT	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.86
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

While the derived Acocks values may not represent entirely the more absolute magnitudes which would be obtained experimentally, they would contain similar inherent errors to those of the variables from land uses for which hydrological response changes are sought. The modelled hydrological impacts of those land uses would thus be relatively correct because of an element of error cancellation.

What have not been considered explicitly in this exercise have, however, been

- impacts of burning on biomass removal and regeneration
- a vegetation types "memory" of previous seasons' drought conditions
- the hydrologically relevant dynamics between grasses and trees in savanna vegetation as influenced by persistent dry or wet years
- the onset of plant water stress, which is species dependent and, generally
- the physiological responses of "the moment" vs those of "the long term" (Rutherford, 2001, pers. com.) as well as
- influences of local variations in soil characteristics or position of the Veld Type in the landscape, e.g. whether it is growing on a crest, the midslope or in the riparian zone.

The process representations as well as soil water budget driven feedforwards and feedbacks in hydrological models such as *ACRU* do, however, implicitly account for some of the shortcomings listed above.

What is nevertheless now available for baseline land covers, as represented by the Acocks Veld Types, is an initial set of consistently derived values of hydrological variables for application with conceptual-physical land use impacts models. This set of values has recently, for example, been used in the study on commercial forest hydrological impacts by Gush *et al*. (2002), which forms the scientific basis of current forest licensing procedures in South Africa.

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CHAPTER 4

NEW DEVELOPMENTS IN, AND REFINEMENTS TO, SUPPORTING SOFTWARE, DOCUMENTATION, USER SUPPORT AND PROMOTION OF THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM

Andrew Pike, Roland Schulze, Lucille Hallowes, Sean Thornton-Dibb, David Clark, Mark Horan, Valerie Taylor and WMA Consultants

4.1 *CalcPPTCor* : A UTILITY TO ASSIST IN THE SELECTION OF RAINFALL STATIONS AND ADJUSTMENT OF RAINFALL DATA

Andrew Pike

"Rainfall is the fundamental driving force and pulsar input behind most hydrological processes" (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995, pg AT3-1). Hydrological responses, in nature and also in a daily model such as ACRU, are highly sensitive to rainfall input, with an error in rainfall estimation often resulting in a doubling (or more) of the error in runoff estimation (Schulze, 1995). A major effort therefore needs to be expended in obtaining subcatchment rainfall values which are as realistic as possible, both spatially and temporally.

The process of selecting the most appropriate driver rainfall stations and calculating correction factors to ensure that the data used by hydrological models to represent the average rainfall of the catchment is often the most time consuming and onerous tasks facing a modeller in the configuration of daily hydrological models.

CalcPPTCor is a utility which was developed to assist the user in selecting the most representative rainfall station for a particular catchment and automatically calculates the month-by-month precipitation adjustment factors required for each subcatchment by *ACRU*.

4.1.1 Selection of Representative Rainfall Stations

To account for the regional, seasonal and daily diversity of rainfall, rainfall stations with daily data in and immediately adjacent to the study area need to be identified. The *CalcPPTCor* rainfall selection utility analyses the geographic and climatological characteristics of these daily rainfall stations to determine the most representative station to be used to "drive" the hydrology of the various subcatchments. All aspects of the selection process may be controlled by the user by way of options contained in an input file created by the user , *viz*.

- A threshold distance beyond which stations should not be considered
- A minimum record length
- The definition of the dry season (if applicable) during which a station is not penalised for being unrepresentative
- The least recent end-of-record date that is acceptable
- The number of months that may be out of range in the critical wet months
- The central meridian (used to calculate distances), and
- The units of the geographic co-ordinates in the output

CalcPPTCor uses the following station information to identify the most suitable station for every subcatchment:

- The start and end years (to ensure that stations that are selected are current or recent)
- The number of years of reliable data recorded at each station (to ensure that stations with very short data sets are excluded from the selection process)
- The geographic coordinates (to calculate the distance of the station from the centroid of the catchment).

An example of an input file containing the user defined parameters and information is provided in Table 4.1.1 while Table 4.1.2 contains an example of typical rainfall station information.

Table 4.1.1 A typical input file for the *CalcPPTCor* rainfall station selection utility

1.	Name of file containing the CCWR rainfall station details (as extracted from TEAMS)
	CCWR.ackn.daily
2.	Starting month of DRY season (month ON OR AFTER which CORPPT is not important; 11=November). Enter 0 to consider all months.
	11
3.	Ending month of DRY season (month BEFORE OR ON which CORPPT is not important; 3=March).
	3
4.	Enter the number of out-of-range months to be used to limit the output i.e. months where CORPPTis out of the range of 0.80 - 1.20 (entering 3 will cut out stations with more than 4 months out-of-range.
	3
5.	Name of the file containing the subcatchment ALT, MAP, and Med Monthly PPT info.
	centriod.csv
6.	Enter the central meridian to be used in distance calculations.
	20.00
7.	Output units for coordinates: Degrees and Minutes (1) Degrees Decimal (2), or Minutes (3)
	1
8.	Distance to be considered for PPT station selection (km)
	20
9.	Minimum record length to qualify a station for selection
	10
10.	Earliest allowable end-of-record date
	1993

Table 4.1.2 An example of daily rainfall station information in *CalcPPTCor*

WB Name and Source Code	Name	Altitude (m)	First Year Of Data	Last Year Of Data	Number Of Years Of Data	Latitude (degrees & minutes)	Longitude (degrees & Minutes)	MAP (mm)
0021441W	KRAAIFONTEIN (BOS)	158	1924	1979	49	3351	1845	526.5
0021591A	ELSENBURG	180	1903	1989	69	3351	1850	597.3
0021591W	ELSENBURG	178	1961	1986	20	3351	1850	596.4
0021655A	NIVV PROEF	150	1878	1982	79	3355	1852	709.2
0021655W	STELLENBOSCH (TNK)	122	1878	1985	92	3356	1852	713.7
0021330W	EERSTERIVIER (BOS)	30	1892	1980	63	3401	1841	530.6
0005545W	PAARDEVLEI	16	1959	1996	18	3405	1849	535.1
0021823W	PAARL (TNK)	125	1878	1986	99	3343	1858	858.5
0021825W	PAARL – AGR	108	1960	1998	32	3345	1858	892.4
0021860A	BIEN DONNE (NIVV)	130	1941	1991	49	3350	1859	810.3
0021860W	WATER VLIET	140	1959	1986	18	3350	1859	775.7

4.1.2 Calculation of Rainfall Adjustment Factors

Rainfall data from the daily rainfall station selected for an ACRU run are frequently not representative of the rainfall of the catchment/subcatchment in question because of some systematic error, necessitating an adjustment correction to be applied to the rainfall, e.g.

- if the rainfall station is outside the catchment, or if a representative station inside the catchment has a short record only, requiring a nearby station with a long record to be used, or
- if the rainfall station is inside the catchment but its observations are not representative of the catchment's areal rainfall.

The usual procedure for use in southern Africa would be for the catchment to be delimited on a 1:250 000 scale map of mean annual rainfall (MAP), from which a weighted catchment MAP would be determined (e.g. by digitisation or from the mean of the 1’ X 1’ of a degree latitude/longitude point rainfall values located within the catchment). This MAP would then be compared with that of the selected rainfall station and a general adjustment factor determined by the ratio of

$$\frac{\text{Catchment MAP}}{\text{Rainfall Station MAP}}$$

Owing to the fact that weather-generating mechanisms at a location may vary in the different seasons of the year, this factor is not necessarily constant throughout the year and typical month-by-month adjustment factors need to be determined, by which the daily rainfall in a given month can be adjusted each of the subcatchments in a simulation (Smithers and Schulze, 1995).

The geographic coordinates of each station are used by *CalcPPTCor* to identify the position of the specified rainfall station in the gridded rainfall and altitude surfaces for South Africa (Dent, Lynch and Schulze, 1989). The program then automatically extracts the relevant altitude, MAP and the 12 median monthly rainfall totals for each station from the gridded information.

CalcPPTCor also requires the user to supply average altitude, MAP and median monthly rainfall information for each catchment in question. The ArcView “Grid Extractor” utility developed by Lynch (2002, personal communication) may be used for this purpose. The ratios between the catchment median monthly rainfall and each station’s median monthly rainfall are then calculated for each subcatchment. These ratios may then be applied to the daily/monthly rainfall to ensure that topographical and climatological influences are minimised so that the resulting data are a fair representation of the rainfall received by the catchment as a whole.

4.1.3 Output from *CalcPPTCor*

Output from *CalcPPTCor* includes, on a subcatchment-by-subcatchment basis:

- an echo of options customized by the user,
- monthly correction factors,
- the number of years making up the period of record,
- the number of years of reliable data in observed record,
- station and subcatchment MAP values,
- station and subcatchment altitude values,
- number of months where unacceptably high correction factors are required,
- the distance of stations from the centroid of the subcatchment,
- a suitability index (0-100), and
- a ranking value suggesting the order of preference of stations for each subcatchment.

An example of the output from *CalcPPTCor* is shown in Table 4.1.3.

Table 4.1.3 An example of output from *CalcPPTCor*

```
Threshhold distance (km) from centroid to limit rainfall stations in output : 100.0km

 The DRY season extends from May to August (during this season the rainfall station is not penalised for CORPPT values which are outside of the range of 0.80 - 1.20)
 Rainfall stations with more than  3 months with CORPPT values out of the range of 0.80 - 1.20 during the WET SEASON have not been included in this printout
 Central meridian used in distance calculations: 31.0 degrees
 All stations in this output have a record length of  2.0 years or more (edit your menu file to change this value)
 All stations have an end year of 1990. or more recent (edit your menu file to change this value)
 Geographic coordinated outputted in Degrees and Minutes

--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
Subcatchment 25                24.50   30.58                                                                                                            I
STATION DETAILS   LAT    LONG |  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC |  Record    #_Yrs  | Subc.   Stat. |  Subc.  Stat. |  Dist. | Bad    | N  | R |
                              |                                                              |   Span            |  Alt     Alt  |   MAP    MAP  |   (km) | WET    | D  | A |
                              |                                                              |                   |  (m)    (m)   |  (mm)   (mm)  |   (31) | corr   | E  | N |
                              |                                                              |                   |               |           .   |        |        | X  | K |
--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
2 0298791 W     28.42   28.57 |  .92  .93 1.00 1.05 1.14  .70 1.30  .70  .74  .89 1.05 1.00 | 1948-1998  51  45 |   980.  1455. |  1317.  1310. |  473.1 |   1    | 41.2|   1 |-1--
4 0299419 W     28.59   29.14 |  .93 1.10  .81  .94 1.11 1.30 1.30  .70  .74 1.01 1.16 1.10 | 1939-1984  46  23 |   980.  1844. |  1317.  1262. |  491.0 |   1    | 32.0|   3 |-1-1
5 0268199 W     29.19   29.37 |  .86 1.00 1.10 1.18 1.30 1.30 1.30  .86  .88  .73 1.09 1.00 | 1955-1998  44  37 |   980.  2059. |  1317.  1242. |  514.5 |   1    | 32.8|   2 |-1--
8 0298818 W     28.38   28.58 |  .97  .99  .98 1.19  .75  .92 1.18  .70  .78  .77 1.00  .88 | 1946-1998  53  29 |   980.  1463. |  1317.  1357. |  465.7 |   2    | 24.5|   5 |-1--
9 0299357 W     28.57   29.12 |  .98  .86  .88 1.25 1.30  .70 1.30  .70  .79  .91 1.09 1.04 | 1936-1998  63  43 |   980.  1524. |  1317.  1300. |  488.8 |   2    | 28.3|   4 |-1--
--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
Subcatchment   26       24.53   30.56                                                                                                                   I
STATION DETAILS   LAT    LONG |  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC |  Record    #_Yrs  | Subc.   Stat. |  Subc.  Stat. |  Dist. | Bad    | N  | R |
                              |                                                              |   Span            |  Alt     Alt  |   MAP    MAP  |   (km) | WET    | D  | A |
                              |                                                              |                   |  (m)    (m)   |  (mm)   (mm)  |   (31) | corr   | E  | N |
                              |                                                              |                   |               |           .   |        |        | X  | K |
--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
2 0298818 W     28.38   28.58 | 1.01 1.03  .98 1.17  .78 1.10 1.30  .70  .81  .79 1.02  .90 | 1946-1998  53  29 |  1019.  1463. |  1343.  1357. |  459.3 |   1    | 37.3|   2 |-1--
3 0298791 W     28.42   28.57 |  .96  .97 1.00 1.03 1.18  .75 1.30  .70  .77  .90 1.08 1.03 | 1948-1998  51  45 |  1019.  1455. |  1343.  1310. |  466.6 |   1    | 38.6|   1 |-1--
5 0299357 W     28.57   29.12 | 1.01  .89  .89 1.22 1.30  .76 1.30  .78  .82  .93 1.11 1.06 | 1936-1998  63  43 |  1019.  1524. |  1343.  1300. |  482.4 |   1    | 37.2|   3 |-1--
6 0299419 W     28.59   29.14 |  .96 1.15  .81  .92 1.15 1.30 1.30  .75  .77 1.03 1.19 1.13 | 1939-1984  46  23 |  1019.  1844. |  1343.  1262. |  484.7 |   1    | 29.4|   5 |-1-1
7 0268199 W     29.19   29.37 |  .90 1.04 1.10 1.15 1.30 1.30 1.30  .99  .92  .74 1.11 1.03 | 1955-1998  44  37 |  1019.  2059. |  1343.  1242. |  508.3 |   1    | 30.3|   4 |-1--
--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

EXCLUSION CODES
---- : station qualifies according to all criteria
---1 : station should be disqualified because its ending year is earlier than cutoff year
--1- : station should be disqualified because the record length of this station is less than cutoff period
-1-- : station should be disqualified because the station is further from the catchment than the cutoff distance
1--- : station should be disqualified because the station has more bad months than the cutoff limit
```

4.2 *ClimClas* : A UTILITY TO CLASSIFY MONTHLY RAINFALL AND TEMPERATURE VALUES INTO FORECAST CATEGORIES

Andrew Pike and Roland Schulze

A project was conducted in conjunction with the University of Cape Town where the consequences, in terms of maize production, of inaccurate climate forecasts were analysed. Maize yields estimated using the seasonal weather forecasts as supplied by the South African Weather Services were compared to historical data in order to assess the sensitivity of maize to the drivers of rainfall and temperature. In the course of the project it became necessary to classify the growing season into “Above Normal”, “Normal” and “Below Normal” classes of rainfall, maximum and minimum temperatures. The thresholds for each of the three components were defined according to the long term 33% and 66% percentile values of Rainfall, Maximum and Minimum temperatures. (Table 4.2.1).

The *ClimClas* utility combines the standard maize yield output from the *ACRU* model with a summary of the monthly codes shown in Table 4.2.1 to identify the “Above Normal” (A), “Normal” (N) and “Below Normal” (B) climate classes for each year of the simulation (see Table 4.2.2). In both Table 4.2.1 and Table 4.2.2 the upper case of the various codes are used to identify the growing season (usually mid-November to mid-April) while lower case is used to denote the fallow months. In the case of December 1980, the total monthly rainfall was 77.5mm (Table 4.2.1), while the average maximum and minimum temperatures were 25.7°C and 14.1°C respectively (Table 4.2.1). This monthly rainfall total (77.5mm) was less that the long term 33-percentile value of 113.4mm (Table 4.1) and the month was consequently classified as a “Below Normal” rainfall month (Table 4.2.1 and Table 4.2.2). In terms of temperature, the average maximum for the month of December 1980 (25.7°C) exceeds the 33 and 66 percentile values of 24.8°C and 25.1°C (Table 4.2.1) and is thus classified as an “Above normal” month. Applying the same criteria results in the average minimum temperature been classified as a “Normal” month (as far as minimum temperatures is concerned).

It is hoped that this utility will be of assistance in future projects where it is important for the model not to predict annual maize yields but also give an indication of the climatic conditions which affected the growth of the crop.

Table 4.2.2 Summarised output from *ClimClas*

```
                    -----------------------------------------
                    |    MAIZE YIELD MODELLING INFORMATION   |
                    |        PRESENT CLIMATE SCENARIO        |
                    -----------------------------------------
      1) Length of growing season: 150 days
      2) Units of maize yield: t/ha/season
      3) ACRU maize yield model:
               - Yield potential estimated from a knowledge of local conditions
      4) Phenological growth phases (GDD=Maize Growing Degree Days)
                                    (LAMDA=Stress Weighting Factor)
                                             GDD    LAMDA
         Phase 0 a - Emergence             100.
         Phase 1 To - Onset of flowering    700.     .4
         Phase 2 To - End of flowering    1100.     .4
         Phase 3 To - Maturity            1700.     .4
      5) Breakeven yield to offset production costs = 3.0 tonnes
      6) Expected selling price per tonne = R1 000.00

              ACRU MAIZE YIELD MODEL: RESULTS
-------------------------------------------------------------------------------------------------------------------
 Season   Plant  |    Accuml  Yield Phase1 Phase2 Phase3    Maize |Monthly Rainfall, Max & Min Temperature Classes|
          date   |   growing  Potnl Et/Etm Et/Etm Et/Etm    Yield |   KEY: A=Above, N=Normal, B=Below, =: N/A     |
                 |   degrees  (t/ha)                        (t/ha)|Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec|
------------------------------------------------------------------|-UPPER CASE & '-' DENOTES THE GROWING SEASON---|
 1978/79  Nov 15 |    1706.9    9.0   .948   .765   .686     6.81 |ABN BBN NAA ABB bnb bbb bna nna anb abb ANN ANB|
 1979/80  Nov 15 |    1672.5    9.0   .924   .816   .212     4.32 |BBB NAA NNB AAA aba bnn abb aba nbb bna NNB NBB|
 1980/81  Nov 15 |    1739.3    9.0   .804   .732   .389     4.99 |NBB BNB BAB BNB nab bab bab bnb abn ban NAN BAN|
 1981/82  Nov 15 |    1681.2    9.0   .809   .586   .592     5.41 |NAA NBN BBB NAN abn abb nbn abb abb bnb AAA BBB|
 1982/83  Nov 15 |    1803.2    9.0   .786   .544   .327     4.10 |BNN NAN ABB BBB bnb nab nnn ban naa naa BNB BAA|
 1983/84  Nov 15 |    1692.4    9.0   .985   .817   .580     6.63 |BAA BNB NAN NAA aaa baa ana nbb naa nbn ABA NNA|
 1984/85  Nov 15 |    1752.4    9.0   .955   .882   .905     8.07 |ANB BBB BBA ANB bbn anb nba nnb ban aaa BBB BAB|
 1985/86  Nov 15 |    1744.2    9.0   .962   .702   .430     5.49 |AAA ANA NNN BAN bbb ban nab baa nan aaa NAA ABN|
 1986/87  Nov 15 |    1802.9    9.0   .936   .866   .764     7.43 |BNB BBB AAN BNA baa aaa ban aan bna nan BBB NNA|
 1987/88  Nov 15 |    1833.3    9.0   .830   .763   .936     7.30 |NBN NAA ANA ANA naa ann abb abn aba nbb NNA BAA|
 1988/89  Nov 15 |    1653.3    9.0   .976   .887   .413     5.96 |NAA ANA ANA NBN ann abn aab naa ban bnb BBN ABB|
 1989/90  Nov 15 |    1654.5    9.0   .936   .535   .873     6.46 |ABN ABB BAN NBN nna nba abn baa bnb bnb ABN AAA|
 1990/91  Nov 15 |    1697.0    9.0   .982   .924   .728     7.63 |BNB ABB ABB ABA nbb nna bna abb bbb abn BAB NBN|
-------------------------------------------------------------------------------------------------------------------

                    ACRU MAIZE YIELD MODEL STATISTICS
                    ---------------------------------
                               MEAN       6.20 tonne
                            MINIMUM       4.10 tonne
                            MAXIMUM       8.07 tonne
                 STANDARD DEVIATION       1.27 tonne
                 COEFF OF VARIATION      20.56 %
                  NUMBER OF SEASONS         13

                            FREQUENCY ANALYSIS
                            ------------------
                                 YIELD   PROFIT
                                 (t/ha)   (R/ha)
                        10.%      4.28     1276.
                        20.%      5.03     2029.
                        33.%      5.47     2471.
                        50.%      6.46     3464.
                        67.%      6.91     3910.
                        80.%      7.42     4415.
                        90.%      7.71     4715.
```

Table 4.2.1 Detailed output from the *ClimClas* climate classification utility

Monthly totals of daily RAINFALL data

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
Mean:	129.6	127.4	119.0	38.8	20.3	17.4	14.0	34.1	86.4	105.6	125.6	128.6--	946.8
1978	161.5	88.3	93.5	59.4	6.1	.8	2.1	19.8	86.1	153.5	132.0	182.4	
1979	97.7	116.7	115.5	50.7	59.6	1.9	32.6	46.7	36.7	72.9	86.4	123.6	
1980	117.6	67.5	41.7	20.3	16.3	.0	2.6	10.5	107.8	38.0	118.2	77.5	
1981	114.6	98.8	45.6	34.7	40.0	33.9	3.9	67.7	59.5	30.3	176.9	54.4	
1982	90.4	93.2	197.7	24.3	8.4	10.9	3.7	4.4	50.4	107.1	82.1	101.3	
1983	80.5	26.4	104.7	35.5	28.7	8.3	37.4	34.1	25.4	73.4	226.7	123.2	
1984	163.8	83.4	89.3	89.6	4.4	25.8	11.5	41.1	24.9	134.3	58.6	112.1	
1985	161.9	313.6	94.7	6.4	3.3	.1	6.4	.8	54.5	180.4	116.2	154.3	
1986	94.1	49.5	164.5	27.8	.0	30.9	.0	45.3	14.3	102.9	63.0	129.1	
1987	136.8	108.8	233.0	55.9	9.3	27.2	18.0	100.8	619.2	104.1	84.8	106.2	
1988	101.0	246.3	213.5	35.3	52.7	59.8	52.8	13.2	24.3	72.5	73.0	199.8	
1989	148.8	170.7	43.5	38.6	16.2	15.7	24.0	2.1	23.4	67.7	282.9	142.9	
1990	75.7	143.6	138.8	49.0	19.5	14.2	.3	82.0	23.1	110.0	43.2	132.7	

Monthly means of daily MAXIMUM temperature data

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
Mean:	25.1	25.3	24.7	23.4	21.4	19.0	19.4	20.9	21.6	22.1	23.2	24.8--	22.6
1978	24.1	25.1	25.7	21.1	21.0	18.4	19.6	20.8	21.5	20.9	22.8	24.8	
1979	24.5	26.7	24.4	24.2	20.6	19.1	17.3	19.8	19.8	22.4	22.9	24.3	
1980	24.0	26.4	25.7	24.1	22.0	19.5	20.0	21.3	19.2	23.1	23.7	25.7	
1981	26.1	23.8	24.3	24.9	20.0	18.4	19.1	18.6	19.5	22.0	25.0	24.8	
1982	24.5	26.6	23.9	21.0	21.4	19.5	19.7	21.4	22.5	23.2	23.5	26.5	
1983	26.1	26.2	26.3	25.4	21.9	19.9	19.4	19.3	24.2	21.5	22.2	24.9	
1984	24.7	24.3	23.5	23.0	20.8	18.7	18.7	20.4	23.2	23.0	22.3	25.6	
1985	27.0	25.4	24.6	24.4	20.4	20.2	19.8	23.8	23.2	24.9	24.7	24.0	
1986	25.2	24.8	25.9	23.5	23.1	20.1	20.4	21.8	22.4	22.5	22.3	24.8	
1987	24.5	27.7	24.7	23.8	23.6	19.0	18.8	19.3	19.6	20.5	22.8	26.0	
1988	25.4	25.6	25.1	22.2	21.3	18.0	20.1	21.9	22.5	21.7	22.8	23.0	
1989	24.5	23.2	25.2	22.8	21.1	18.0	18.7	24.0	22.3	21.8	21.8	25.1	
1990	25.1	23.7	22.9	23.0	20.5	18.9	19.6	19.3	20.8	20.7	24.6	22.9	

Monthly means of daily MINIMUM temperature data

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
Mean:	15.3	15.4	14.2	10.8	6.9	3.1	3.6	6.2	8.8	10.6	12.7	14.2--	10.1
1978	15.1	15.6	15.0	10.0	6.1	.8	4.0	7.6	7.9	10.0	12.8	13.4	
1979	14.1	16.0	13.5	11.5	7.5	3.3	2.8	6.5	8.2	10.8	11.7	13.8	
1980	13.4	14.2	13.5	9.8	6.0	2.4	2.5	5.8	8.5	10.8	12.8	14.1	
1981	16.0	15.2	13.5	10.3	7.2	2.5	3.6	5.6	6.7	7.8	13.0	13.9	
1982	15.5	15.1	13.3	9.7	6.5	3.0	3.7	6.4	10.1	10.8	12.0	14.6	
1983	16.3	14.9	14.2	12.2	7.6	4.8	4.3	4.7	9.8	10.8	13.4	14.9	
1984	14.8	14.8	14.6	9.8	6.6	2.3	4.6	5.9	8.5	11.9	12.1	13.5	
1985	16.3	15.7	14.0	10.3	6.1	3.5	2.7	6.6	9.2	11.7	13.3	14.2	
1986	15.1	14.4	14.1	12.3	7.3	3.7	3.7	6.4	9.4	10.8	12.0	14.4	
1987	15.4	16.8	14.4	12.9	7.9	3.1	3.0	5.9	9.8	10.3	13.8	15.8	
1988	15.9	16.7	15.9	10.7	6.9	3.1	3.1	6.8	8.9	10.6	12.6	13.5	
1989	15.3	14.8	14.2	10.2	7.9	3.6	3.8	6.8	7.9	9.7	12.9	14.4	
1990	14.8	14.5	13.8	12.2	6.5	3.6	4.7	5.4	7.9	10.7	12.5	14.1	

Monthly 33% and 66% values

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
RFL	33%	98.1	88.9	90.6	28.6	8.5	8.6	2.7	10.9	24.9	73.0	82.4	113.4
RFL	66%	147.4	140.4	136.0	47.7	19.7	24.5	17.2	44.8	58.9	109.7	130.3	141.7
TMAX	33%	24.5	25.1	24.3	23.0	20.9	18.4	19.1	19.9	20.9	21.6	22.8	24.8
TMAX	66%	25.4	26.4	25.1	24.2	21.9	19.4	19.8	21.4	22.5	22.5	23.6	25.1
TMIN	33%	15.1	14.9	13.9	10.0	6.5	3.0	3.2	5.9	8.3	10.6	12.5	13.9
TMIN	66%	15.8	15.7	14.3	11.4	7.3	3.6	4.0	6.5	9.4	10.8	13.0	14.4

Classification of monthly RAINFALL totals
(Above, Normal, or Below)

J	F	M	A	M	J	J	A	S	O	N	D	
1978	A	B	N	A	b	b	b	n	a	a	A	A
1979	B	N	N	A	a	b	a	a	n	b	N	N
1980	N	B	B	B	n	b	b	b	a	b	N	B
1981	N	N	B	N	a	a	n	a	a	b	A	B
1982	B	N	A	B	b	n	n	b	n	n	B	B
1983	B	B	N	N	a	b	a	n	n	n	A	N
1984	A	B	B	A	b	a	n	n	b	a	B	B
1985	A	A	N	B	b	b	n	b	n	a	N	A
1986	B	B	A	B	b	a	b	a	b	n	B	N
1987	N	N	A	A	n	a	a	a	a	n	N	B
1988	N	A	A	N	a	a	a	n	b	b	B	A
1989	A	A	B	N	n	n	a	b	b	b	A	A
1990	B	A	A	A	n	n	b	a	b	a	B	N

Classification of monthly MAXIMUM temperature averages
(Above, Normal, or Below)

J	F	M	A	M	J	J	A	S	O	N	D	
1978	B	B	A	B	n	b	n	n	n	b	N	N
1979	B	A	N	A	b	n	b	b	b	n	N	B
1980	B	N	A	N	a	a	a	n	b	a	A	A
1981	A	B	B	A	b	b	b	b	b	n	A	B
1982	N	A	B	B	n	a	n	a	a	a	N	A
1983	A	N	A	A	a	a	n	b	a	b	B	N
1984	N	B	B	N	b	n	b	n	a	a	B	A
1985	A	N	N	A	b	a	a	a	a	a	A	B
1986	N	B	A	N	a	a	a	a	n	a	B	N
1987	B	A	N	N	a	n	b	b	b	b	N	A
1988	A	N	N	B	n	b	a	a	a	n	B	B
1989	B	B	A	B	n	b	b	a	n	n	B	A
1990	N	B	B	B	b	n	n	b	b	b	A	B

Classification of monthly MINIMUM temperature averages
(Above, Normal, or Below)

J	F	M	A	M	J	J	A	S	O	N	D	
1978	N	N	A	B	b	b	a	a	b	b	N	B
1979	B	A	B	A	a	n	b	a	b	a	B	B
1980	B	B	B	B	b	b	b	b	n	n	N	N
1981	A	N	B	N	n	b	n	b	b	b	A	B
1982	N	N	B	B	b	b	n	n	a	a	B	A
1983	A	B	N	A	a	a	a	b	a	n	A	A
1984	B	B	A	B	n	b	a	b	n	a	B	B
1985	A	A	N	N	b	n	b	a	n	a	A	N
1986	B	B	N	A	a	a	n	n	a	n	B	A
1987	N	A	A	A	a	n	b	n	a	b	A	A
1988	A	A	A	N	n	n	b	a	n	b	N	B
1989	N	B	N	N	a	a	n	a	b	b	N	A
1990	B	B	B	A	b	a	a	b	b	n	B	N

4.3 *MB3 :* THE NEW *ACRU* MENUBUILDER

Lucille Hallowes and Sean Thornton-Dibb

The GUI facility in MS Access has also been used to develop a new Windows based "MenuBuilder". This utility will replace the existing DOS based program and will be compatible with both the *ACRU3.00* and *ACRU2000* versions of the ACRU modelling system. Screenshots of the main directory form and examples of one of the data entry forms are provided in Figures 4.3.1, 4.3.2 and 4.3.3.

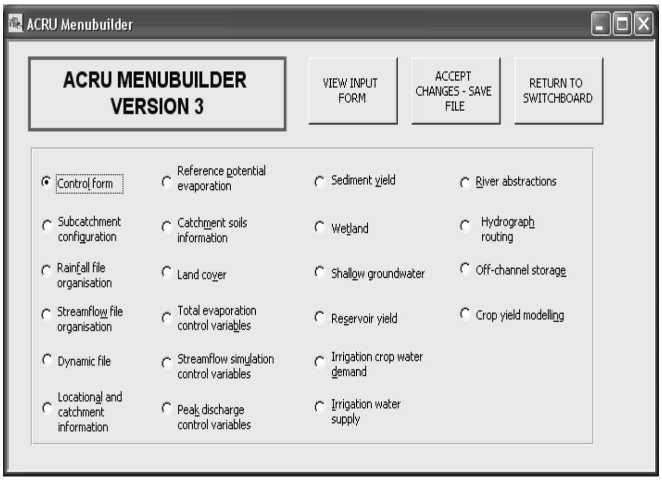


Figure 4.3.1 Screenshot of the Windows version of the *ACRU* MenuBuilder (v3.00)

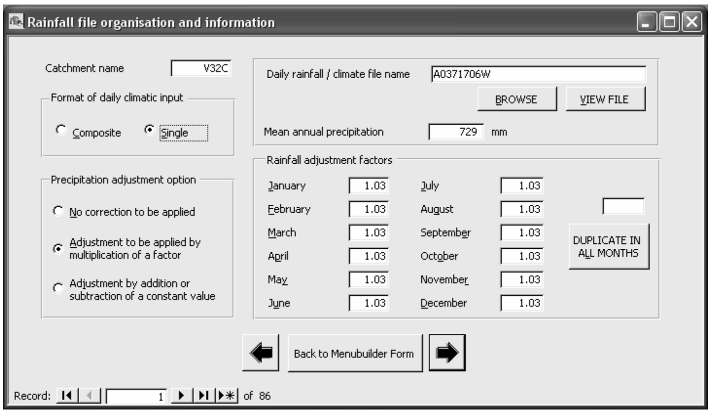


Figure 4.3.2 Another screenshot of the Windows version of the *ACRU* MenuBuilder (v3.00)

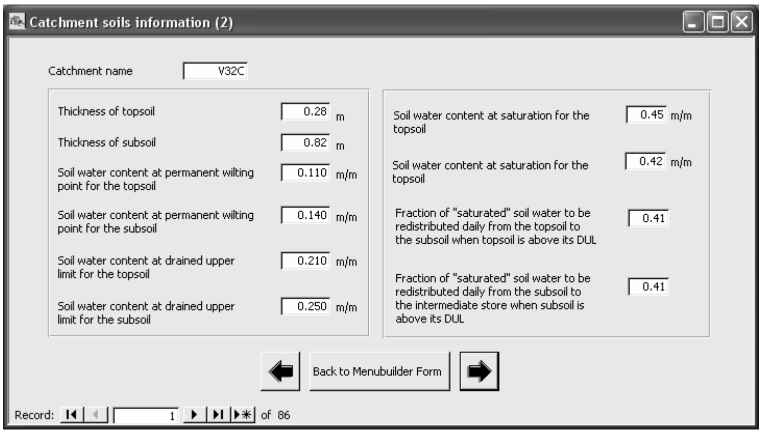


Figure 4.3.3 Further screenshot of the Windows version of the *ACRU* MenuBuilder (v3.00)

4.4 *Bin2DBF* : BINARY TO DBF CONVERTER

Andrew Pike and David Clark

Version 3 of the *ACRU* modelling system writes output to Binary files which may then to converted to an ASCII file of the User's choice. *ACRU2000* also produces the same Binary files (to facilitate the use of the old version 3 post-processing utilities) but also offers the additional option of Dbase IV files which are compatible with most spreadsheet, statistical and graphical applications and which is used by the *ACRU*View post-processing package (*cf*. Section 4.7). A utility has been developed in the JAVA Object Orientated programming language which converts the Binary files (UNIX or Windows) outputted by both versions of the *ACRU* modelling system, to Dbase IV format for later use in *ACRU*View. Screenshots of this utility and its Help facility are shown in Figure 4.4.1.

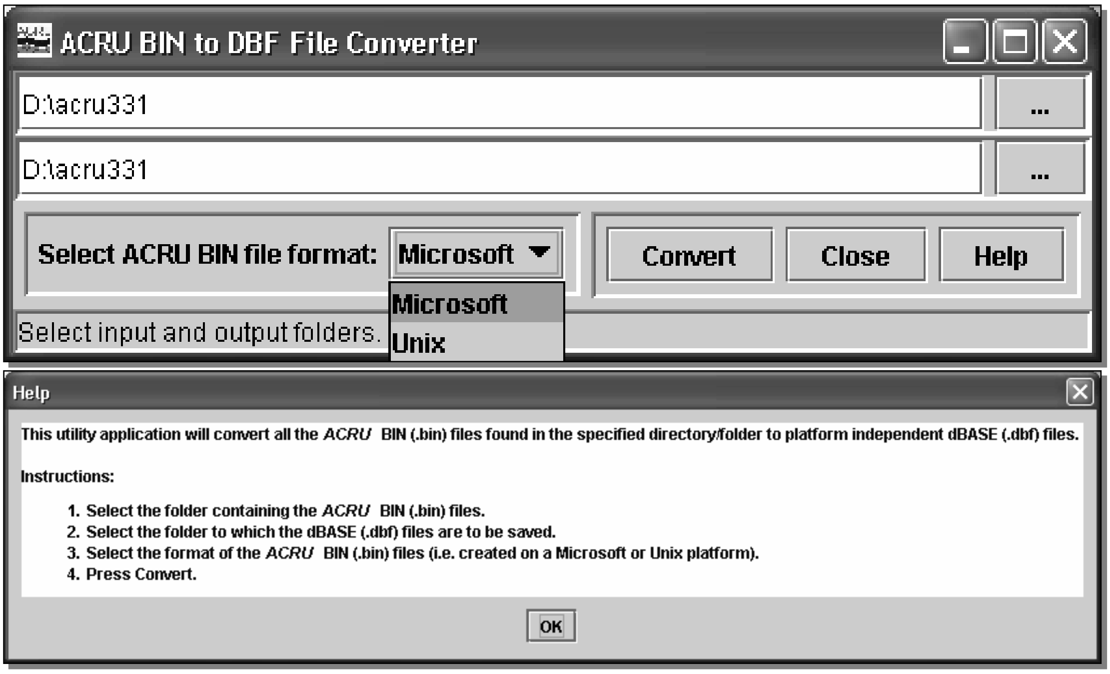


Figure 4.4.1 Screenshots of the *Bin2DBF* converter and help facility

4.5 *OVS* : OUTPUT VARIABLE SELECTOR
Andrew Pike and David Clark

The "heart" of the *ACRU* model is a daily multi-layer soil water budget, and hence the model simulates the components and processes of the hydrological cycle affecting this soil water budget, including

- canopy interception of rainfall by vegetation
- net rainfall reaching the ground surface
- infiltration of net rainfall into the soil
- total evaporation (transpiration as well as soil water evaporation) from the various horizons of
- the soil profile to root depth
- suppression of soil water evaporation by litter or mulch
- the redistribution of soil water in the soil profile, both saturated and unsaturated and
- percolation of soil water into the intermediate groundwater zone.

The model can output any of the above components. In the present output routines, provision has been made to output on a daily basis, or as monthly and annual totals of the daily values, *inter alia*

- rainfall
- effective rainfall
- reference potential evaporation
- maximum evaporation (i.e. "potential evapotranspiration") from the vegetation under conditions of freely available soil water
- total evaporation (i.e. "actual evapotranspiration") in the form of transpiration and soil water evaporation from top- and subsoil horizons respectively and
- soil water content of top- and subsoil layers and drainage into the intermediate zone (Schulze, 1995).

A DOS based utility (OB.EXE) to assist the user in the selection of the particular components of interest was provided with the previous version of the *ACRU* modelling system. This utility has been rewritten (and renamed the '*ACRU* Output Variable Selector', or *OVS*) in the JAVA Object Orientated programming language and is platform independent and compatible with both *ACRU*2000 and Version 3 of *ACRU*. Screenshots of this utility showing in normal operating mode as well as the summary option and the Help facility are provided in Figures 4.5.1, 4.5.2 and 4.5.3 respectively.

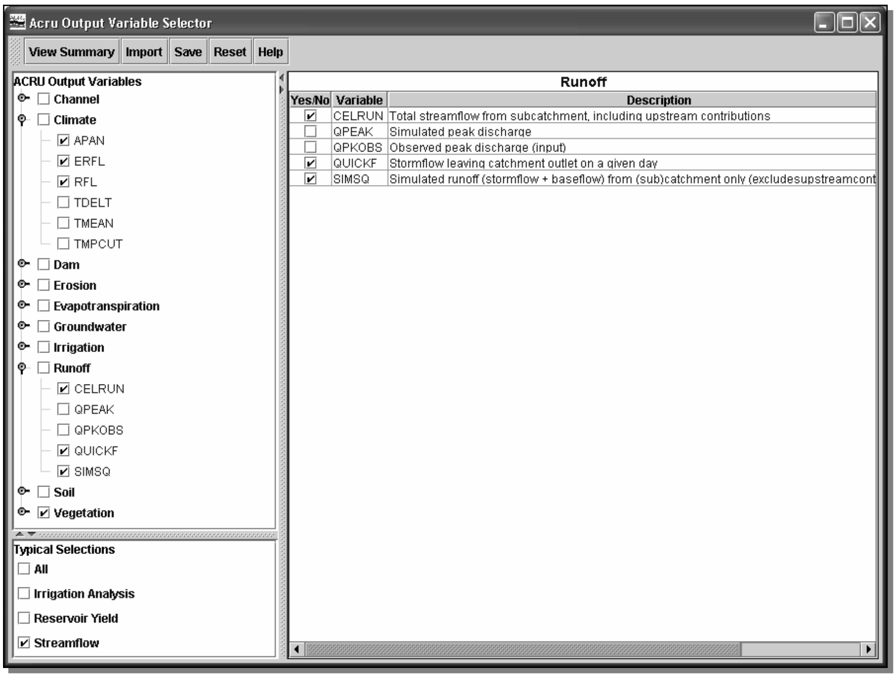


Figure 4.5.1 Screenshot showing the *OVS* in operation

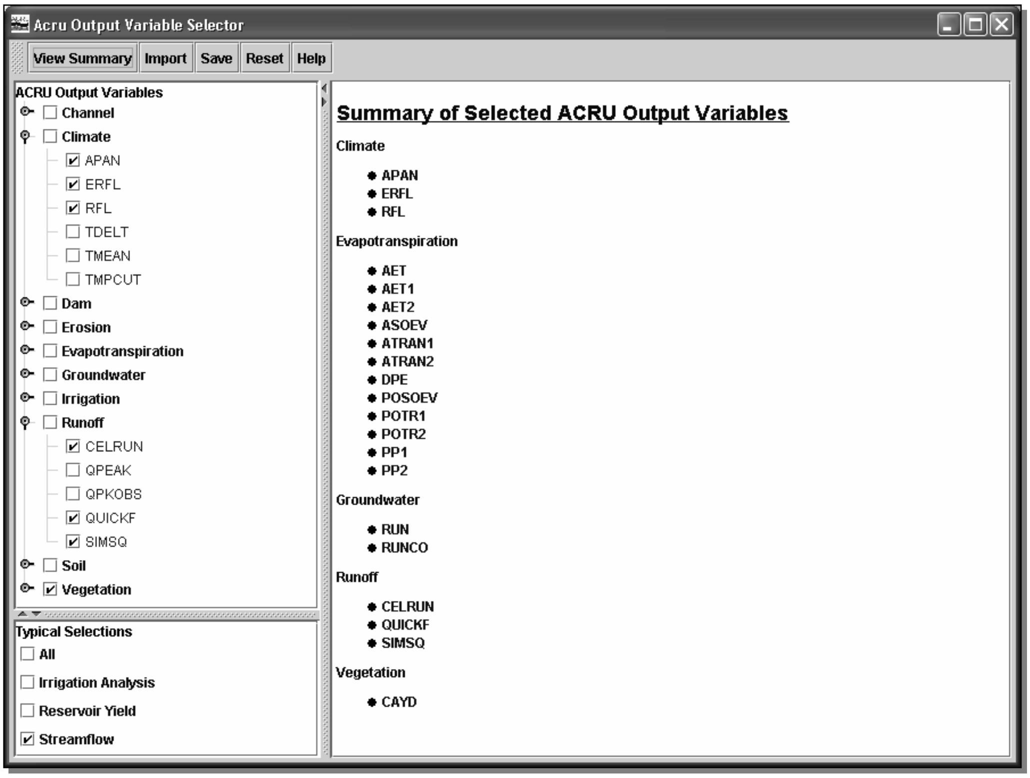


Figure 4.5.2 Screenshot of the output from the *OVS* summary option

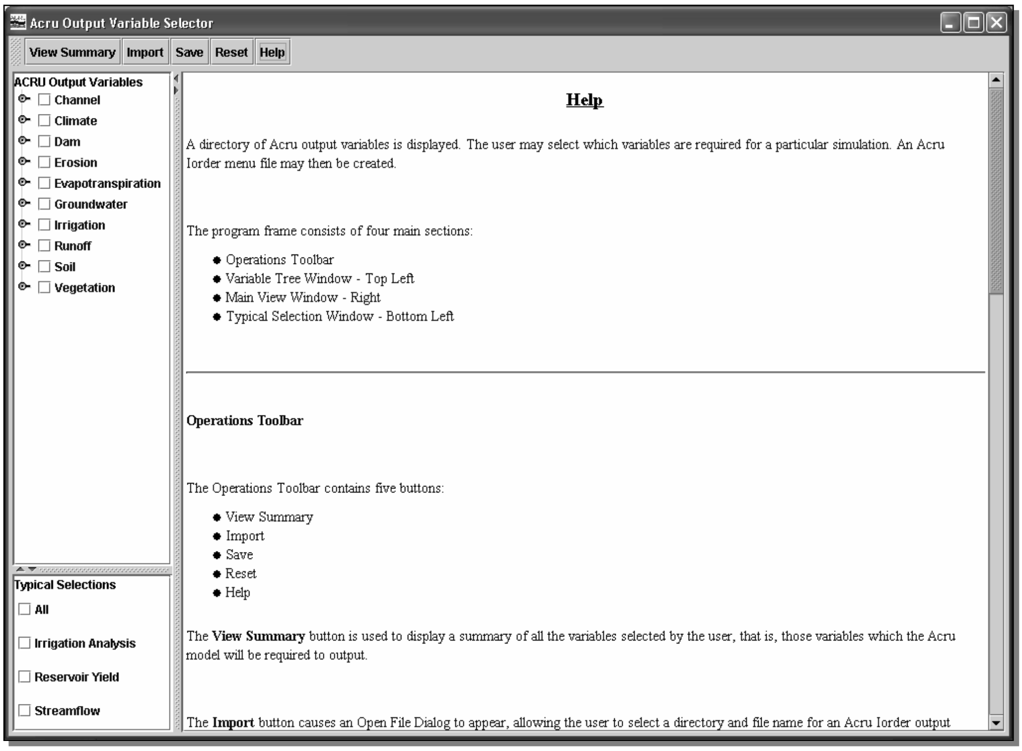


Figure 4.5.3 Screenshot of the *OVS* help facility

4.6 *ACRU*2000 MENU CONVERTER

Andrew Pike

In both versions of the *ACRU* modelling system, the input data and information are provided to the model by way of ASCII “menu” files. Version 3 of the model uses one large file which contains all the information required by the model, while the same information is supplied to *ACRU*2000 in a control menu (“control.men”) and a separate input file for each land segment (e.g. “LandSeg_1.men”). A conversion utility (“Old To New *ACRU* Menu Converter”) has been developed to assist users in converting old Version 3 input menus to files which are compatible with *ACRU*2000. A screenshot of this utility is shown in Figure 4.6.1

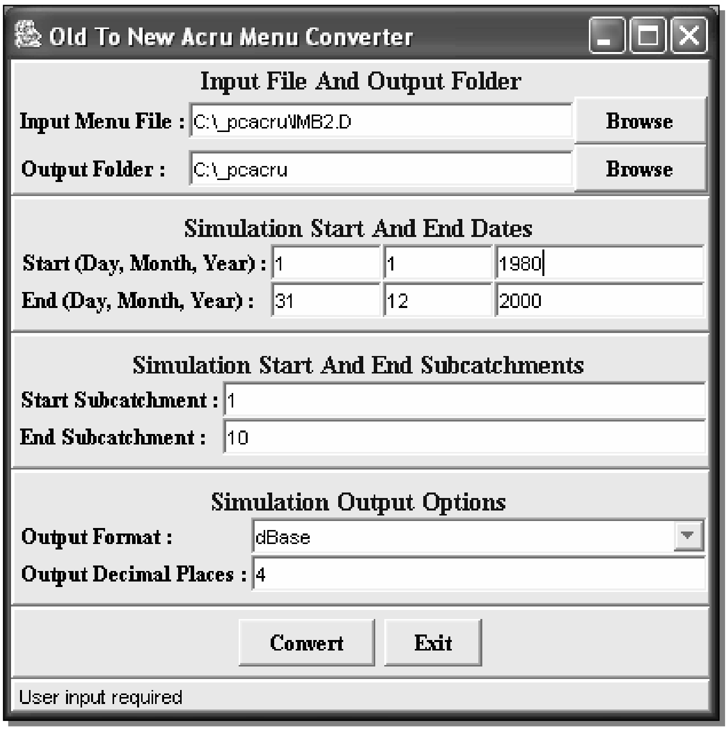


Figure 4.6.1 Screenshot of the “Old To New *ACRU* Menu Converter”

4.7 *ACRU*View : A VISUALISATION AND STATISTICAL PACKAGE FOR THE *ACRU* MODEL WMA Consulting

WMAC consultants were subcontracted to produce an Excel and Visual Basic based software package for the visualisation and statistical analysis of time series output from *ACRU*2000.

The software uses the DBF files produced by *ACRU*2000 as input, but can be modified to read output from any daily model. Functionality of the software includes:

- daily and monthly analysis and display of time series with the facilities to zoom into specific time periods, scroll through the simulation period and synchronise graphs of different variables and/or timesteps
- comparative regressions of observed and simulated values
- extreme value analysis of model output
- flow duration curves and
- run hydrographs.

The User Manual on *ACRU*View, to assist Users wishing to utilise this software in the analysis and display of their model outputs and observed data, is presented as Chapter 5 of this report. The software and User Manual is also available for downloading from the *ACRU* Homepage (*cf*. Chapter 4.8).

4.8 DEVELOPMENT OF THE *ACRU* MODEL WEBSITE
Andrew Pike

A website has been published for the *ACRU* model at http://www.beeh.unp.ac.za/acru (*cf*. Figure 4.8.1) while an online Discussion Group has also been created at http://groups.yahoo.com/group/acru for users to interact on modelling related issues (Figure 4.8.2).

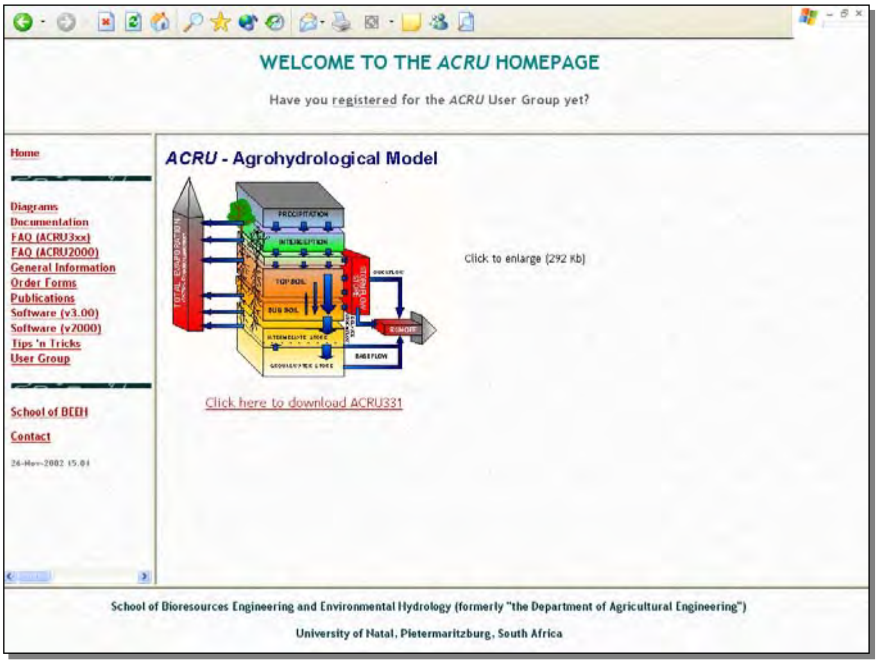


Figure 4.8.1 Screenshot of the *ACRU* Homepage

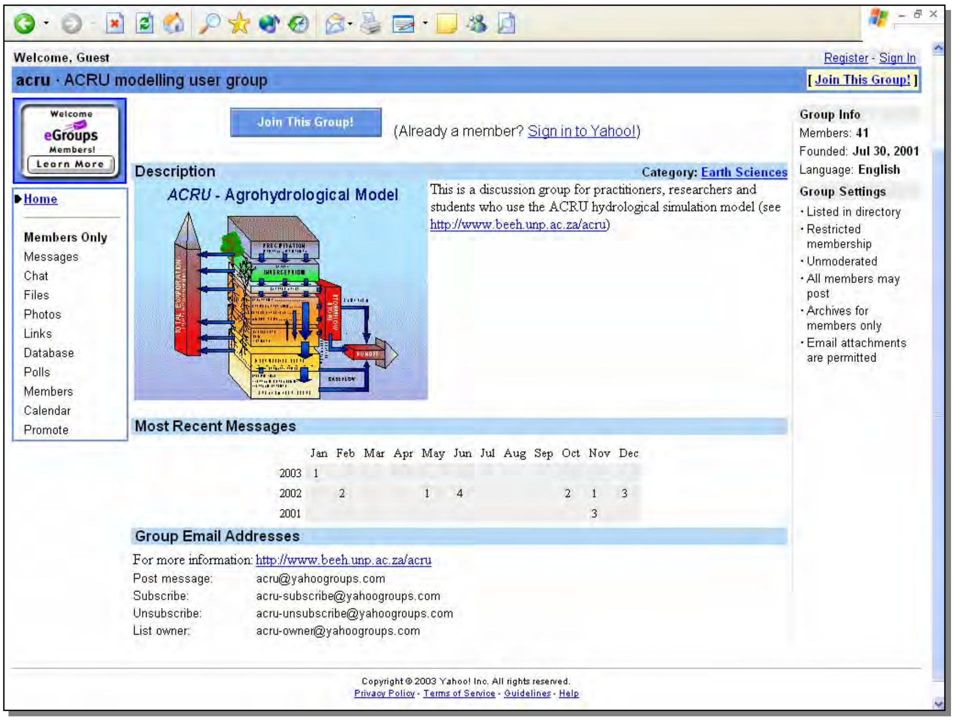


Figure 4.8.2 Screenshot of the *ACRU* User Group hosted by Yahoo Groups

The site provides access to:

- relevant diagrams
- documentation (online manuals)
- frequently asked questions (FAQ)
- general background information including
  - historical perspective
  - concepts of the *ACRU* model
  - general structure of *ACRU* for water budgeting
  - output simulated by *ACRU*
  - typical applications of the *ACRU* model
  - *ACRU* as a distributed model
  - components and linkages of the *ACRU* modelling system
  - the *ACRU* utilities software
  - computerised decision support systems
  - postgraduate studies in Hydrology
- order forms for the *South African Atlas of Agrohydrology and –Climatology* (Schulze, 1997), the *ACRU* and SCS-SA (Schulze *et al*., 1993) software packages and an example registration form for an *ACRU* course
- publications of research papers or projects which have applied the *ACRU* model
- the full *ACRU* modelling software and
- a “Tips 'n Tricks” section which contains information which may be helpful in setting up the model.

The website also provides the user the opportunity to register online with the *ACRU* User Consultant. The registered users will be notified of future courses and updates of the documentation and software.

4.9 DEVELOPMENT OF ELECTRONIC, ONLINE VERSIONS OF THE *ACRU* THEORY MANUAL AND THE USER MANUAL
Andrew Pike

The *ACRU* Theory and User have been converted to Portable Document Format (PDF) documents and placed on the *ACRU* website. Chapter 20 of the *ACRU* Theory manual titled "Forest Hydrology" has been completely revised to reflect the more recent research in the field of forest hydrology. A screenshot of page AT2-4 of the *ACRU* Theory Manual is shown in Figure 4.9.1.

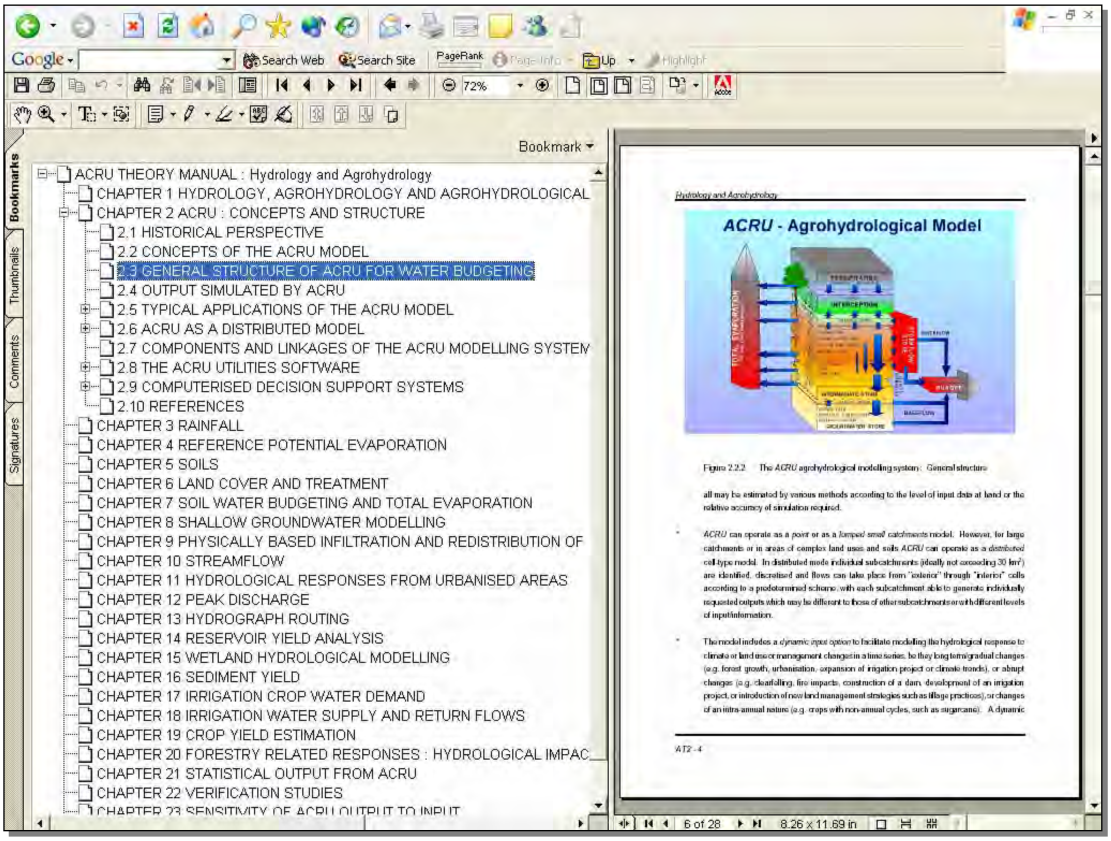


Figure 4.9.1 A sample page from the electronic version of the *ACRU* Theory Manual

4.10 PUBLICATION OF A BROCHURE FOR THE *ACRU* MODELLING SYSTEM

Mark Horan, Valerie Taylor and Roland Schulze

Economic Benefits of *ACRU*

Initial development as well as subsequent refinement and enhancement of *ACRU* over the past 20 years have been funded mainly by the Water Research Commission (WRC). The WRC recently commissioned an independent evaluation on the economic benefit to cost ratio of supporting the development of the *ACRU* model, and this was found to be 6:1 for the timber and sugarcane industries alone. This evaluation of *ACRU* does not yet include those benefits arising from the model's many recent applications in Integrated Water Resources Management (IWRM), conflict management and design hydrology (SCS-SA) in South Africa and IWRM in Zimbabwe and Swaziland.

Who Benefits from Using *ACRU*?

Department of Water Affairs and Forestry; Water Utilities; Irrigation Boards; Prospective CMAs; Water Users Associations; Timber Industry; Sugar Industry; Agricultural Industry; Conservation Services; Design Engineers; Researchers; other WRC projects.

Why the *ACRU* Model?

The *ACRU* model was developed in South Africa for Southern African water resources' needs. *ACRU* has database support for South African land use, soils and climate and is backed by local specialist expertise. The model undergoes continual refinement based on local as well as international experimental fieldwork.

Partners in the Development of *ACRU*

Water Research Commission (WRC); *University of Natal;* Computing Centre for Water Research (CCWR); *Department of Water Affairs and Forestry (DWAF);* National Research Foundation (NRF); *Universities of Bonn and Jena in Germany, Cornell and Florida in the USA, Free State, and Stellenbosch in RSA;* SA Sugar Association Experiment Station (SASEX); *European Union (EU);* Council for Scientific and Industrial Research (CSIR); *UNESCO HELP : Hydrology for Environment, Life and Policy UK;* Department for International Development (DFID); *WMAC: Water Management Area Consultants;*

Model Verification

Streamflows (including stormflows, baseflows, peak discharge, and routed hydrographs) simulated with the *ACRU* modelling system have been verified successfully under varying hydro-climatic conditions and catchment scales. Such verifications have been performed on catchments in South Africa, Zimbabwe, Swaziland, Chile, the USA and Germany.

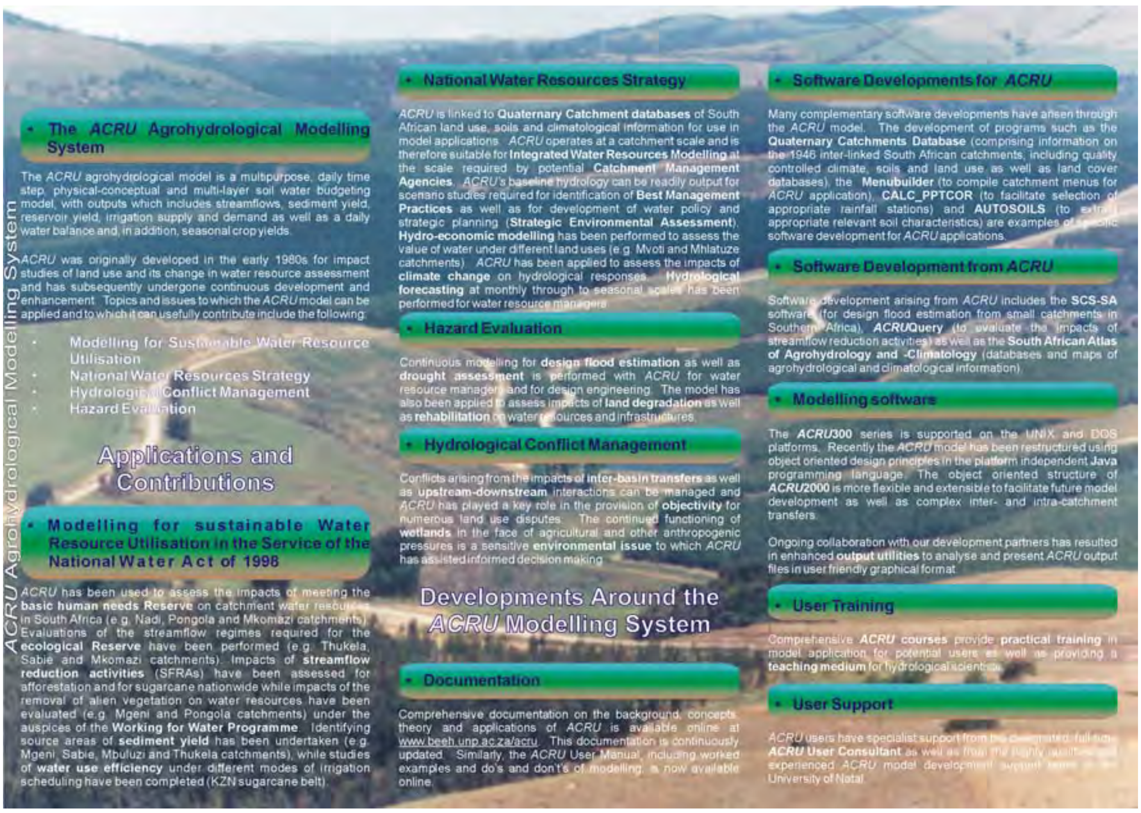
In addition to successfully outputing a final integrated variable such as streamflow, **individual model components** and **internal state variables** have been verified extensively against field observations in order to confirm that "right hydrological results have been simulated for the right reasons". These include soil moisture, actual evapotranspiration, groundwater fluctuations, sediment yield and wetland responses.

The **impacts of different land uses** (e.g. commercial forestry, sugarcane production as well as the "natural" conditions they replace) on streamflows have been verified from research catchments to establish confidence in *ACRU* simulations. Furthermore, the crop yield output (maize, sugarcane, winter wheat, primary production of grasslands) has undergone successful history matching under varying land management/climatic conditions.

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg
Private Bag X01, 3209 Scottsville
South Africa
Tel: +27 (0)33 260 5490
Fax: +27 (0)33 260 5818

ACRU
Agrohydrological
Modelling
System
www.beeh.unp.ac.za/acru

Figure 4.10.1 The *ACRU* brochure : Side one



The *ACRU* Agrohydrological Modelling System

The *ACRU* agrohydrological model is a multipurpose, daily time step, physical-conceptual and multi-layer soil water budgeting model, with outputs which includes streamflows, sediment yield, reservoir yield, irrigation supply and demand as well as a daily water balance and, in addition, seasonal crop yields.

ACRU was originally developed in the early 1980s for impact studies of land use and its change in water resource assessment and has subsequently undergone continuous development and enhancement. Topics and issues to which the *ACRU* model can be applied and to which it can usefully contribute include the following:

- Modelling for Sustainable Water Resource Utilisation
- National Water Resources Strategy
- Hydrological Conflict Management
- Hazard Evaluation

Applications and Contributions

Modelling for sustainable Water Resource Utilisation in the Service of the National Water Act of 1998

ACRU has been used to assess the impacts of meeting the **basic human needs Reserve** on catchment water resources in South Africa (e.g. Nadi, Pongola and Mkomazi catchments). Evaluations of the streamflow regimes required for the **ecological Reserve** have been performed (e.g. Thukela, Sabie and Mkomazi catchments). Impacts of **streamflow reduction activities** (SFRAs) have been assessed for afforestation and for sugarcane nationwide while impacts of the removal of alien vegetation on water resources have been evaluated (e.g. Mgeni and Pongola catchments) under the auspices of the **Working for Water Programme**. Identifying source areas of **sediment yield** has been undertaken (e.g. Mgeni, Sabie, Mbuluzi and Thukela catchments), while studies of **water use efficiency** under different modes of irrigation scheduling have been completed (KZN sugarcane belt).

National Water Resources Strategy

ACRU is linked to **Quaternary Catchment databases** of South African land use, soils and climatological information for use in model applications. *ACRU* operates at a catchment scale and is therefore suitable for **Integrated Water Resources Modelling** at the scale required by potential **Catchment Management Agencies**. *ACRU*'s baseline hydrology can be readily output for scenario studies required for identification of **Best Management Practices** as well as for development of water policy and strategic planning (**Strategic Environmental Assessment**). **Hydro-economic modelling** has been performed to assess the value of water under different land uses (e.g. Mvoti and Mhlatuze catchments). *ACRU* has been applied to assess the impacts of **climate change** on hydrological responses. **Hydrological forecasting** at monthly through to seasonal scales has been performed for water resource managers.

Hazard Evaluation

Continuous modelling for **design flood estimation** as well as **drought assessment** is performed with *ACRU* for water resource managers and for design engineering. The model has also been applied to assess impacts of **land degradation** as well as **rehabilitation** on water resources and infrastructures.

Hydrological Conflict Management

Conflicts arising from the impacts of **inter-basin transfers** as well as **upstream-downstream** interactions can be managed and *ACRU* has played a key role in the provision of **objectivity** for numerous land use disputes. The continued functioning of **wetlands** in the face of agricultural and other anthropogenic pressures is a sensitive **environmental issue** to which *ACRU* has assisted informed decision making.

Developments Around the *ACRU* Modelling System

Documentation

Comprehensive documentation on the background, concepts, theory and applications of *ACRU* is available online at www.beeh.unp.ac.za/acru. This documentation is continuously updated. Similarly, the *ACRU* User Manual, including worked examples and do's and don't's of modelling, is now available online.

Software Developments for *ACRU*

Many complementary software developments have arisen through the *ACRU* model. The development of programs such as the **Quaternary Catchments Database** (comprising information on the 1946 inter-linked South African catchments, including quality controlled climate, soils and land use as well as land cover databases), the **Menubuilder** (to compile catchment menus for *ACRU* application), **CALC_PPTCOR** (to facilitate selection of appropriate rainfall stations) and **AUTOSOILS** (to extract appropriate relevant soil characteristics) are examples of specific software development for *ACRU* applications.

Software Development from *ACRU*

Software development arising from *ACRU* includes the **SCS-SA** software (for design flood estimation from small catchments in Southern Africa), ***ACRU*Query** (to evaluate the impacts of streamflow reduction activities) as well as the **South African Atlas of Agrohydrology and -Climatology** (databases and maps of agrohydrological and climatological information).

Modelling software

The ***ACRU*300** series is supported on the UNIX and DOS platforms. Recently the *ACRU* model has been restructured using object oriented design principles in the platform independent **Java** programming language. The object oriented structure of ***ACRU*2000** is more flexible and extensible to facilitate future model development as well as complex inter- and intra-catchment transfers.

Ongoing collaboration with our development partners has resulted in enhanced **output utilities** to analyse and present *ACRU* output files in user friendly graphical format.

User Training

Comprehensive ***ACRU* courses** provide **practical training** in model application for potential users as well as providing a **teaching medium** for hydrological scientists.

User Support

ACRU users have specialist support from the designated full-time ***ACRU* User Consultant** as well as from the highly qualified and experienced *ACRU* model development support teams at the University of Natal.

Figure 4.10.2 The *ACRU* brochure : Side two

A popular synthesis containing background information to the model, past applications and potential uses of the model, benefits of using daily hydrological models and verification information was requested by the Project Steering Committee and subsequently produced in the form of a two sided, six panel fold-out brochure. The two sides of the brochure are shown on the previous page in Figures 4.10.1 and 4.10.2.

4.11 RUNNING THE MODELLING SYSTEM AND SUPPORTING UTILITIES

Andrew Pike

Version 3 of the *ACRU* modelling system was coded in FORTRAN, was DOS based and therefore only operated in a Windows environment and operated on a subcatchment-by-subcatchment basis. The model has since been completely restructured to run on a time increment-by-time increment basis (in so-called "parallel" mode) and recoded in the JAVA Object Orientated programming language (Kiker and Lynch, 2001). In order to run *ACRU*2000, the JAVA Runtime Environment (Version 1.3 or later) needs to be installed. The latest versions of the Java platform for different operating systems may be downloaded from the JAVA website at http://java.sun.com/j2se/downloads.html. Once the Runtime Environment has been installed the various JAVA applications may be run by double-clicking the relevant .jar icon from Windows Explorer (in the Windows environment) or by opening a CMD/DOS or UNIX window and typing "java –jar" followed by the filename of the application, e.g., java –jar *ACRU*2000.jar. Table 4.11.1 shows the various applications contained in the JAVA version of the *ACRU* modelling system.

Table 4.11.1 Applications contained in the JAVA version of the *ACRU* modelling system

*ACRU*2000.jar	The JAVA version of the *ACRU* modelling system
*Acru*MenuConverter.jar	A utility to convert Version 3 *ACRU* menus to *ACRU*2000 input files
OutputVariableSelector.jar	A utility to assist the user in the selection of variables to be outputted by the model
BinToDbfW.jar	A utility to convert the binary files produced by both versions of the *ACRU* modelling system to Dbase IV files

4.12 USER SUPPORT

Andrew Pike and Roland Schulze

4.12.1 Objectives

One objective of the WRC is that products developed through their funding be applied as widely as possible. In 1995 already the WRC therefore created the post of *ACRU* User Consultant, through one of its projects at the time, within the School of BEEH. The objective was for the incumbent of this post to provide "excellent user support" for the many current and prospective users of the *ACRU* modelling system as well as the many other hydrological products applied frequently by outside users and which have been developed over the years in BEEH, through WRC funding.

This objective has been met through various general and specialised courses on the *ACRU* modelling system, one-on-one tuition, assistance via telephonic and Email discussions, undertaking collaborative work with other WRC projects and for government and private clients, and developing a number of software programs to assist in the configuration of the *ACRU* model as well as in the analysis of results from model simulations.

4.12.2 Clients Served

Table 4.12.1 presents an overview of the various sections undertaken by the *ACRU* User Consultant in the course of this particular project. Where appropriate, the work of the *ACRU* User Consultant has been published in the *ACRU*cons report series, where the "*cons*" stands for the *con*solidation of research and *cons*ultation with clients requesting model applications by the *cons*ortium of team members within BEEH. Many of these *ACRU*cons reports are in the public domain, requests for some others require the collaborating organisation's permission before they are made available on request.

In summary, the activities listed in Table 4.12.1 illustrate the scope of activities of the *ACRU* User Consultant through

- provision of public and in-house model training
- model demonstrations and the interpretation of the results
- development of new internal model routines
- development of new routines to assist in the interpretation of the results
- development of potential inter-model linkages
- research collaboration with South African partners
- research collaboration with international partners
- applications, particularly on land use impacts on water resources studies and
- assisting private consultants both within and outside South Africa, as well as the state and parastatal sectors

Table 4.12.1 Recipients of information or support from the *ACRU* User Consultant for the period January 2000 to December 2002

	Contact	**Organisation (Project)**
Information Supplied	Rolf Albrecht	The Namibia Water Corporation Ltd. (Namwater) (Information Provided on the *ACRU* Model)
	Nastaran Rahimi	Ph.D. Student, Environmental Science (Iranian Energy Information Center) (Information Provided on the *ACRU* Model)
	Iran Ghazi	University of Newcastle, UK (Information Provided on the *ACRU* Model)
	Sam Perkins	Graduate Student, University of Kansas (Information Provided on the *ACRU* Model)
	David Mungai	University of Nairobi, Kenya (Information Provided on the *ACRU* Model)

	Contact	Organisation (Project)
	Max Bleiweiss	U.S. Army Research Laboratory, White Sands Missile Range, New Mexico, USA (Information Provided on the *ACRU* Model)
	Andreas Güntner	University of Freiburg, Germany (Information Provided on the *ACRU* Model)
	Craig Schultz	ARCUS GIBB (Information Provided on the *ACRU* Model)
	Mark Summerton	Umgeni Water (Information Provided on the *ACRU* Model)
	Matthew Wilson	Ph.D. student, University of Southampton (Information Provided on the *ACRU* Model)
	Andrew Close and Dr Ben Dyer	Murray Darling Basin Commission (Information and a Demonstration Provided on the *ACRU* Model)
User Support	Francis Mugabe	Chiredzi Research Station, Zimbabwe (*ACRU* User Support with the Configuration of the Romwe Catchment)
	Greg Matthews	Wates, Meiring and Barnard (*ACRU* Information, User Support and Model Customization for the Estimation of Water Use in the Riparian Zone by Alien Invasives)
	Emmanuel Obeng Bekoe	PhD Student, Institute of Water and Environment, Cranfield University, Silsoe, Bedfordshire, UK (*ACRU* User Support)
	Thomas Kjeldsen	Ph.D. Student, Environment & Resources, Technical University of Denmark (*ACRU* User Support)
	Tembi Dzuvkama	Ninham Shand Consulting Engineers (Personal Tuition; Configuration of the Upper Berg Catchment to Estimate the Water Use by Alien Invasives in the Riparian Zone)
	Siphesihle Shange	Umgeni Water (Configuration of the Umzinto Catchment)
	Darius Mnguni	DMM Environment & Water Resources (*ACRU* Information and User Support)
	Washington Tunha	DWAF, Mpumalanga (*ACRU* Course and User Support)
	Daniel Tevera & Dr Dominic Mazvimavi	University of Zimbabwe (User Support for the Configuration of the Muphure Catchment for the EU Project "Integrated Water Resources Management System")
	Dennis Dlamini & Prof Jonathan Matondo	University of Swaziland (User Support for the Configuration of the Mbuluzi Catchment for the EU Project "Integrated Water Resources Management System")
	Lucille Hallowes	CPH Water (User Support for the Configuration of the Mhlatuze Catchment)
	Kevin Meier	Land Resources International (LRI) (User Support and Model Customisation for the Estimation of Water Use in the Riparian Zone by Alien Invasives)
Assistance With Other WRC Or DWAF Projects	Dave Clark	University of Natal and LRI (Validation of *ACRU*2000)
	Trevor Lumsden	University of Natal ("Development of Models to Quantify Streamflow Reduction Caused by Commercial Afforestation in South Africa", WRC 1110)
	Mark Gush	CSIR ("Modelling the Impacts of Land Cover and Land Management Practices on Stream Flow Reduction", WRC 1015)
	Marilyn Royappen	CSIR ("Analysis of Streamflow Generation Mechanisms in a Wide Range of catchments", WRC 1193)

	Contact	**Organisation (Project)**
	Tinisha Chetty	University of Natal (“Regionalisation of Rainfall Statistics for Design Flood Estimation”, WRC 1060)
	James Mackenzie	Ph.D. Student, Centre for Water in the Environment, Wits University (“Rule-based Modelling of Riparian Vegetation and Technology Transfer to Enable Strategic Adaptive Management of the Kruger National Park”, WRC 1063)
	Paul Matthews and Cor Langhout	BKS Consulting Engineers (*ACRU* Course and User Support in the Configuration of the Upper Olifants Catchment)
	Graham Jewitt	University of Natal and the Institute for Natural Resources (INR) (Thukela Water Project: Hydrology Specialist Study)
	Andrew Birkhead	Streamflow Solutions (Provided Simulated Streamflows for the Geomorphology Change Models for the Sabie River in the Kruger National Park)
	Theunis Morgenthal and Paul Clark	Ecologist/Taxonomist, Viridus Technologies Trading As EKO REHAB (Estimation of Leaching in Mine Dumps)
***ACRU* Courses**	Gordon Chrystal	DWAF, Durban (*ACRU* Course)
	Ivor Hoareau	DWAF, Durban (*ACRU* Course)
	Norman Ward	DWAF, Durban (*ACRU* Course)
	Cameron Tylcoat	DWAF, Durban (*ACRU* Course)
	Final Year Hydrology Students	University of Natal (Instruction and Assistance with Practical Modelling Courses)
	Final Year Engineering Students	University of Natal (Instruction and Assistance with Practical Modelling Courses)
	Hydrology Honours Students	University of Natal (Instruction and Assistance with Practical Modelling Courses)

CHAPTER 5

***ACRU*View : A VISUALISATION AND STATISTICAL PACKAGE FOR USE WITH THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM**

ACRUView
USER MANUAL

Version 1.0
December 2002

TABLE OF CONTENTS

INTRODUCTION

*ACRUV*iew is a Microsoft Excel based application designed to analyse and view information produced by the *ACRU* agrohydrological model The information is imported in the form of DBF files and processed internally for statistical and graphical analysis. Values imported into *ACRUV*iew are named as a “Scenario”. After importing values, *ACRUV*iew is a saved as a “Project”.

The *ACRUV*iew application consists of 7 main forms:

- Home
- Statistics
- Graphs
- Comparative Statistics
- Extreme Value Analysis (EVD)
- EVD graph and
- Flow Duration Curve (FDC) graph.

A menu bar assists in navigating between forms and is used to save and close the application. The “Variable Dictionary” and “Add Variable’ user dialogue boxes are also accessed using toolbar buttons.

This manual describes, in brief, the various functions of *ACRUV*iew and is aimed at the experienced PC user with advanced hydrological knowledge.

*ACRU*View MENU BAR

The *ACRUV*iew menu bar (Figure 1) consists of the following command buttons:

- ***Main*** : This displays the following sub-items
  - *Home* : Displays the home page
  - *Save* : Saves the project
  - *Save As* : Saves the project with new name and/or path
  - *Close* : Closes the application
- ***View Stats*** : Displays the Statistics form
- ***View Graphs*** : Displays the Graphs form
- ***View Comparative Stats*** : Displays the Comparative Statistics form
- ***View EVD Calculator*** : Displays the Extreme Value Analysis (EVD) form
- ***View FDC Calculator*** : Displays the Flow Duration Curve (FDC) form
- ***Edit App*** : Used to edit application, and requires a password
- ***Go Back*** : Returns to previously viewed from
- ***Add New Variable*** : Guides the user through the calculation of a new variable (calculator image)
- ***Dictionary*** : Displays the dictionary of variables (open book image).

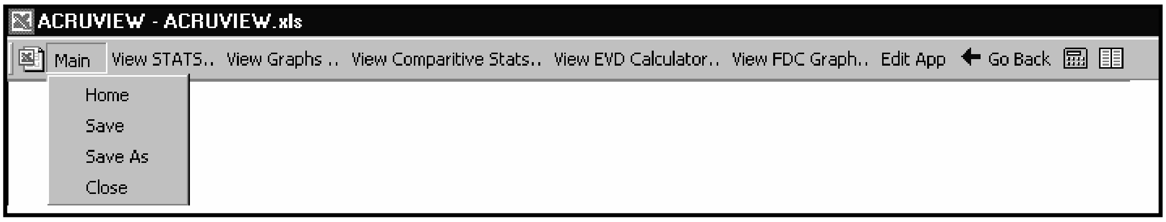


Figure 1 The *ACRUV*iew menu bar

HOMEPAGE

Upon opening *ACRUView* a homepage, as shown in Figure 2, is displayed. This form contains the project name, number of scenarios saved and a number of buttons. The buttons are:

- ***New Project*** : Starts user dialogue box for importing data into a new project
- ***Existing Project*** : Opens another project
- ***New Scenario*** : Starts user dialogue box for importing data
- ***Delete Scenario*** : Deletes a scenario.

The lower set of buttons, which are grayed out until a scenario is loaded, are:

- ***Statistics*** : Displays the Statistics form
- ***Comparative Statistics*** : Displays the Comparative Statistics form
- ***Graphs*** : Displays the Graphs form
- ***EVD Calculator/ Runlength Analysis*** : Displays the Extreme Value Analysis form
- ***Flow Duration Curves*** : Displays the Flow Duration Curve form

Figure 2 The *ACRUView* homepage

Starting a New Project and Importing Information/Values

The button "New Project" shows a user dialog box, as in Figure 3. To start a new project a DBF containing the required values must be selected. "Find Data" initiates this process by showing a dialogue box, as in Figure 4, which enables the user to select the required file. The scenario and project are then named. "OK" imports values if the preceding steps have been accomplished.

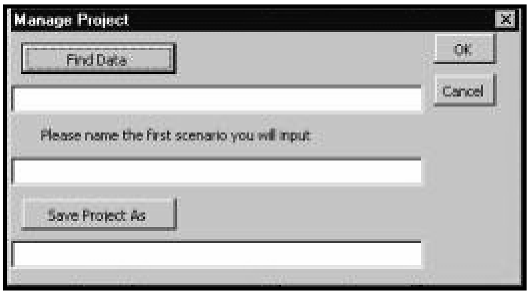


Figure 3 The "Manage Project" dialogue box for importing a scenario and saving a project

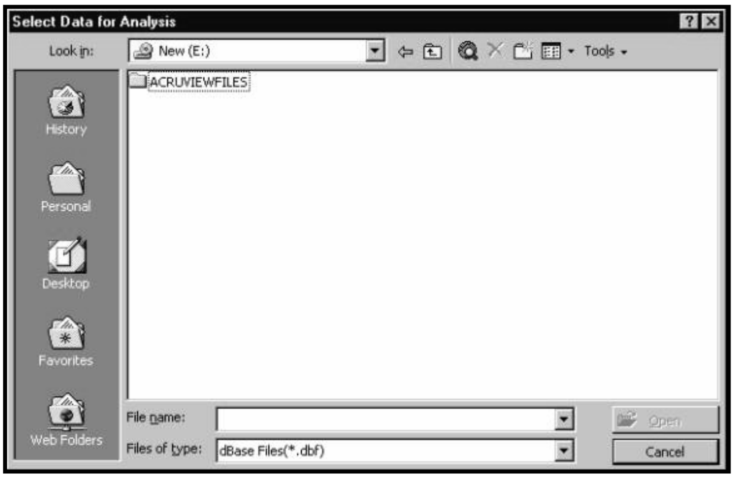


Figure 4 The "Select Data for Analysis" dialogue box

If a new project has already been saved, scenarios can be imported as above by clicking "New Scenario". A project will not have to be named.

It is important that DBF files are constructed as follows:

Date	Variable 1	Variable 2	Etc.

The first column contains dates (either daily or monthly). Values generated by *ACRU* can then fill the remaining 255 columns.

Deleting a Scenario

By clicking "Delete a Scenario" a dropdown box is shown from which a scenario may be selected. Upon selection the chosen scenario is deleted.

The Variable Dictionary

The "Variable Dictionary" (Figure 5) may be called from any form. It enables the user to select any *ACRU* variable for a description. Clicking on the "Import New Dictionary" button enables the importation of a new dictionary as a DFB file. This procedure is meant for University of Natal *ACRU* operators only.

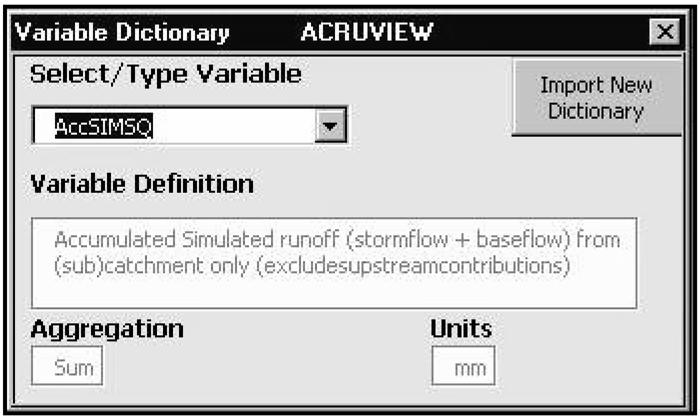


Figure 5 Example of the “Variable Dictionary” screen

STATISTICS

The statistics form (Figure 6) enables calculation of statistics for daily or monthly values.

- A scenario and variable is first selected using the dropdown controls “Scenario” and “Variable”.
- Clicking the “Run Statistics” button initiates calculations.
- The start of the hydrological year, shown as 9, i.e. September, in Figure 6, can be changed by typing an integer value between 1 and 12 in the relevant cell.
- The user can further select monthly or daily values (if daily values have been imported) as the basis for calculation.
- Results can be saved as a text file using the “Save as Text” button.
- “View a Variable” navigates to previously calculated statistics, and is useful if statistics for a number of variables have been calculated.
- The viewed variable can be deleted with “Delete Selected Stats”.
- Right clicking on the form displays a short cut menu “View Box Whisker Graph” (Figure 7).
- Clicking this option brings up a window showing a Box Whisker type plot for the variable in view (Figure 8).

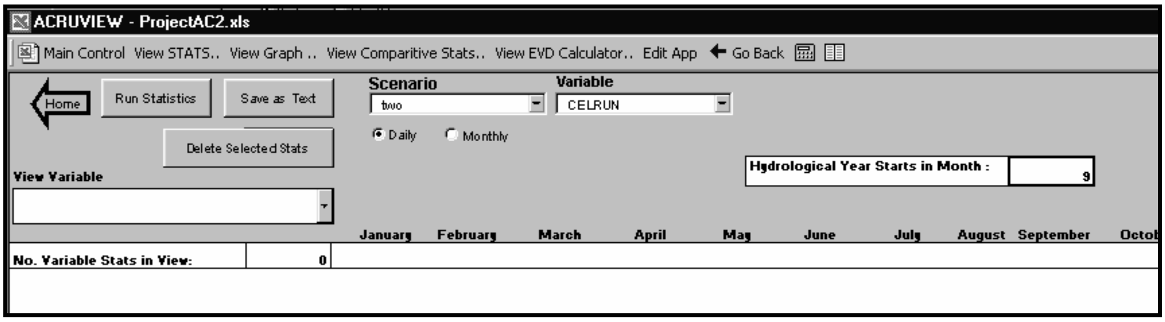


Figure 6 Statistics form

Figure 7 Short cut menu seen after right clicking “In the Statistics” form

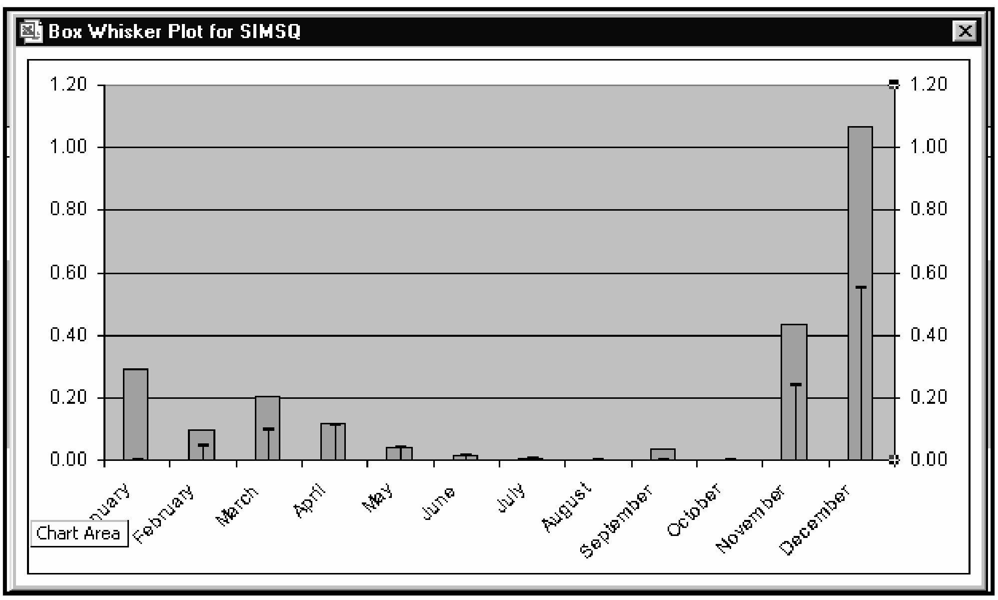


Figure 8 The “Box Whisker” plot screen: Example for the variable SIMSQ

GRAPHS

The graph form (Figure 9) is used to plot time series or variable vs. variable graphs. It is the only form with a dedicated tool bar (Figure 10). Hovering over a button with the mouse produces a tool tip indicating the function of the button.

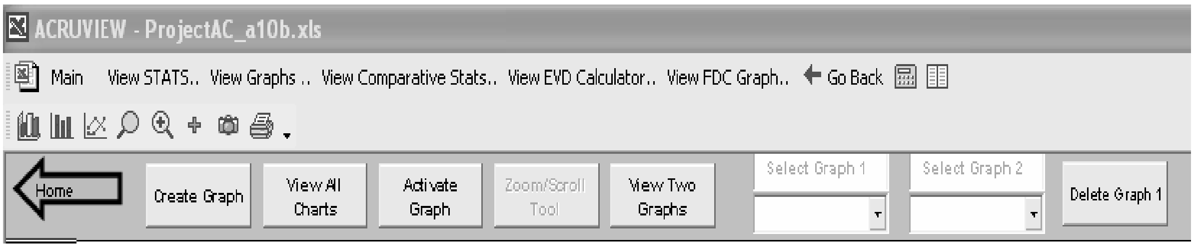


Figure 9 The graph form

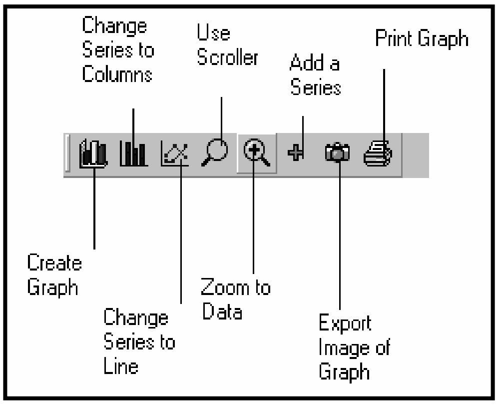


Figure 10 The graph tool bar

The following controls are used in the graph form.

- ***Create Graph*** : Displays a dialogue box, which guides the user through the plotting of a graph.
- ***View All Charts*** : Shows all the charts currently saved in “window pane” format (*cf*. Figure 11).
- ***Activate Graph*** : Activates the graph in view. This operation is necessary for various operations.
- ***Zoom/Scroll Tool*** : Enables a user to scroll through time series data and zoom to a selected time period (only visible if graph is active).
- ***View Two Graphs*** : Displays two graphs provided both graphs are based either on daily or monthly data (Figure 12).
- ***Select Graph 1*** : Select a graph to view.
- ***Select Graph 2*** : Select a second graph if the “Compare 2” function is to be employed.

Create a Graph

Clicking on the "Create Graph" button (on the form or tool bar) invokes the user dialogue box, as shown in Figure 13.

- Using this dialogue a graph type ("Variables vs. Time" or "Compare Variables"), scenarios, variables to be plotted and time period are selected.
- Upon clicking "Create Graph" the user will be asked to type in a heading for the graph and to provide a unique short name. A graph is then plotted (Figure 14).

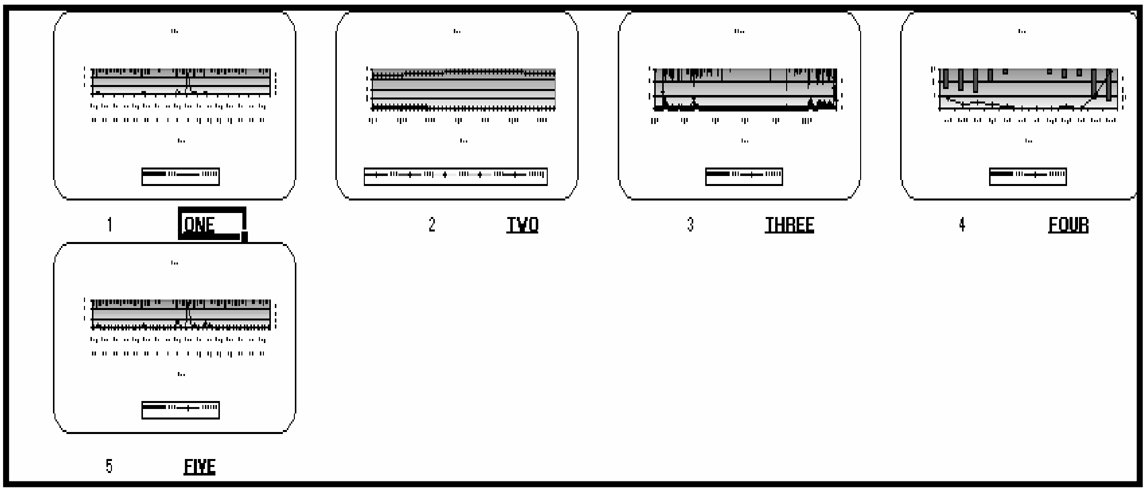


Figure 11 All available graphs represented in "window pane" format

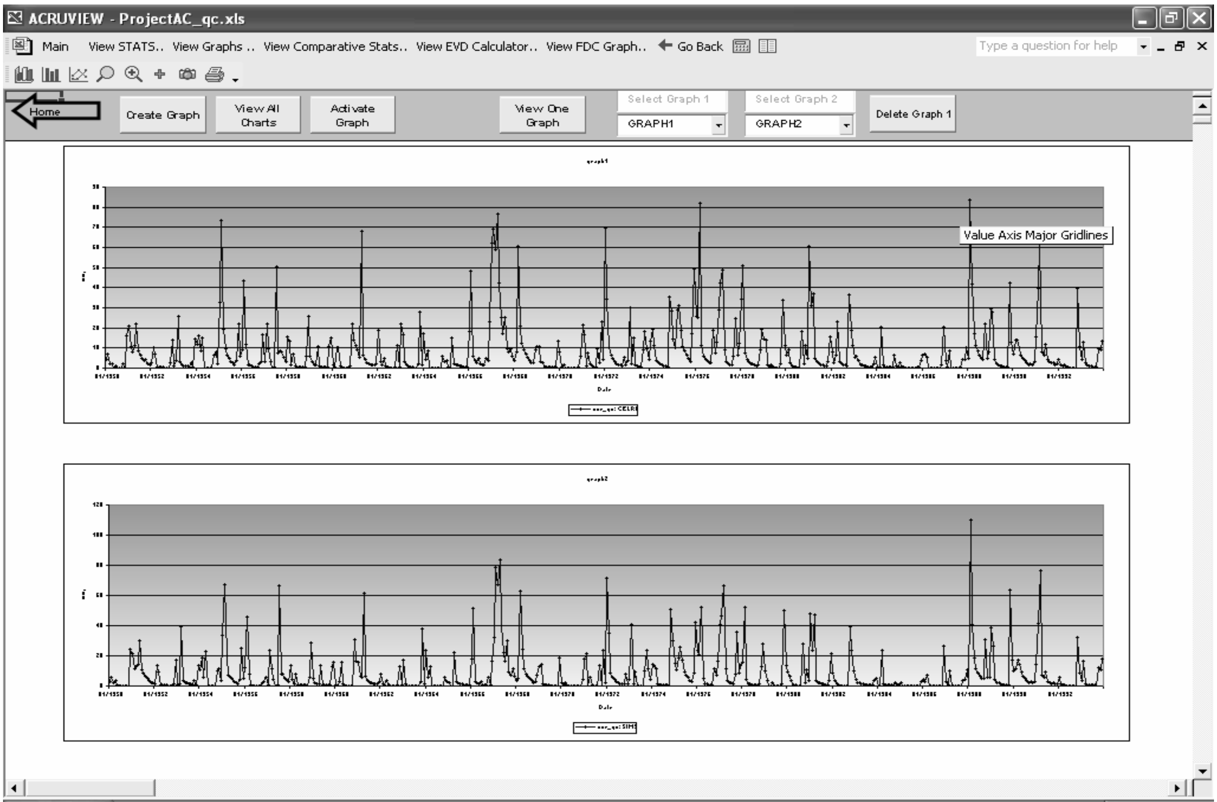


Figure 12 Use of the "Scroller/Zoom" tool when comparing two graphs

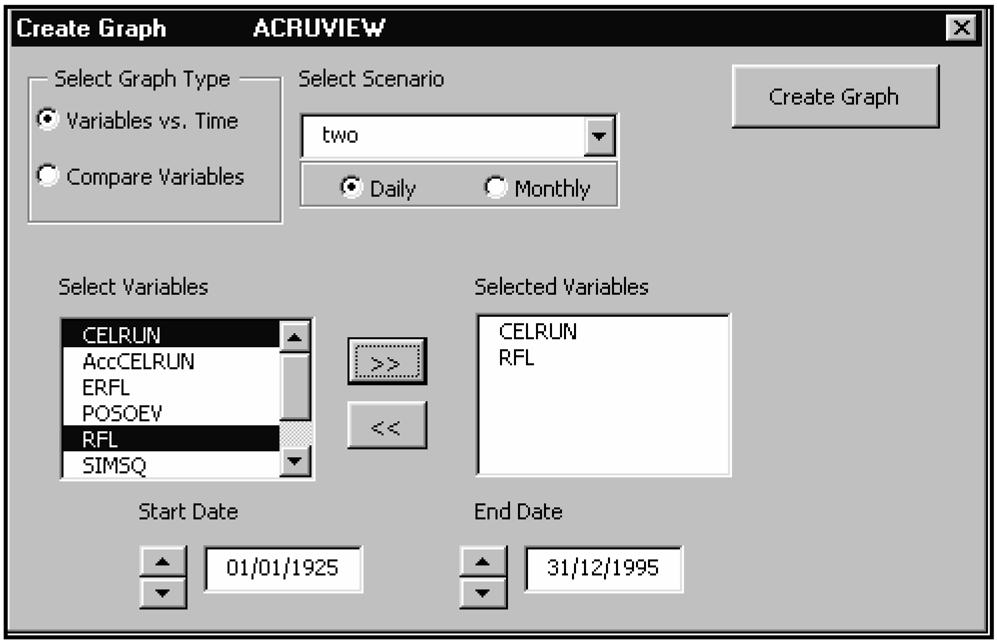


Figure 13 The “Create Graph” dialogue box

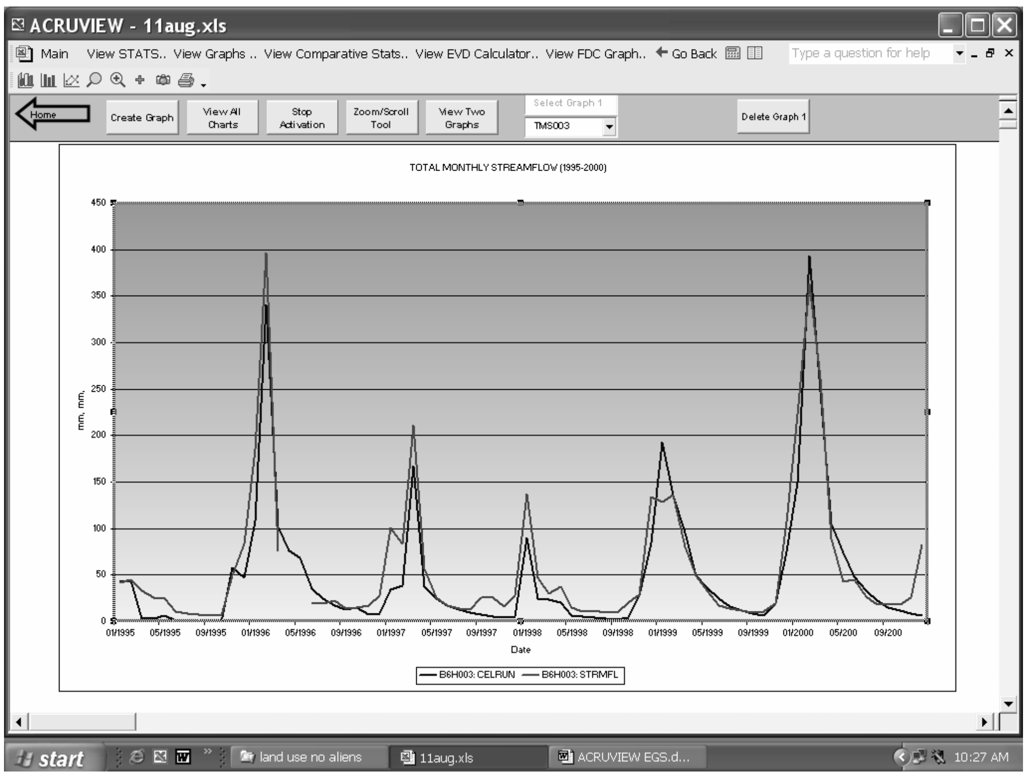


Figure 14 Example of a time series plot with two variables (observed and simulated streamflows)

Using the Scroller/Zoom Tool

- Activate a graph using the “Activate” button and then initiate a tool with the “Scroll/Zoom” button (form or tool bar).
- A tool is deployed which enables the user to scroll through time using the scroll bar (Figure 15) or to zoom to a specified period. While scrolling the current time interval plotted remains constant.
- Selecting the “Zoom” option enables start and end dates to be adjusted.
- Clicking on the “Set Zoom” button plots the graph for the selected period. If two graphs are being compared the zoom tool synchronises the time period viewed in both graphs according to the first graph (Figure 12).

View Data
Using the tool bar it is possible (if a graph is activated) to select a series view the data (Figure 16).

Add Series
Using the tool bar it is possible (if a graph is activated) to add a new series.

Change Graph Type
Using the tool bar it is possible (if a graph is activated) to select a series and change the graph type to line or column.

Print or Export Image
Using the tool bar it is possible (if a graph is activated) to print a graph or export an image of that graph.

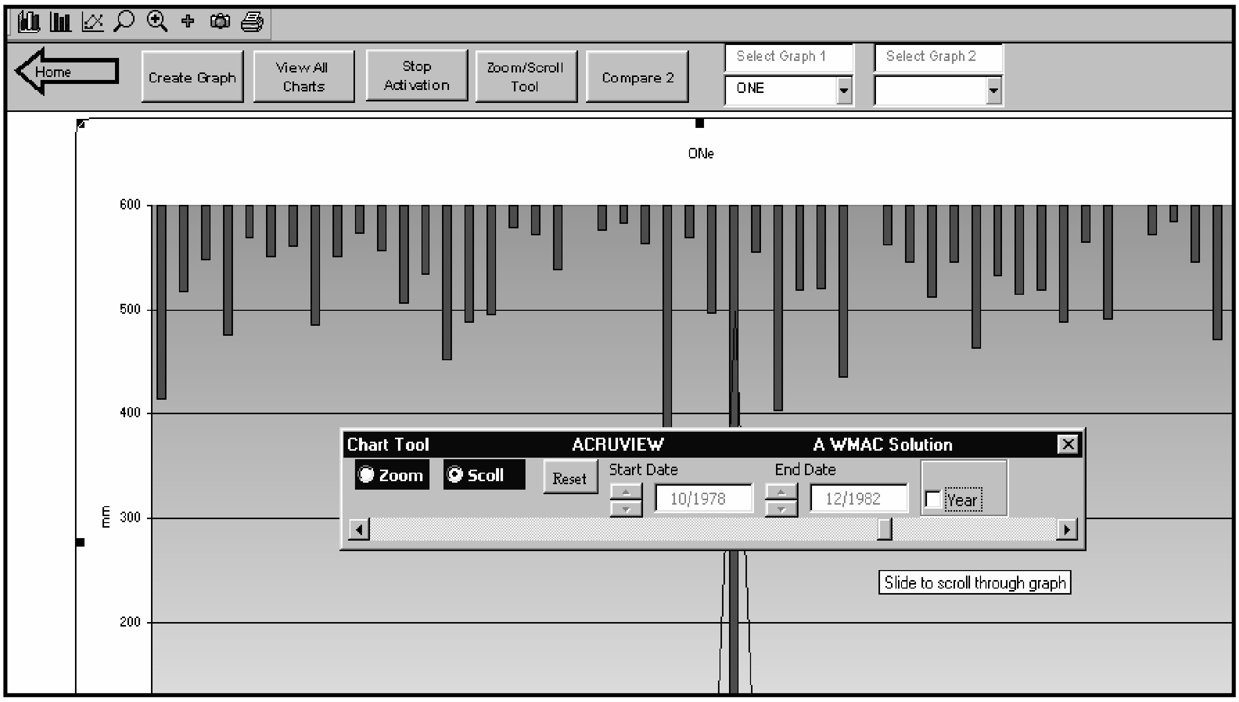


Figure 15 Use of the “Scroller/Zoom” tool

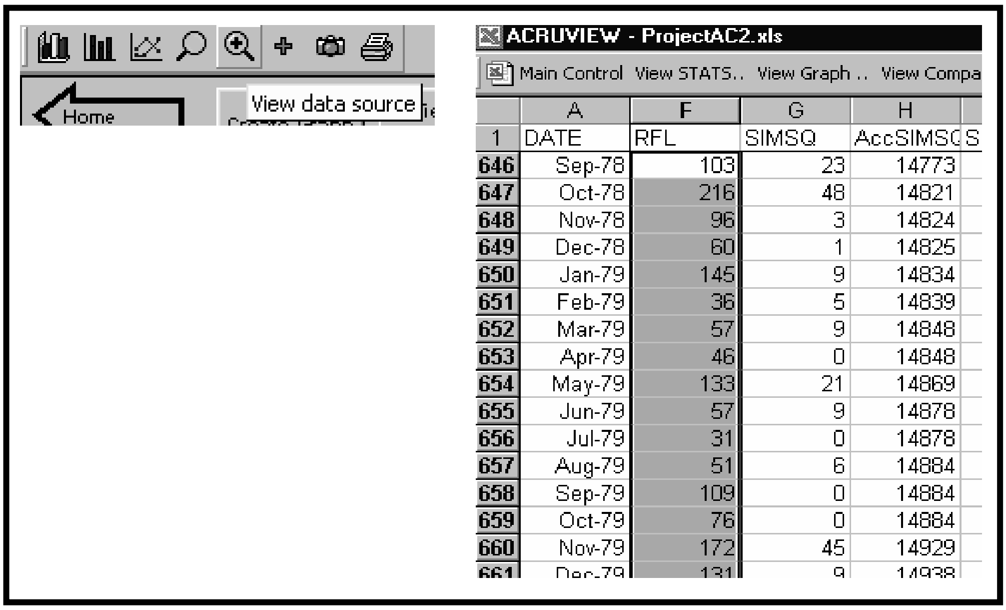


Figure 16 Viewing a data series

COMPARATIVE AND OTHER STATISTICS

Comparative Statistics

The “Comparative Statistics” form (Figure 17) enables statistical comparison of two variables. The major controls are:

- ***New Comparison*** : This invokes the “Select Variable” dialogue box, allowing the user to select observed and simulated variables for comparison
- ***Save Text File*** : Saves statistics as a text file
- ***View Chart*** : This displays a scatter plot of the two variables and a linear regression line (Figure 18).

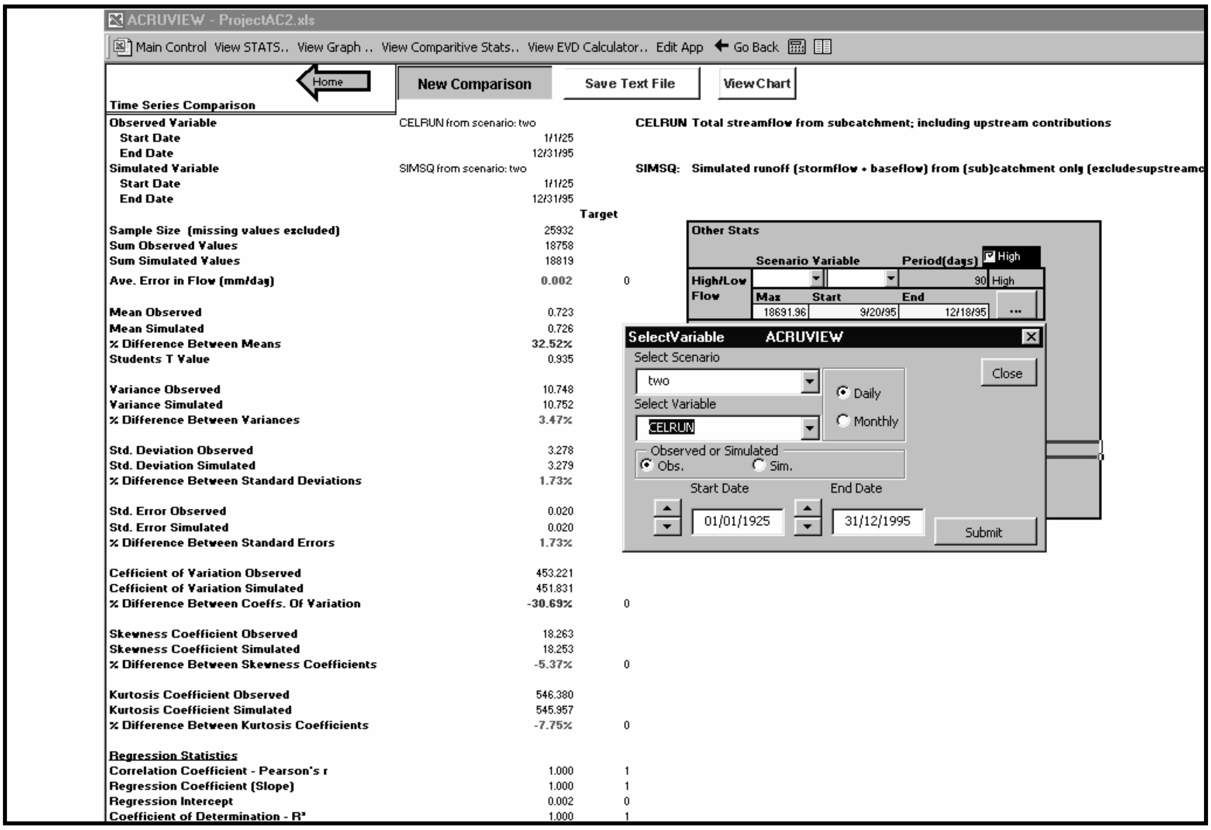


Figure 17 The “Comparative Statistics” form

Other Statistics

The “Other Stats” option determines the dates within which a period of highest or lowest flow for a selected variable occurs. The length of this period is entered under the heading “Period (days)”.

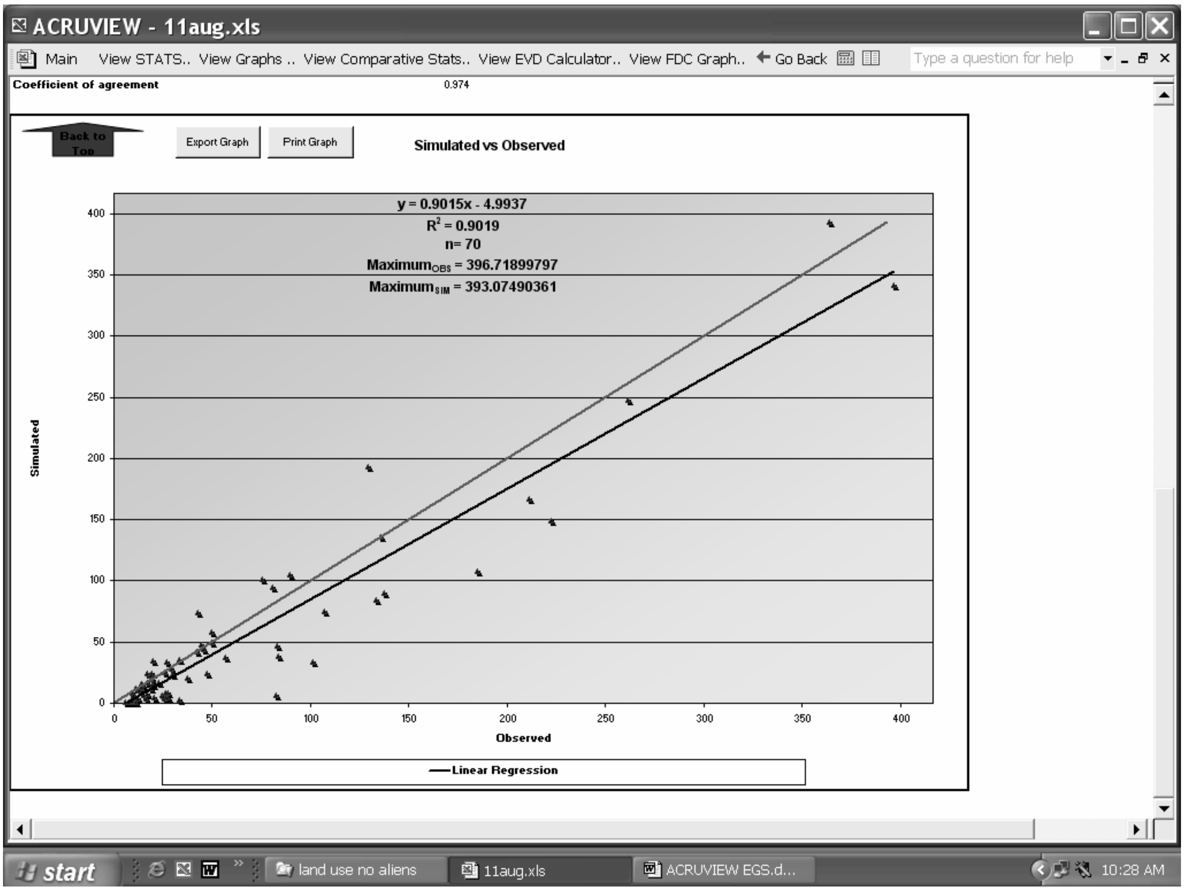


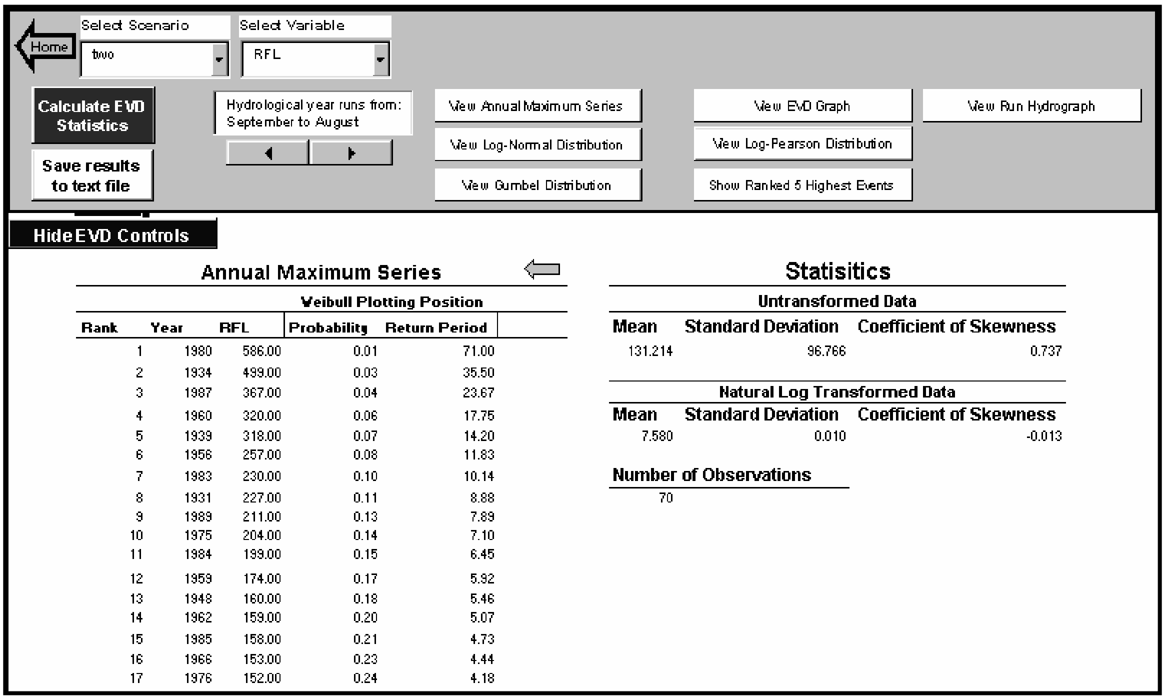
Figure 18 Example of a “Comparative Statistics” graph

EXTREME VALUE ANALYSIS

The Extreme Value Analysis (EVD) form (Figure 19) operates in a similar way to the Statistics form.

- EVD statistics are calculated after selecting a variable from a scenario and clicking on the “Calculate EVD Statistics” button.
- A start and end month for the hydrological year to be analysed can also be selected.
- The EVD form contains a number of self-explanatory navigation buttons.
- It should be noted that the Ranked 5 highest events are appropriate only for the variable for which statistics have been calculated (Observed and Simulated variables are shown as 0).
- The “Save Results to Text File” button saves a text file of the calculated statistics.

Two graphs can be viewed via the EVD form, *viz*. a runlength analysis (Figure 20) and an EVD graph (Figure 21).



Rank	Year	RFL	Veibull Plotting Position: Probability	Return Period
1	1980	586.00	0.01	71.00
2	1934	499.00	0.03	35.50
3	1987	367.00	0.04	23.67
4	1960	320.00	0.06	17.75
5	1939	318.00	0.07	14.20
6	1956	257.00	0.08	11.83
7	1983	230.00	0.10	10.14
8	1931	227.00	0.11	8.88
9	1989	211.00	0.13	7.89
10	1975	204.00	0.14	7.10
11	1984	199.00	0.15	6.45
12	1959	174.00	0.17	5.92
13	1948	160.00	0.18	5.46
14	1962	159.00	0.20	5.07
15	1985	158.00	0.21	4.73
16	1966	153.00	0.23	4.44
17	1976	152.00	0.24	4.18

	Mean	Standard Deviation	Coefficient of Skewness
Untransformed Data	131.214	96.766	0.737
Natural Log Transformed Data	7.580	0.010	-0.013

Number of Observations: 70

Figure 19 The EVD form

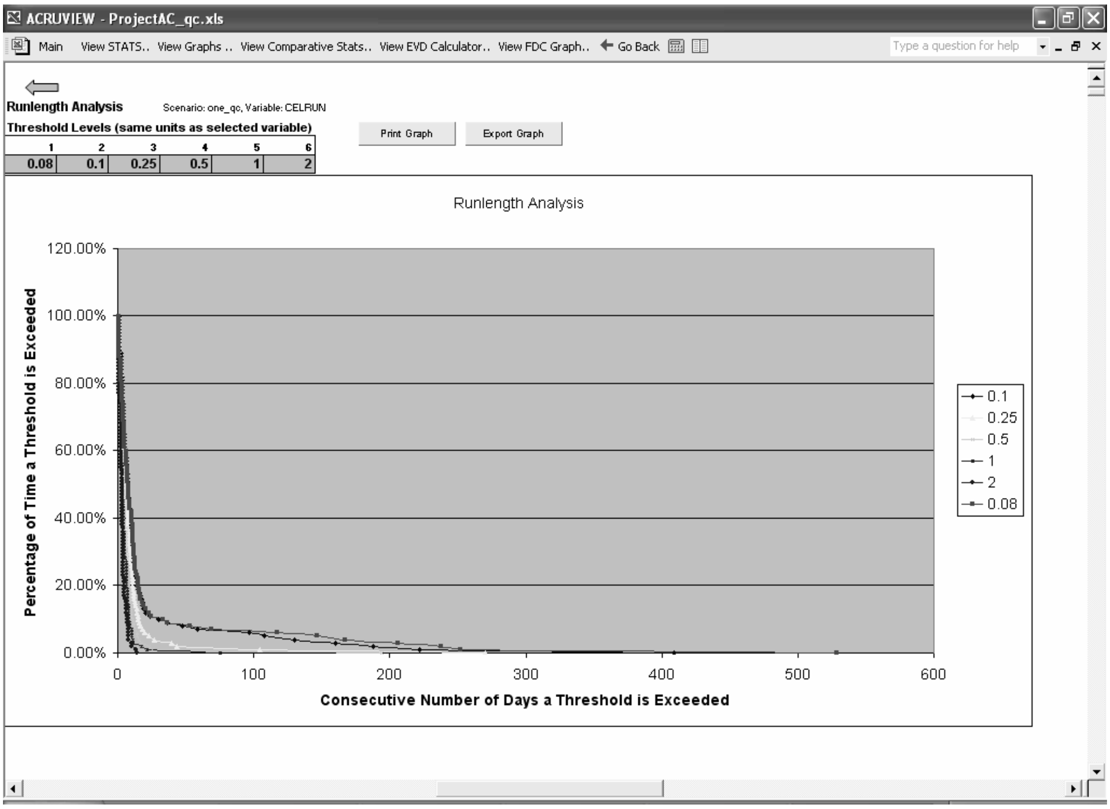


Figure 20 Example of a "Runlength Analysis"

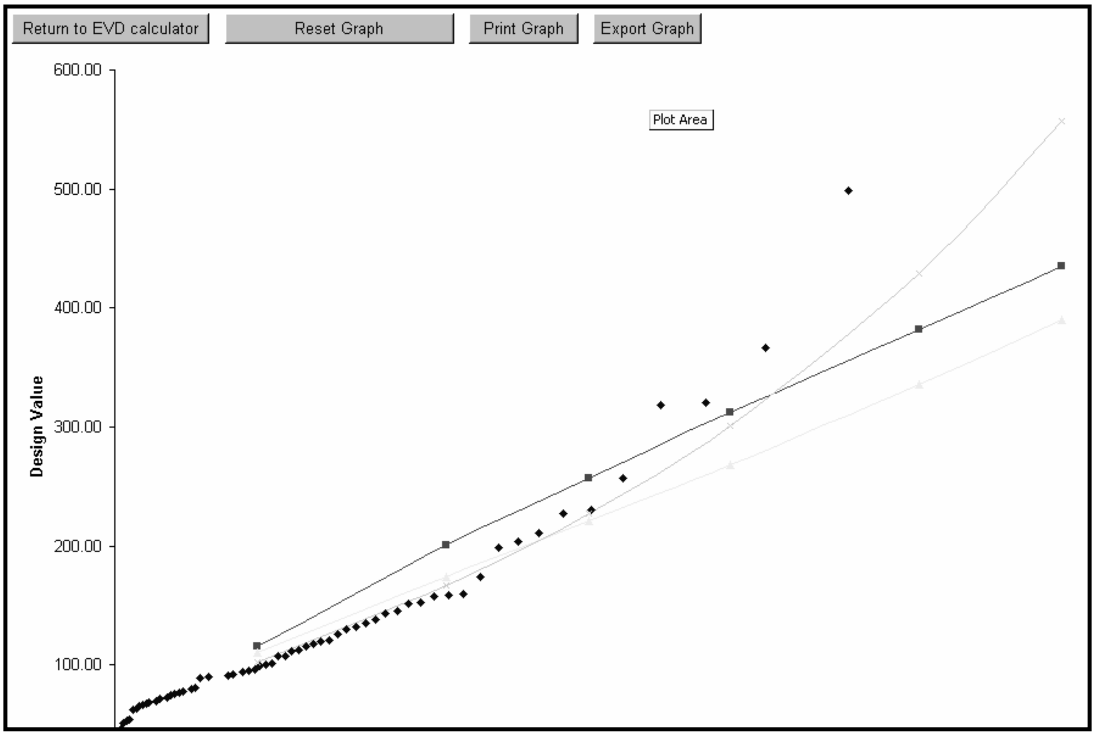


Figure 21 Example of the "EVD Graph"

FLOW DURATION CURVES

- The FDC form enables the user to display up to 5 flow duration curves for various variables from any scenario loaded.
- Prior to adding a variable the form looks like Figure 22.
- After adding variables (select “Scenario”, “Variable” and click “Add to Graph”) a figure as in Figure 23 will be seen.
- It is possible to “zoom” in or out by using the corner scroll bars (essentially these bars adjust the maximum value of the axis).
- Further controls allow a series to be individually deleted, the graph to be cleared, printed or exported as an image.

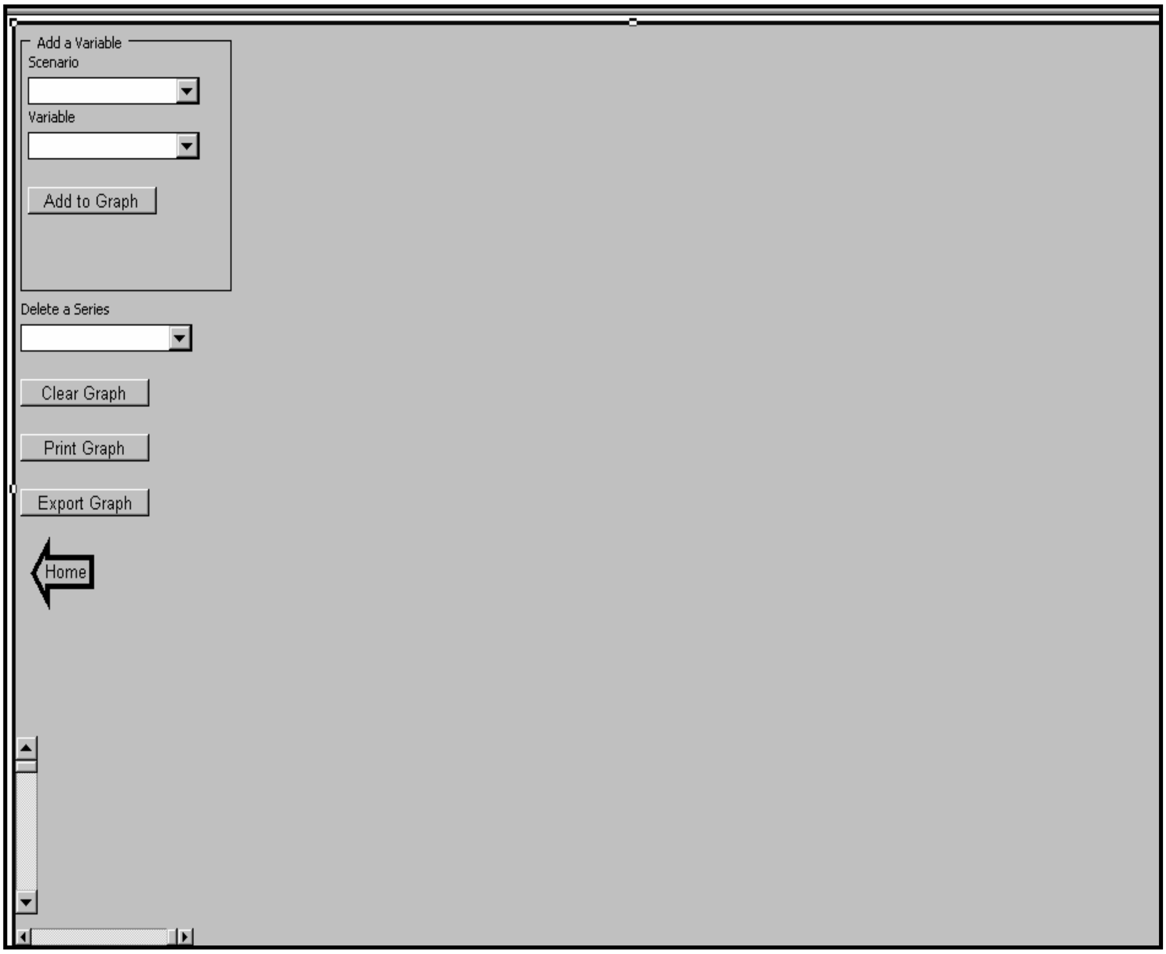


Figure 22 The FDC form

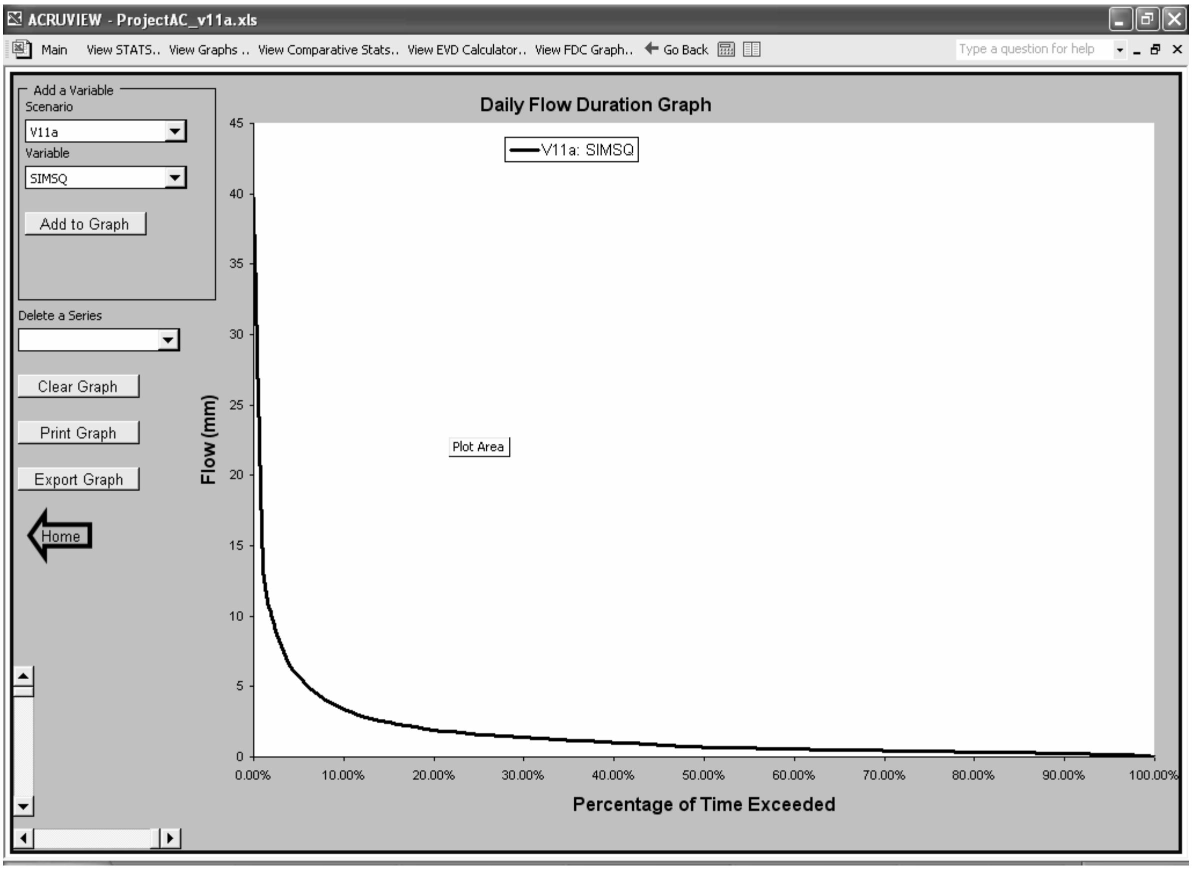


Figure 23 Example of a flow duration curve graph

CALCULATING A NEW VARIABLE

Clicking the “Add Variable” button on the main menu displays a three-page dialog box (Figure 24), which enables the addition of a new variable to a scenario. The box must be completed page by page and is explained below.

Select Operation

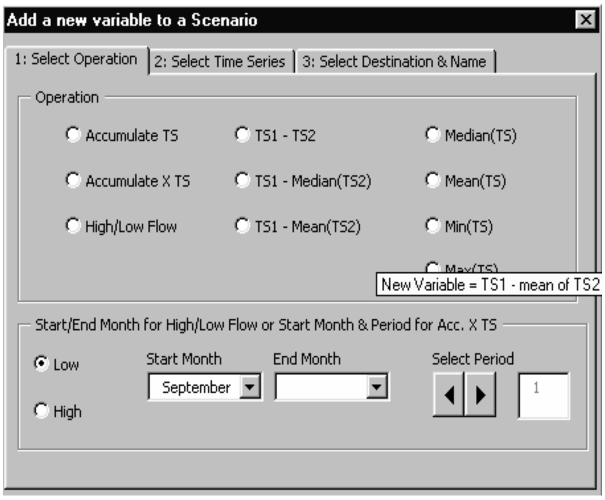
- ***Accumulate TS*** : Calculates a new variable as the daily accumulation of a selected time series (TS) variable.
- ***Accumulate X TS*** : Calculates a new variable as the accumulation of a selected time series (TS) variable over a chosen period (X). The “Select Period” spin buttons on the bottom right are used to determine X. The start month of accumulation must also be selected (bottom of box).
- ***High/Low Flows*** : Calculates a new variable based on the high or low flows of a selected TS. The start and end period must be selected (bottom of box) and High or Low must be selected.
- ***TS1 –TS2*** : Calculates a new variable by subtracting a TS from another TS.
- ***TS1 – Median (TS2)*** : Calculates a new variable by subtracting a TS from the mean of another TS.
- ***TS1 – Median (TS2)*** : Calculates a new variable by subtracting a TS from the median of another TS.
- ***Median (TS)*** : Calculates a new variable as the Median of a selected TS.
- ***Mean (TS)*** : Calculates a new variable as the Mean of a selected TS.
- ***Min (TS)*** : Calculates a new variable as the Minimum of a selected TS.
- ***Max (TS)*** : Calculates a new variable as the Maximum of a selected TS.

Select Time Series

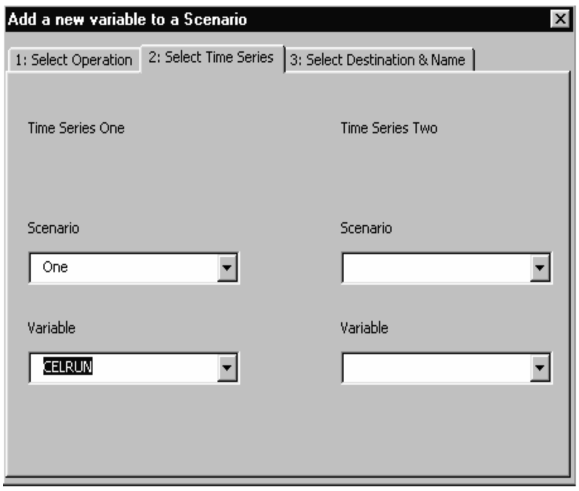
On this page the variable(s) used in the calculation are selected.

Select Destination and Name

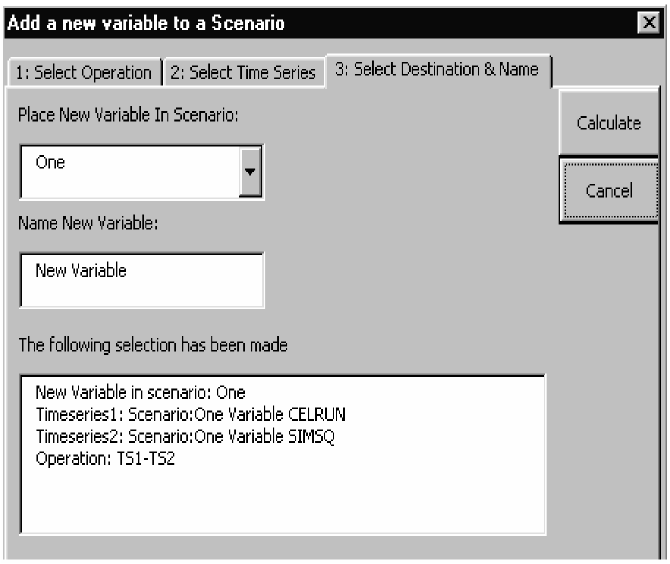
The final page requires selection of the destination of the new variable. This is always an existing scenario. The variable must also be named. The box “The Following Selection Has Been Made” summarises the action that will be made on clicking “Calculate”.



1



2



3

Figure 24 The “Add a Variable” dialogue box, pages 1 to 3

CHAPTER 6

SOUTH AFRICAN NATIONAL QUATERNARY CATCHMENTS DATABASE: REFINEMENTS TO, AND LINKS WITH, THE *ACRU* MODEL AS A FRAMEWORK FOR INSTALLED HYDROLOGICAL MODELLING SYSTEMS

Lucille Hallowes, Roland Schulze, Mark Horan and Andrew Pike

6.1 OVERVIEW AND OBJECTIVES

The inputs required for the *ACRU* model need to be written into the model's input menu prior to simulation of any catchment. Instead of storing the information pertaining to each catchment in the *ACRU* input menu in preparation to perform agrohydrological simulations in southern Africa, the information required for the *ACRU* simulations has been stored in a Quaternary Catchments database. An interface has been developed whereby information can be selected from an *ACRU* Input Database and automatically read into the *ACRU* model's input menu for the model to run.

Briefly, an *ACRU* Input Database at the level of Quaternary Catchments is established containing information required by the *ACRU* model for agrohydrological simulations. A variety of climate information can be used in the simulation, which includes the option of using a future climate scenario from a selected General Circulation Model (GCM). Relevant catchment information stored in the database can be extracted for simulation. Selected output from the model runs can be displayed in the form of maps or time series. This process will be expanded upon in greater detail in subsequent sections.

As shown in Figure 6.1, four main themes constitute this chapter. The first theme is the *ACRU* Input Database structure developed for use with the *ACRU* model. The next theme is the interface between this Input Database and the model. The third theme is the simulation of agrohydrological responses using *ACRU* using this automated system and lastly the extraction of output from the model for presentation of results.

In Section 6.2 the initial structure of the *ACRU* Input Database used to simulate agrohydrological responses of the Quaternary Catchments is outlined (*cf*. Figure 6.1). This database structure was found to be limiting and was subsequently revised, as described in Section 6.3. These revisions are continuing. The new database structure allows for greater flexibility when carrying out an *ACRU* simulation for agrohydrological simulations. In addition, this revised structure facilitates the option of subdividing the Quaternary Catchments into the next level of disaggregation, *viz*. Quinary Catchments, in those Quaternaries with a high intra-catchment variability and which, through subdivision, may result in a more realistic hydrological simulation.

This revised database structure was used to store the *ACRU* input parameters for the 1946 Quaternary Catchments in southern Africa as a pre-populated database which can be accessed by multiple users. However, the information stored in the *ACRU* Input Database for each Quaternary Catchment needed enhancement, as highlighted in Section 6.4.

The next objective was to develop an interface to link the *ACRU* Input Database to the *ACRU* model's input menu. This interface facilitates the incorporation of future climate scenarios, different levels of temperature input (Section 6.5) and the rapid selection of catchments whose information has been stored in the database (Section 6.6). When using this interface there is the choice of simulations methods, i.e. either simulating the hydrology of selected catchments individually or as cascading interlinked catchments. The methodology used for the simulation of catchments in *ACRU* is explained in Sections 6.7 and 6.8. Lastly, the extraction of output from *ACRU* for input into a GIS or for display as a time series is described in Section 6.9. This chapter provides an overview of the Quaternary Catchments database as of 2002.

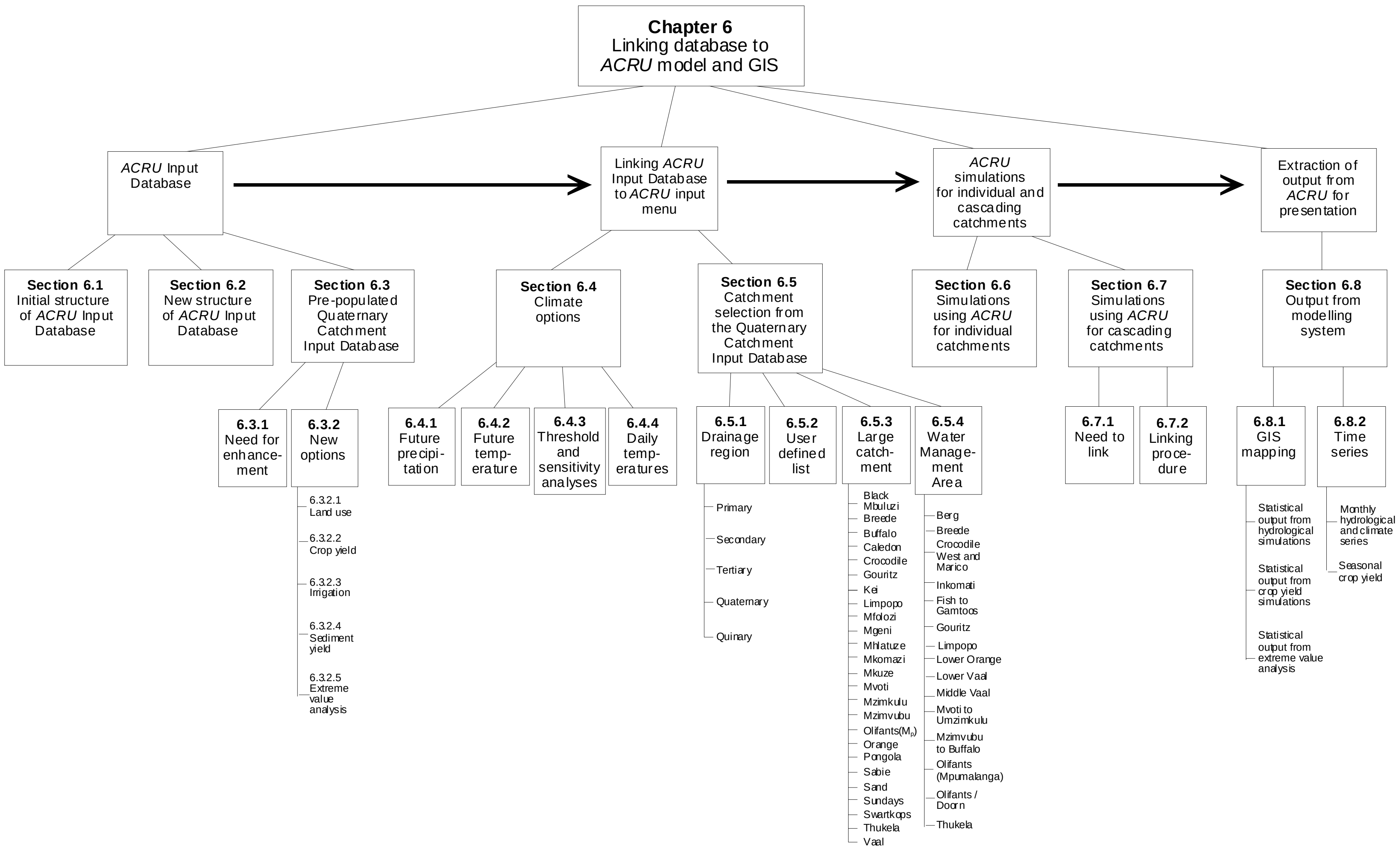


Figure 6.1 Layout plan of Chapter 6: Linking the *ACRU* Input Database to the *ACRU* model and GIS

6.2 INITIAL STRUCTURE OF THE *ACRU* INPUT DATABASE

Various inputs, *viz*. information on soils, land use and climate for each catchment being simulated are required for the *ACRU* model for agrohydrological simulations and are input into the model's input menu. The *ACRU* input menu is a formatted ASCII file in which the various hydrological variables required by *ACRU* are entered prior to simulation. Meier (1997) established an *ACRU* Input Database structure for the input data required for simulating hydrological responses from the Quaternary Catchments using the *ACRU* model. However, this structure was found to be limiting when subdivision of the Quaternary Catchments was potentially required. For this reason the *ACRU* Input Database was restructured to allow for the inclusion of information on the subdivided Quaternary Catchments, as expanded upon in Section 6.3.

The procedure of storing the Quaternary Catchment database information in direct access ASCII files and reading them into an *ACRU* input menu was automated by Meier (1997). Each Quaternary Catchment was assigned a numerical identity as a reference. The input information for *ACRU* could then be written to a direct access ASCII file in the order of the numerical identity, such that each line number represented a particular Quaternary Catchment. Thus, once the Quaternary Catchment in question had been selected, it was possible to identify its corresponding numerical identity and, using this number, directly access the hydrological information pertaining to it from the respective files (Meier, 1997). Using this method of reference to the numerical identification number, seven ASCII files were created for each Quaternary Catchment by Meier (1997) containing information on

- the daily rainfall station file number;
- 12 values of monthly means of daily maximum temperature;
- 12 values of monthly means of daily minimum temperature;
- 12 values of monthly totals of A-pan equivalent reference potential evaporation;
- catchment attributes (e.g. area, mean altitude, mean annual precipitation, centroid latitude and longitude);
- soils attributes (e.g. horizon thicknesses, soil water contents at the lower limit, drained upper limit and porosities of the top- and subsoil horizons, termed hereafter A and B horizons, as well as saturated drainage redistribution rates from the A to B horizons and from the B horizon into the intermediate groundwater zone); and
- land cover attributes required by the *ACRU* model (e.g. monthly values water use coefficient, vegetation interception losses per rainday, rooting distributions of the A horizon).

Meier (1997) compiled a UNIX script whereby the Quaternary Catchment database information could be extracted and be written to the *ACRU* menu. The menu consists of a set number of lines with each line having the same length. The *ACRU* model can then use the input menu as a direct access file to read input information from any required line number. The running of the *ACRU* model and subsequent saving of portions of the output could then be performed automatically on each Quaternary Catchment.

6.3 REVISED STRUCTURE OF *ACRU* INPUT DATABASE

Assigning each Quaternary Catchment a numerical identify from which all information pertaining to that Catchment could be identified via direct access became limiting when additional catchments needed to be added to the database. In addition, this database structure could only be used for simulating agrohydrological responses of the Quaternary Catchments and not, say, the next level of spatial disaggregation, i.e. Quinary Catchments. Therefore, the *ACRU* Input Database was restructured to allow for both information on additional catchments to be added as well to allow flexibility of the system to be able to store *ACRU* input information on any catchment in southern Africa in a database.

The first stage of this restructuring involved reorganising the *ACRU* input information into a single file. The single file is stored in a spreadsheet, thereby allowing more flexible modification and manipulation of the *ACRU* input information in a familiar format. Each row in the spreadsheet refers to a catchment and each column to an *ACRU* input. The column names follow the parameter names used in the *ACRU* input menu, however, the columns need not be in the same order as they occur in the input menu. The first column is the name of the catchment, e.g. U10A. In total there are 612 *ACRU* inputs possible into this particular version of the *ACRU* input menu. However, not every input is used in a simulation, for example, if no irrigation is specified in a catchment then irrigation information is not required by the model.

Once the database has been established it is exported from the spreadsheet in comma delimited format and is subsequent converted to an array through a Fortran script. The row containing the *ACRU* input information pertaining to the catchment selected for simulation can be extracted by matching the catchment selected with the catchment name recorded in the first column of the database. This allows for greater flexibility with the naming of the catchments using either alphabetic or numerical identity.

In the previous database structure the seven ASCII files mentioned in Section 6.2 stored the information which pertained to the Quaternary Catchments, and any additional information, e.g. inputs required to carry out a sediment yield analysis that had to be hard-coded into the Fortran program used in creating the *ACRU* input menus. This system is restricting and the problem was addressed when establishing the new database structure. Greater flexibility in adding new *ACRU* input information was achieved by giving each new *ACRU* input variable added to the database, over and above the original input information, a new input name. For example, the standard name for the *ACRU* input name referring to the raingauge used to "drive" the hydrology of a particular catchment is RAINSTA. However, the situation might arise that an improved driver station is found and, therefore, this new raingauge name needs to be recorded in the database as an new option. This updated list of rain gauges could be added to the Input Database under the header of, say, RAINSTA2.

The user can then create another spreadsheet file which contains the list of

- the standard *ACRU* input variable name;
- the additional *ACRU* input variable name; and
- a description of what information is containing under this new heading.

Multiple new options can be added to what is termed the New Options File. This file is also exported as a comma delimited file from the spreadsheet package and converted to an array using a Fortran script. The various additional options available in the database can be selected or deselected depending on the information required for the simulation as is expanded upon in Section 6.8.

The information pertaining to each Quaternary Catchment stored in the ASCII files, as well as the information that had been hard-coded in the original linking program, was imported into the new database structure and this pre-populated database is described in the following section.

6.4 THE PRE-POPULATED QUATERNARY CATCHMENT INPUT DATABASE

The Quaternary Catchment Input Database can be used as input to simulate agrohydrological responses of Quaternary Catchments in southern Africa. As updated information is obtained for each Quaternary Catchment it can be included in the database and become available to users of this Input Database.

6.4.1 Need for Enhancement of the Quaternary Catchment Input Database

The linkage of the *ACRU* Input Database to the *ACRU* model marked a continuation of work on agrohydrological regionalisation previously undertaken by the School of BEEH (e.g. Dent *et al.*, 1989; Schulze and Lynch, 1992; Schulze *et al.*, 1993). However, the operational facilities for simulating the responses from the Quaternary Catchments were limiting, for the following reasons:

- There was no direct facility to easily change the land use attributes of, say, veld in fair hydrological condition to, for example, veld in poor or good condition in a Quaternary Catchment.
- No direct option was available for the simulation of crop yield or irrigation requirement estimations.
- There was no option to perform any extreme value analysis of, say, floods or perform sediment yield analysis.

Each of these limitations is addressed, as described in the following section.

6.4.2 Enhancement of the Quaternary Catchment Input Information

Enhancements to the Quaternary Catchment Input Database included the incorporation of information on different land use options as well as the *ACRU* inputs required to carry out crop yield simulations, irrigation scenarios, sediment yield estimates and extreme value analysis.

6.4.2.1 Land Use Options

Previously all simulations undertaken for climate change studies at a southern Africa scale in the School of Bioresources Engineering and Environmental Hydrology assumed a baseline land cover of veld in fair hydrological condition, as described by Schulze, Kiker and Kunz (1993) and Schulze, Lecler and Hohls (1995). As an additional option it was felt necessary to allow the user to at least be able to specify the land use as being the equivalent of veld in poor or good hydrological condition in addition to veld in fair condition, in order for simple impact studies of grazing management on, say sediment yield, to be undertaken.

This required changes to the monthly values of the water use coefficient, leaf area index, and the coefficient of initial abstraction depending on the condition of the veld specified. The monthly values of the coefficient of initial abstraction have been calculated for typical rainfall intensity characteristics depending on which rainfall seasonality region the Quaternary Catchment falls into. The values for these new parameters were added to the Quaternary Catchment Input Database as options for simulations and are recorded in the New Options File for the Quaternary Catchment Input Database.

An option has been added to *ACRU* to generate the monthly values of the water use coefficient, vegetation interception loss and fraction of roots in the A horizon from minimum temperatures. Alternatively the monthly parameter values set in the database can be used.

6.4.2.2 Crop Yield Options

Information on plant dates, length of growing season and biomass indicators for maize, winter wheat, sugarcane and primary production have been added to the Quaternary Catchment Input Database. The default plant dates and lengths of the growing seasons that are used for the Quaternary Catchments are given in Table 6.1. However, if updated input information is obtained for different regions these can be incorporated into the Input Database for use.

When simulating maize yield in *ACRU*, crop transpiration and soil water evaporation are modelled separately according to the Ritchie (1972) method and the *ACRU* variable EVTR is manually set to 2. The winter wheat model also separates transpiration from soil water evaporation on a daily basis, but this done internally within the routine and variable EVTR is specified as equal to 1. For the sugarcane and primary production options transpiration and evaporation are modelled as a single entity (EVTR = 1). The estimation of maize yield, winter wheat yield, sugarcane yield and primary production is explained in more detail in Schulze, Domleo, Furniss and Lecler (1995).

Table 6.1 Default values of plant dates and lengths of growing season for various crops yields which can be simulated using *ACRU* at a Quaternary Catchment scale

Crop	Plant Date	Length of Growing Season
Maize	15 November	150 days
Sugarcane	1 July	N/A (yields are annualised)
Winter Wheat	15 May	150 days
Primary Production	1 August	N/A (yields are annualised)

An example of a crop yield analysis is provided in Figure 6.2, in which median maize yields under present climatic conditions are shown at Quaternary Catchments level.

6.4.2.3 Irrigation Water Demand Options

ACRU contains routines which can simulate irrigation water requirements for a range of crops under a variety of soil conditions and different modes of applying, i.e. scheduling, the irrigated water, as well as routines for the supply of water from different sources.

When the default irrigation water demand option is selected for Quaternary Catchment comparisons, a number of simplifying assumptions are, however, made for the sake of convenience. First, irrigation demand in *ACRU* is activated for each month of the year (rather than for only selected months) assuming an areal unit of irrigation (e.g. per hectare) within each Quaternary Catchment. The mode of scheduling is specified as demand irrigation, i.e. applying irrigation water to refill the soil profile to the drained upper limit with an unlimited supply of water for irrigation once profile plant available water has been depleted to 50%. The other simplifying assumptions that are made when the irrigation option is selected are given in Table 6.2.

The *ACRU* model's irrigation output options in regard to water requirements are, obviously, water demand on a month-by-month basis *per se*, but also unit stormflow from irrigated fields (for the default inputs) as well as deep percolation from irrigated fields. Figure 6.3 illustrates, at Quaternary Catchment scale, spatial differences in annual deep percolation from irrigated lands, using the default values given in Table 6.2.

6.4.2.4 Sediment Yield Analysis

Soil erosion is a serious problem in southern Africa (Lorentz and Schulze, 1995). Rooseboom (1992) estimated that the average annual sediment yield in southern Africa varies between 30 and 330 $t.km^2$. To date a simple method has not been found to estimate sediment yield from a catchment. Complex deterministic models are available to estimate erosion processes and sediment transport, however, these models are limited in their application owing to their reliance on calibration.

The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), is an equation which has received recognition as an empirical method useful for initial planning and design purposes. This method is the foundation for other empirical equations which can be applied at a catchment scale to estimate sediment yield, such as the daily stormflow event based Modified Universal Soil Loss

Equation, MUSLE (Williams, 1975), which has been widely verified world-wide and also in South Africa (Kienzle *et al.*, 1997).

Sediment yield at any Quaternary Catchment outlet may be estimated in *ACRU* using the MUSLE, expressed as

$$Y_{sd} = \alpha_{sy}(Q_v x q_p)^{\beta_{sy}} KxLSxCxP$$

where
Y_{sd} = sediment yield from an individual stormflow event (t)
Q_v = stormflow volume for the event (m^3)
q_p = peak discharge for the event ($m^3.s^{-1}$)
K = soil erodibility factor ($t.h.N^{-1}.ha^{-1}$)
LS = slope length and gradient factor (-)
C = cover and management factor (-)
P = support practice factor (-).

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones. However, default values in *ACRU* set at 8.934 for α_{sy} and 0.56 for β_{sy} were assumed in this study.

At a Quaternary Catchment scale for southern Africa sediment yield can now be estimated for veld being either in good, fair or poor hydrological condition. A cover factor is required for the calculation of the MUSLE and the default values were obtained from the *ACRU* User Manual (Smithers and Schulze, 1995), depending on the veld type, as shown in Table 6.3. The same default cover factor is used in all months of the year.

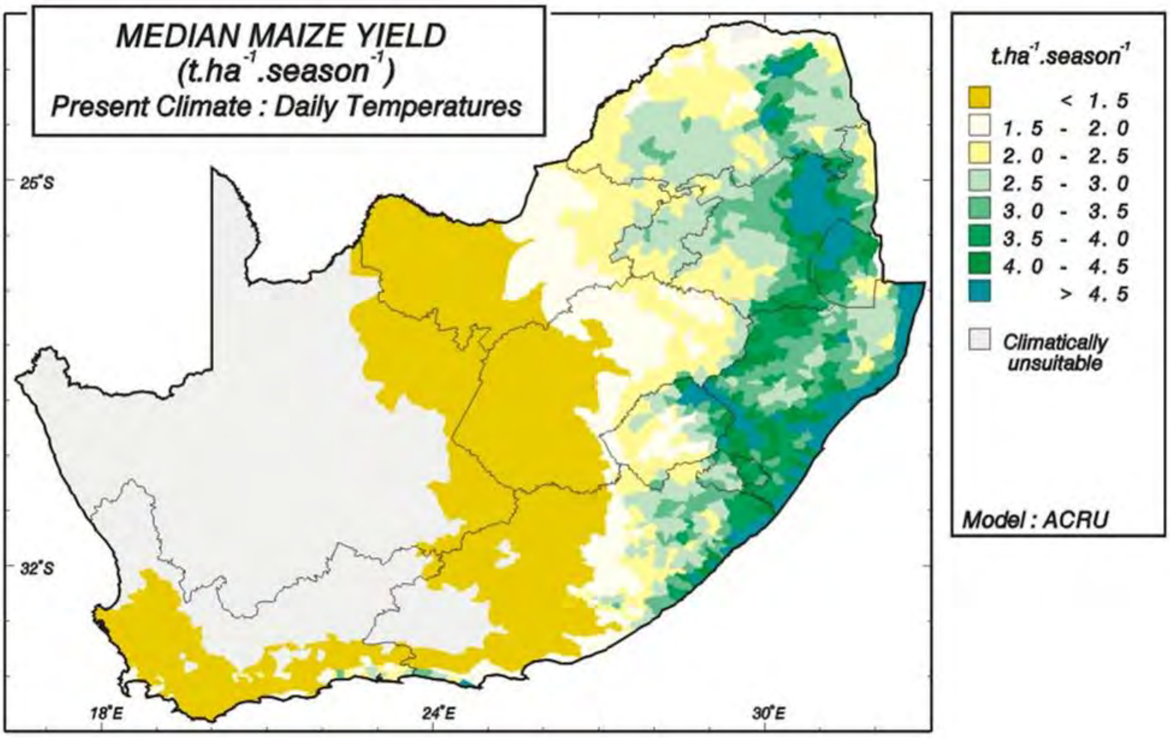


Figure 6.2 Simulated median maize yields ($t.ha^{-1}.season^{-1}$) per Quaternary Catchment for present climatic conditions

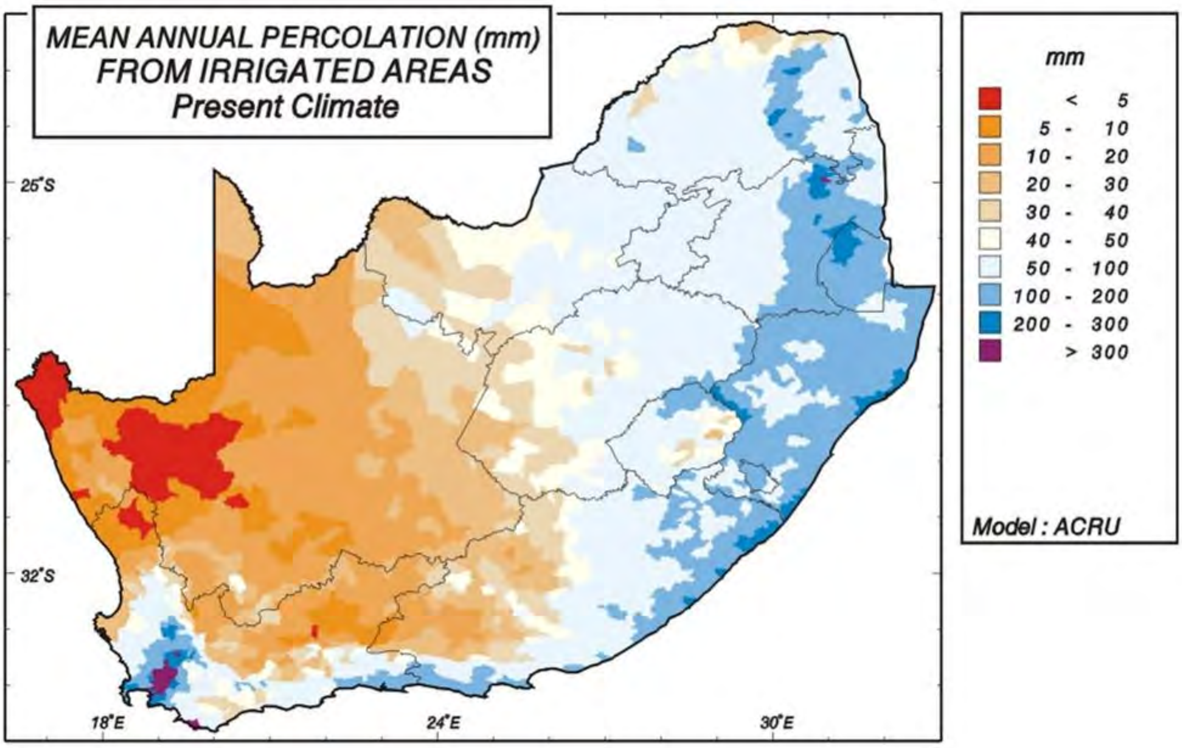


Figure 6.3 Simulated mean annual percolation (mm) per Quaternary Catchment per areal unit of irrigation, for present climatic conditions

Table 6.2 Inputs used in *ACRU* for default irrigation option

ACRU Input	Assumption for Irrigation
Monthly value of the coefficient for initial abstraction for the irrigated area	0.3
Texture of soil in the irrigated area	Sandy clay loam
Soil water content at lower limit for the soil being irrigated	0.160 $m.m^{-1}$
Soil water content at the drained upper limit for the soil being irrigated	0.260 $m.m^{-1}$
Soil water content at saturation (i.e. porosity) for the soil being irrigated	0.440 $m.m^{-1}$
Water use coefficient for each month of the year	0.8
Interception loss for the crop under irrigation	1.5 $mm.irrigation^{-1}$ or $mm.rainday^{-1}$
Potential rooting depth of the irrigated crop under the prevailing conditions	0.8 m
Soil depth to which the majority of soil water extraction takes place for a fully grown irrigated crop	0.8 m
Water use coefficient of the irrigated crop when the rooting depth reaches a maximum	0.8
Water use coefficient of the irrigated crop at which ground cover is a maximum	0.8
Maximum amount of ground covered by the irrigated crop	100 %
Critical leaf water potential of the irrigated crop	-1000 kPa
Fraction of plant available water at which irrigation water is applied	0.5
Conveyance losses, i.e. the fraction of the irrigated water that is lost in conveying it from the source to the application point.	0.1
Spray evaporation and wind drift losses	0.1

Table 6.3 Default cover factor and runoff curve numbers used in the determination of sediment yield at Quaternary Catchment scale, depending on the veld type selected

Hydrological Condition of the Veld	Cover Factor	Curve Number
Veld in poor hydrological condition	0.17	83
Veld in fair hydrological condition	0.07	75
Veld in good hydrological condition	0.02	68

When the sediment yield option is selected, then the peak discharge for each Quaternary Catchment needs to be simulated for each stormflow event. For these simulations the SCS peak discharge as equation modified by Schulze and Schmidt (1995) is used, in which

$$q_p = 0.2083QA/1.83\ L$$

where q_p = peak discharge ($m^3.s^{-1}$)
Q = stormflow depth (mm)
A = catchment area (km^2)
L = catchment lag (response) time (h)
= $H_l^{0.8} (S' + 25.4)^{0.7} / 7069S_{\%}^{0.5}$

with	H_l	=	hydraulic length (m) of the main channel of the catchment
	S'	=	catchment retardance factor
		=	25400 / CN_{II} - 254
	$S_{\%}$	=	average catchment slope (%)
	CN_{II}	=	Runoff Curve Number unadjusted for catchment antecedent wetness.

Information needed for each Quaternary Catchment thus includes

- the mean catchment slope, $S_{\%}$, which was obtained from the previously established database (Meier, 1997) using a one minute by one minute of a degree latitude / longitude (1' x 1') digital elevation model;
- the hydraulic length, H_l (m), of the main channel was estimated from a SCS derived default equation given in the *ACRU* User Manual (Smithers and Schulze, 1995) and using catchment area (km^2), such that

$$H_l \text{ (m)} = 1738 \times A^{0.6}$$

  and

- the SCS Runoff Curve Number, CN_{II} , unadjusted for antecedent soil moisture conditions of the catchment. The Curve Number is given for various land / use treatment classes, hydrological soil groups and stormflow potentials by the SCS and the *ACRU* User Manual (Smithers and Schulze, 1995). The default CN_{II} values selected for the various veld types are given in Table 6.3.

An output of sediment yield at Quaternary Catchments level, using the equations and default assumptions described above, is given in Figure 6.4.

6.4.2.5 Extreme Value Analysis

Predicting the expected magnitude of a rainfall and flood amount at a given recurrence interval is an important component of hydrological planning and design (Schulze, Lynch, Smithers, Pike and Schmidt, 1995). When undertaking simulations at a Quaternary Catchment scale using the *ACRU* model, extreme value analyses can be performed on the following variables, *viz*.

- observed daily rainfall depth (mm);
- observed streamflow depth (mm);
- simulated streamflow depth (mm);
- observed peak discharge (m^3.s^{-1}); and
- simulated peak discharge (m^3.s^{-1}).

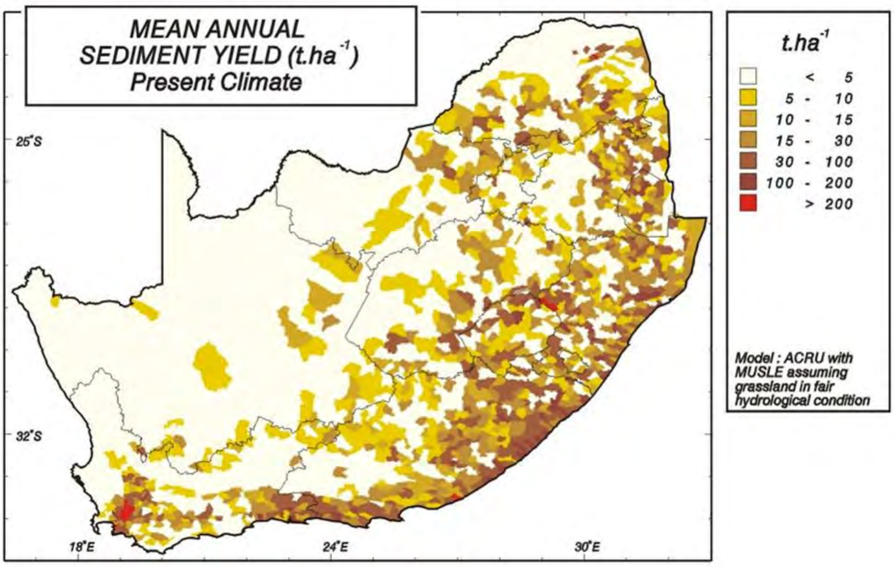


Figure 6.4 Simulated mean annual sediment yield (t.ha^{-1}) per Quaternary Catchment assuming grassveld in fair hydrological condition, for present climatic conditions

However, as observed streamflow and peak discharge information are not available in the present Quaternary Catchment Input Database, whenever the option to perform an extreme value analysis is selected it is for the Annual Maximum Series of either

- daily rainfall (mm);
- daily simulated streamflow depth (mm); or
- daily simulated peak discharge ($m^3.s^{-1}$

The Annual Maximum Series takes the largest event from each '*n*' years of record and the extreme values are calculated for either one, or all, of the Gumbel, Log-Normal and Log-Pearson Type III extreme value distributions using this sample of *n* values, which represent the design magnitude in the *n* year record.

The information pertaining to these additional options has been added to the Quaternary Catchment Input Database and can be selected via the New Options File for use in an *ACRU* simulation of selected Quaternary Catchments.

6.5 INCORPORATION OF FUTURE CLIMATE SCENARIOS AND DAILY TEMPERATURES

Previously there was no facility available in *ACRU* to perform simulations directly at the Quaternary Catchment or smaller scale using future projected temperature and precipitation changes as simulated by large scale atmospheric models (GCMs). Monthly output for 2 x CO_2 equivalent scenarios from five GCMs, *viz*.

- UKTR (1995), excluding sulphate forcing (UKTR-S);
- HadCM2 (1998), excluding sulphate forcing (HadCM2-S);
- HadCM2 (1998), including sulphate forcing (HadCM2+S);
- CSM (1998), excluding sulphate forcing; and
- Genesis (1998), excluding sulphate forcing

can be used in simulations of potential future climate conditions using this system. Detail on background and preparation of the output from the five GCMs can be obtained in Perks *et al.* (2000). When performing an *ACRU* simulation with the assumption of future climatic conditions, one of the five GCM climate perturbations available must be chosen as the future climate scenario.

The methodology of including future scenario values of precipitation and temperature in an *ACRU* simulation is described in Sections 6.5.1 and 6.5.2. The options of performing a sensitivity or threshold analysis have also been included and the methodology used to perform these studies is presented in Section 6.5.3. In addition, the option of using daily values of maximum and minimum temperatures instead of monthly means of daily temperature inputs for the present climate scenario has also been included as an option for use with the *ACRU* Input Database in conjunction with the *ACRU* model, as explained in Section 6.5.4.

6.5.1 Incorporation of Monthly Future Precipitation Estimates

Rainfall data from the daily rainfall station selected as the driver station for each catchment are frequently not representative of the rainfall of the catchment in question because of some systematic error (e.g. station located on the watershed, or in a valley). This necessitates an adjustment to be applied to the rainfall (Smithers and Schulze, 1995). Therefore, in *ACRU* a precipitation adjustment factor can be specified when adjusting rainfall from a point estimate to that representing the catchment scale and is calculated for the *i*-th month as

$$\text{precipitation adjustment factor } i = \frac{\text{catchment rainfall } i}{\text{station rainfall } i} .$$

The catchment rainfall for a given month is usually calculated using the *ZONALSTATS* command in ARC/INFO and is obtained by finding the average rainfall for the catchment from the 1' x 1' of a degree latitude / longitude grid of median monthly and mean annual rainfalls developed for South Africa, Lesotho and Swaziland by Dent *et al.* (1989). Therefore, the rainfall on any day is multiplied by the precipitation correction factor to obtain a representation of the catchment rainfall for that day.

In order to perturb the present day daily values to reflect future estimates of precipitation given by the GCMs the precipitation correction factor has to be adjusted again. It is necessary to extract the ratio change in precipitation (future / present climate) for each month as simulated by the GCM selected. To achieve this, each quarter of a degree latitude / longitude (¼˚) grid of monthly change in precipitation for each GCM was converted to an ASCII file using the *GRIDASCII* command in ARC/INFO.

Using a Fortran program written by Kiker (1999, pers. com) and modified for use in this study, the ratio change in precipitation for the GCM selected for each month of the year is extracted from the 12 ASCII files using the centroid of each catchment. In the example shown in Figure 6.5 the ratio change in precipitation extracted for this catchment would be 1.2 (i.e. a 20% increase in precipitation is simulated by the GCM).

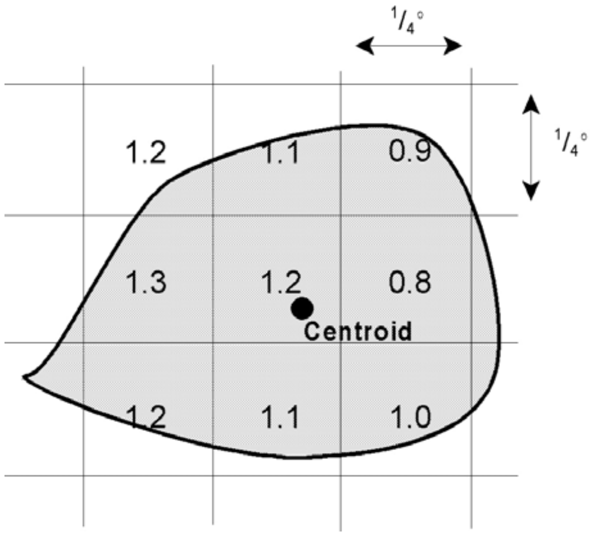


Figure 6.5 A schematic example of the use of the centroid of a catchment to isolate the ratio change in precipitation from an ASCII file representing the quarter of a degree grid for a GCM for a particular month

Thus, the adjustment factor for each month (*i*) for future precipitation is calculated as

future precipitation adjustment factor *i* = (present precipitation adjustment factor *i*) x (ratio change in precipitation *i*).

The future precipitation adjustment factor is then input into the *ACRU* input menu to replace the present precipitation adjustment factor when simulating hydrological responses under a future climate. In this way both the catchment adjustment from the point to areal rainfall estimate, and the change in precipitation resulting from climate change, are taken into account in a single step.

6.5.2 Incorporation of Monthly Future Temperature Estimates

Estimates of monthly temperatures for a future climate scenario are calculated using the difference in temperature between the future and present estimates of temperature provided by the GCMs in conjunction with baseline monthly temperatures. The differences in temperature at the centroid of each catchment for each month of the year are extracted from ASCII files of the gridded temperature changes using the procedure described in Section 6.5.1 above.

All five GCMs predict an increase in temperature with climate change. Thus, future temperature for each month of the year (*i*) to be input into the *ACRU* input menu when assuming a future climate scenario is calculated as future temperature *i* = (present temperature *I*, from the baseline database) + (difference in temperature *i* from GCM).

The UKTR-S and HadCM2 GCMs output simulated changes of both maximum and minimum temperature. However, only simulated changes in mean temperatures were available from the CSM (1998) and Genesis (1998) GCMs. As maximum and minimum temperature inputs are required in *ACRU*, it is assumed for these two GCMs that the same difference between future and present mean temperatures could be applied to both maximum and minimum temperature.

6.5.3 Performing a Threshold Analysis

Figure 6.6 illustrates the methodology used for threshold analyses of climate change on hydrological responses and crop yield in southern Africa.

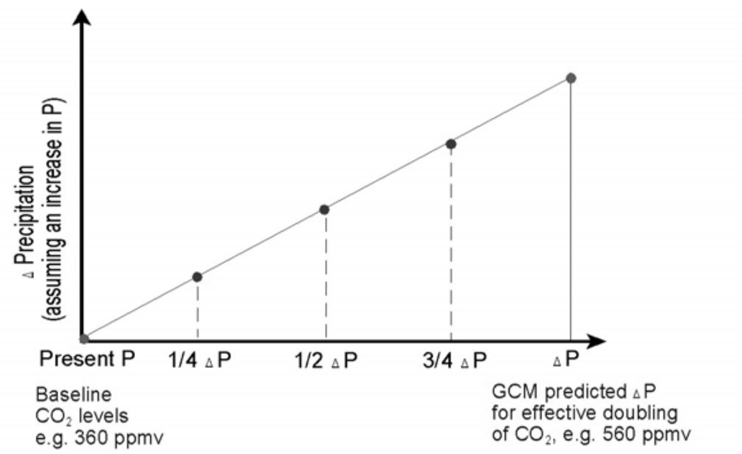


Figure 6.6 Methodology used for a threshold analysis, using precipitation (P) as an example

A threshold analyses for any agrohydrological output from *ACRU* can be performed using the predicted changes in precipitation and temperature from a selected GCM. Five simulations need to be carried out using

- present precipitation and temperature;
- ¼ change in GCM predicted precipitation, temperature and CO_2;
- ½ change in GCM predicted precipitation temperature and CO_2;
- ¾ change in GCM predicted precipitation temperature and CO_2; and
- GCM future precipitation, temperature and CO_2 as climatic input.

In the case of $^1/_4$ change in GCM predicted climate, when subscripts 'p' and 'f' denote present and future (2X CO_2) climates, then

¼ ΔP	=	$[¼ (P_f / P_p - 1) +1] \times P_p$ for each month of the year
¼ ΔT	=	$[¼ (T_f - T_p)] + T_p$ for each month of the year
¼ ΔCO_2	=	¼ of 15% transpiration suppression in *ACRU* for C3 plants
	=	¼ of 22% transpiration suppression in *ACRU* for C4 plants.

In the case of the other fractional changes in GCM predicted variables, the $^1/_4$ in the above equations was substituted by½, ¾ and 1 respectively.

Not all plants respond equally to an increase in CO_2 concentrations. Most tree and grass species follow a C3 photosynthetic pathway and show a significant increase in their photosynthetic rate from an increase in CO_2 concentrations. C3 plants constitute 95% of the world's plants, including wheat, rice, soybean and most horticultural crops. Some plants, *viz*. those with a C4 photosynthetic pathway, while constituting only a small percentage of the world's plants do, however, include important agricultural crop species such as maize, millet, sorghum, sugarcane and most weed species. In these plants the effect of enhanced CO_2 concentrations on photosynthesis is not as marked as in their C3 counterparts (Rosenzweig and Hillel, 1998).

If estimated dates are assigned to the $^{1}/_{4}$, $^{1}/_{2}$, $^{3}/_{4}$ and 1X change simulations points (marked as dots in Figure 6.6), maps can be created showing when, in future, a critical change in response of a variable might occur; or alternatively, what the anticipated magnitude of change of a hydrological response would be by a certain year. Figure 6.7 illustrates the concept of a threshold analysis spatially, showing that for a given climate change scenario a 10% change in mean annual runoff could occur in the western third of South Africa by 2015 already.

6.5.4 Performing Sensitivity Analyses

In the case of the sensitivity studies the options are to perform a sensitivity analysis of changes in temperature, precipitation and CO_2. The monthly temperatures input for a catchment can be increased by 1.5, 2.0, 2.5, 3.0 or 3.5 °C to assess the sensitivity of hydrological response to a change in temperature. In the case of precipitation, the precipitation correction factor can be increased or decreased by 10 or 20%. To perform a sensitivity analysis of CO_2, the CO_2 transpiration suppression option in *ACRU* can be included or excluded from the simulation.

6.5.5 Incorporation of Daily Maximum and Minimum Temperatures in Simulations

The centroid latitude, longitude and mean elevation can be extracted from the *ACRU* Input Database for a particular catchment and used to generate daily maximum and minimum temperatures following the procedure described in Section 2.4 of Perks *et al.* (2000). This method of deriving daily temperatures can be applied to any catchment where the aforementioned parameters are available. If daily temperatures are required, then a composite file is created containing the daily rainfall and temperatures for each catchment selected for the period of simulation.

If a future climate scenario simulation is selected and the option of daily temperatures is required, then the daily temperature values for the month are increased by the monthly GCM predicted change in precipitation for every day of the month.

6.6 SELECTIONS OF CATCHMENTS FROM THE QUATERNARY CATCHMENT INPUT DATABASE

Using the *ACRU* model, the hydrological responses of catchments can be generated either with the catchments operating as

- individual (i.e. non-linked) catchments, which is suited for determining where, within a region, streamflow is actually generated (Section 6.7); or as
- cascading (i.e. hydrologically connected, linked) catchments, used to determine cumulative flows down a river system, and hence the total available water at any point within a large catchment (Section 6.8).

Previously the user of the interface could only simulate the hydrology of all the Quaternary Catchments in southern Africa as individual entities and was not able to isolate a cluster of Quaternary Catchments to model them as individual lumped or as cascading interlinked Quaternary Catchments.

The facility has now been incorporated whereby the user can select to model hydrological responses from a group of Quaternary Catchments which can be delimited by

- drainage region (any Primary, Secondary, Tertiary or Quaternary Catchment within southern Africa);
- a user specified list of Quaternary Catchments;
- a large catchment in southern Africa; or
- a Water Management Area.

These options are described in the sections which follow.

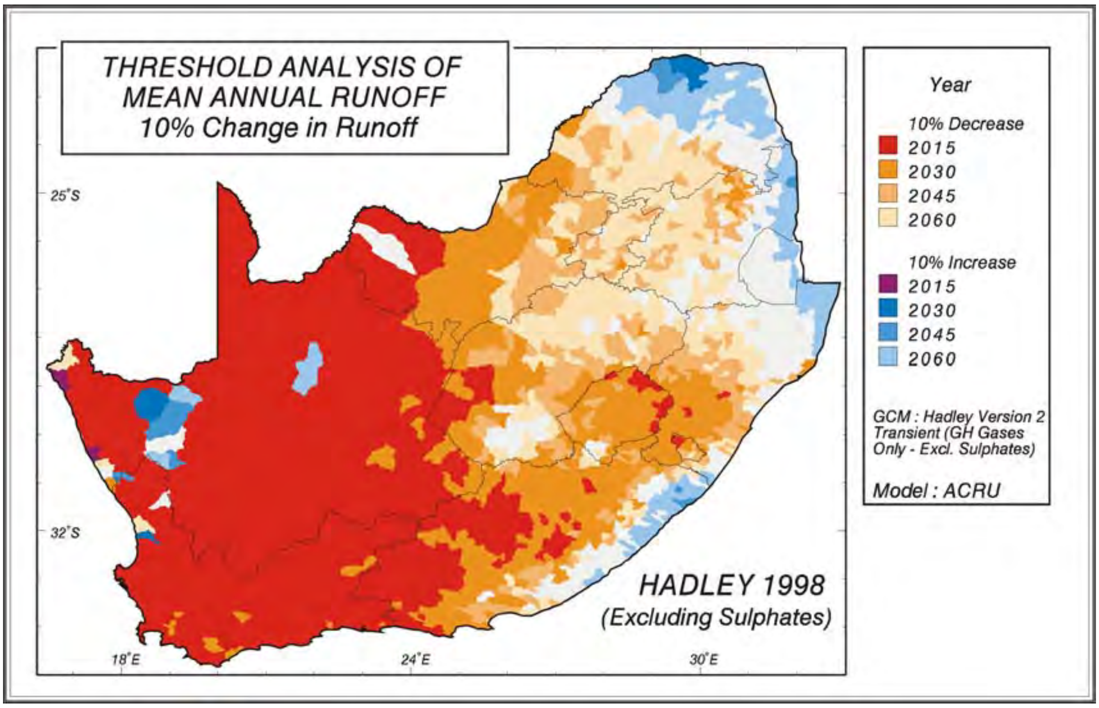


Figure 6.7 Example of a threshold analysis of change in mean annual runoff over South Africa

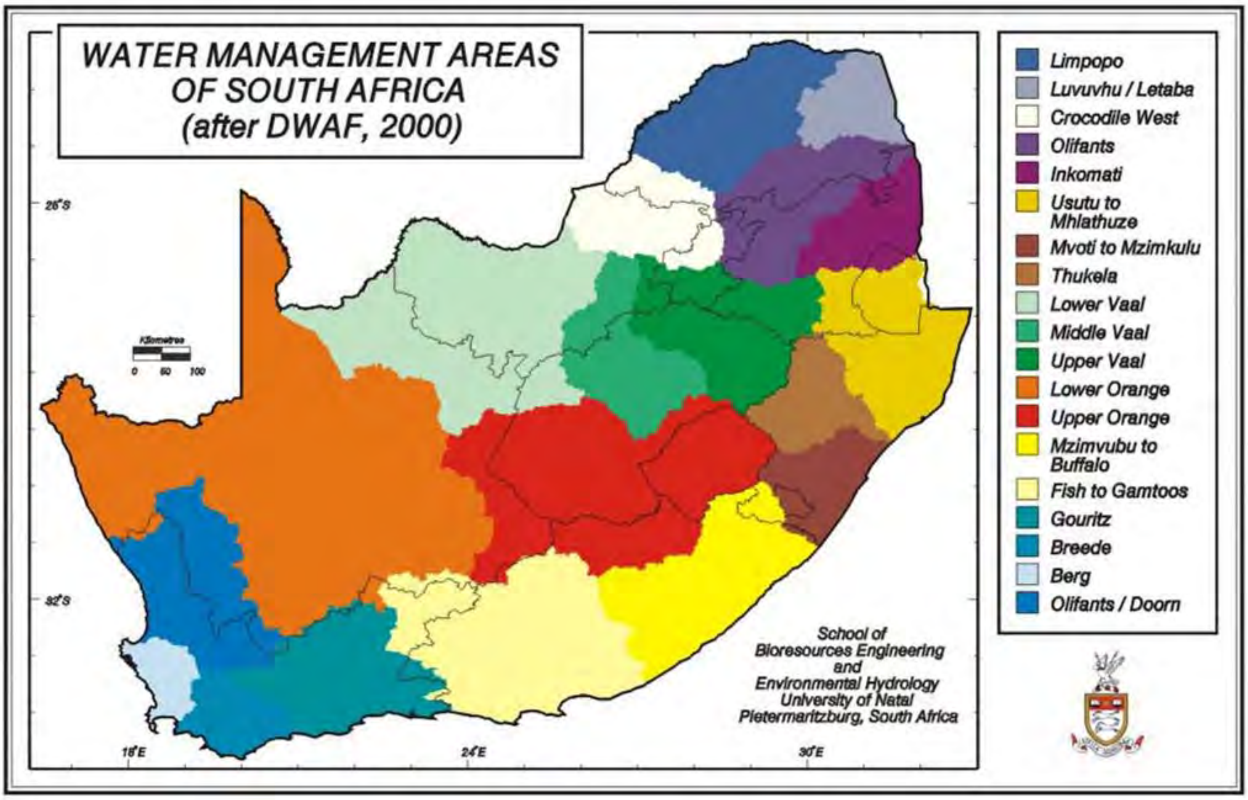


Figure 6.8 The Water Management Areas of South Africa (after DWAF, 2000)

6.6.1 Delineation of Southern Africa into Drainage Regions

If, for example, the Primary Catchment "A" is selected then, using a Fortran script, all the Quaternary Catchments that start with the letter "A" are isolated in an ASCII file and the number of Quaternary Catchments in the selected Primary Catchment written to the screen. Each Quaternary Catchment in that Primary Catchment can then be modelled as an individual, lumped catchment using *ACRU*. The same procedure applies for Secondary and Tertiary Catchments, using the first two and first three characters respectively of the Quaternary Catchment numbering system. In addition, a Quaternary Catchment or a cluster of Quaternary Catchments can be selected, based on the numerical identities assigned to them. The option remains to select all the Quaternary Catchments in southern Africa for simulation.

6.6.2 A User Defined List of Quaternary Catchments

The situation may arise where a selection of Quaternary Catchments is required for simulation, however, they may be situated in scattered locations across southern Africa. In this instance, the user can enter the name of a pre-prepared list of the catchments required.

6.6.3 Option of Selecting a Large Catchment in Southern Africa

Files containing lists of the Quaternary Catchments which fall into large catchments in southern Africa were created to allow the following entire catchments to be selected for simulation using *ACRU*:

- Black Mbuluzi
- Breede
- Buffalo
- Caledon
- Crocodile
- Gouritz
- Kei
- Limpopo
- Mfolozi
- Mgeni
- Mhlatuze
- Mkomazi
- Mkuze
- Mvoti
- Mzimkulu
- Mzimvubu
- Olifants (Mpumal)
- Orange
- Pongola
- Sabie
- Sand
- Sundays
- Swartkops
- Thukela
- Vaal

This eliminates the need for the user to know which Quaternary Catchments fall into the large catchment of interest as the names of these catchments are stored and automatically extracted.

6.6.4 Option of Selecting a Water Management Area in Southern Africa

South Africa has been divided into 19 Water Management Areas (WMAs), as shown in Figure 6.8. Similar ASCII files as those described in Section 6.6.3 were created for each WMA. In future each WMA is to be operated by a Catchment Management Agency (CMA) in accordance with the new National Water Act (NWA, 1998).

The option of individually simulating the hydrology of the Quaternary Catchments that are located in each Water Management Agency is therefore available for decisions to be made by the future CMAs.

6.7 SIMULATION OF AGROHYDROLOGICAL RESPONSES OF INDIVIDUAL CATCHMENTS

The simplified flow chart in Figure 6.9 illustrates the steps taken to enable automated generation of *ACRU* input menus using the *ACRU* Input Database. Firstly, the name of the database being used must be specified, as shown in Figure 6.9. Any new input options that are required must be selected from the New Options File. Options of the hydrological condition of the veld, crops planted or irrigation being applied can be activated for use from the Quaternary Catchment Input Database, for example. These options are not shown in the flow chart. In addition, the options of performing a sediment yield analysis (not shown in flow chart) and/or an extreme value analysis could be selected (*cf*. Section 6.4).

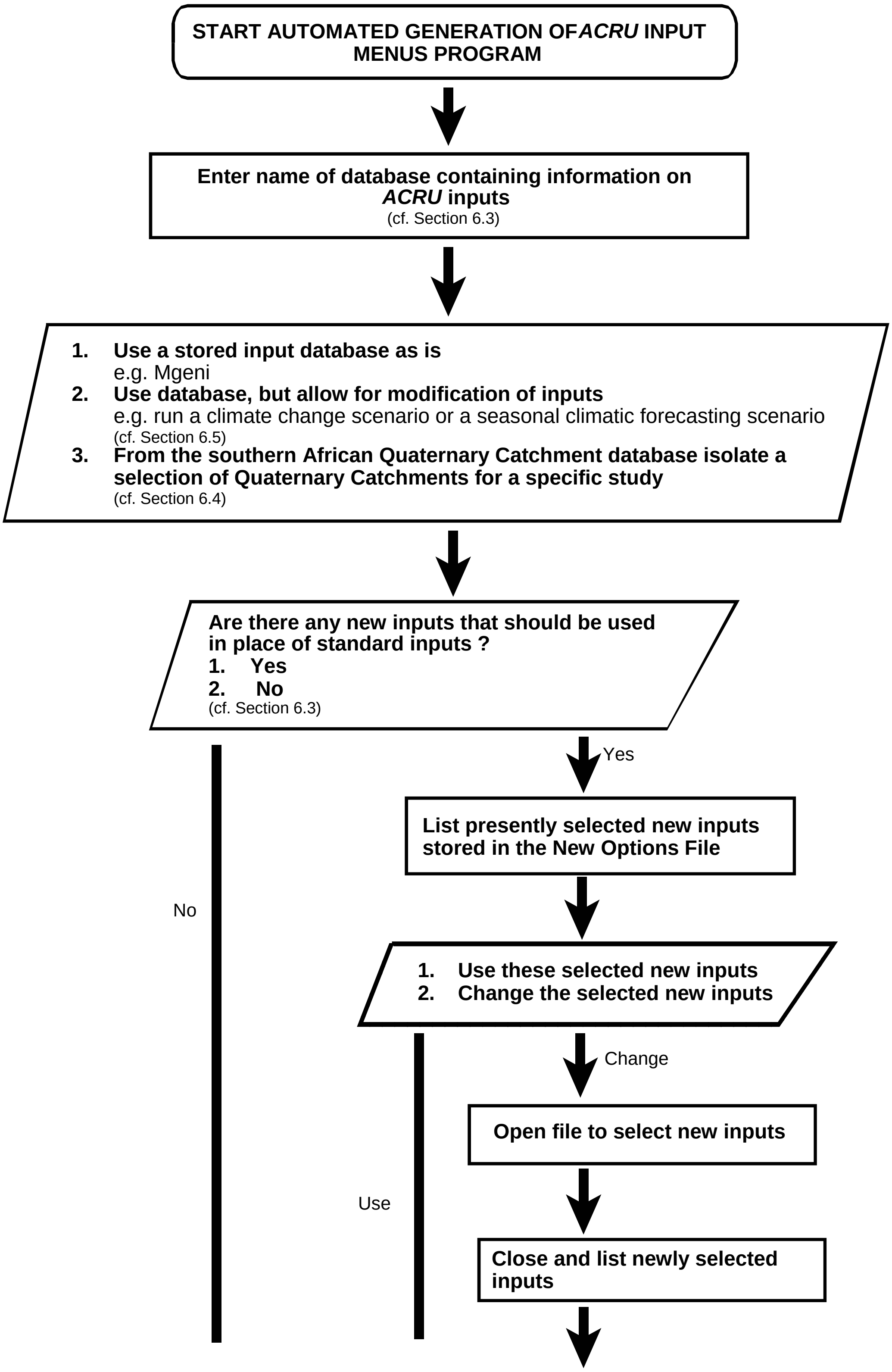


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

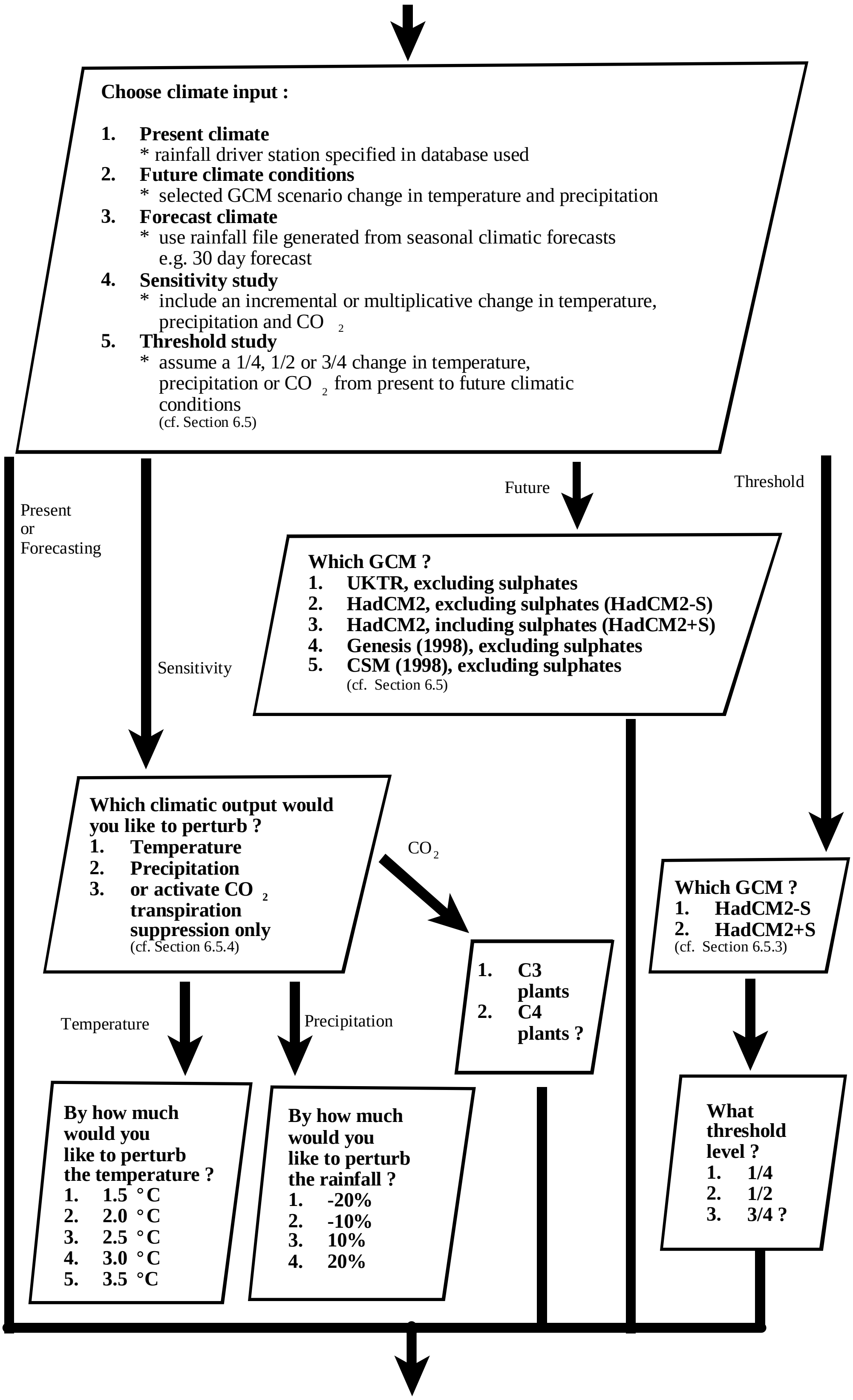


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

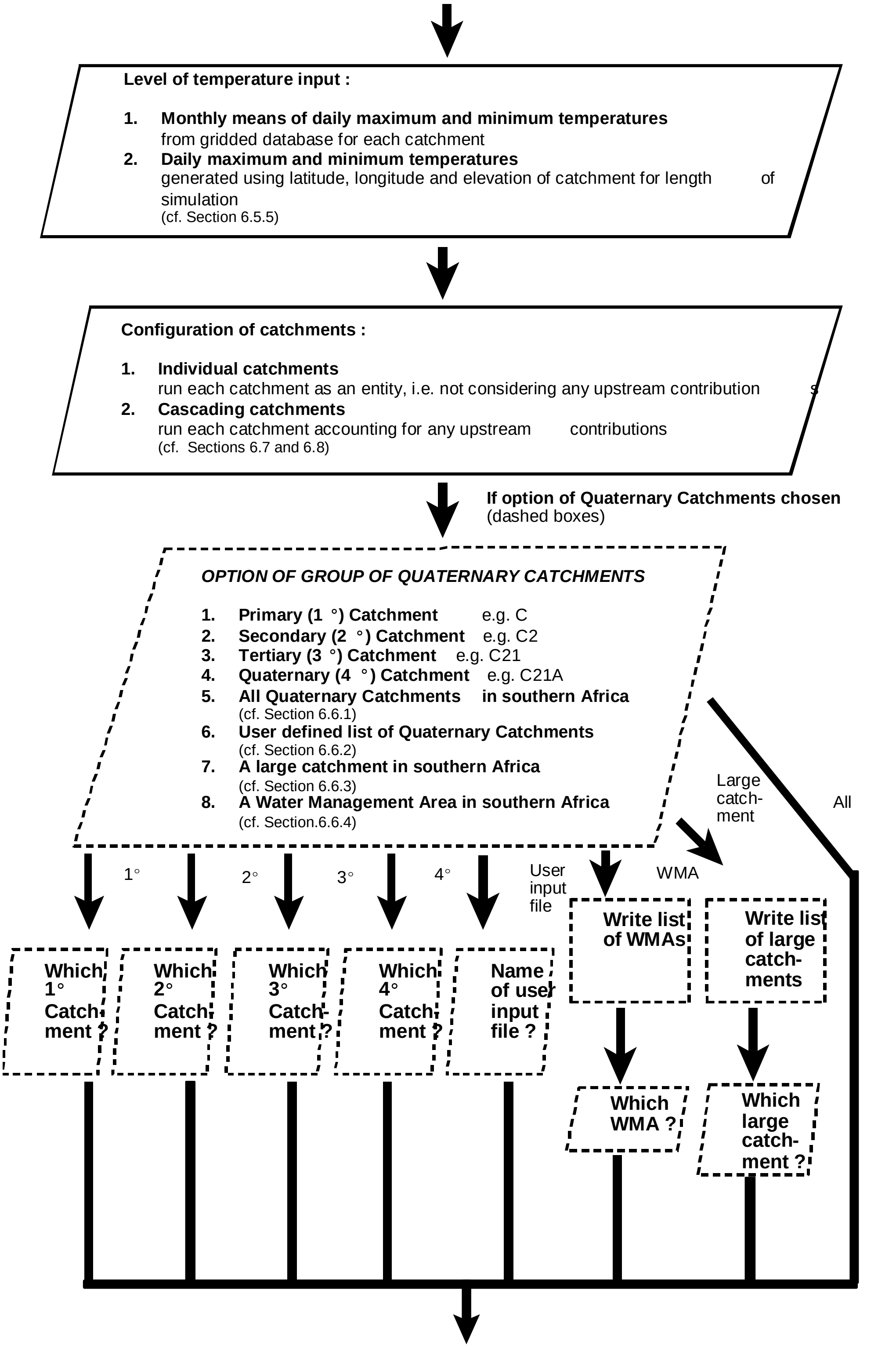


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

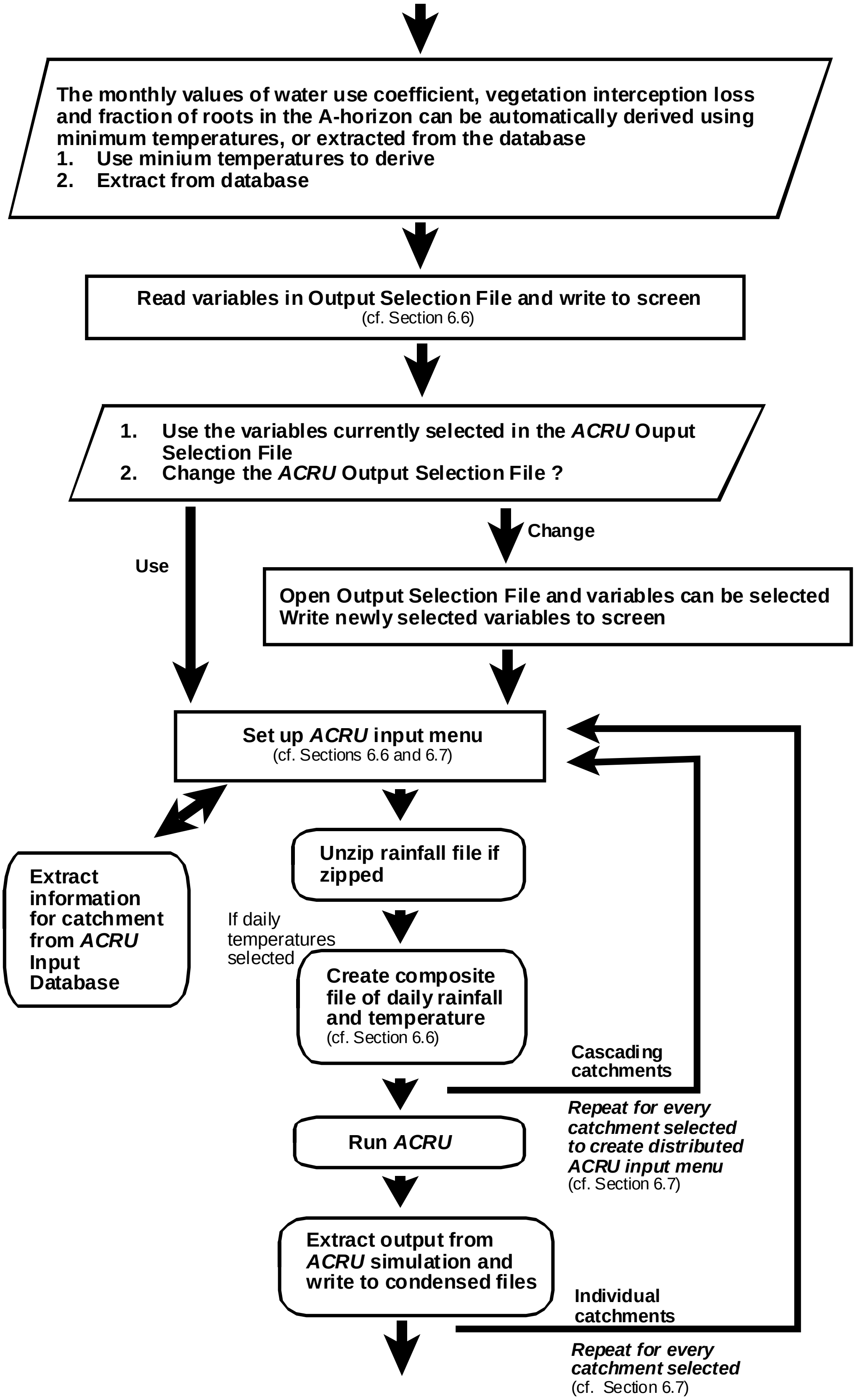


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

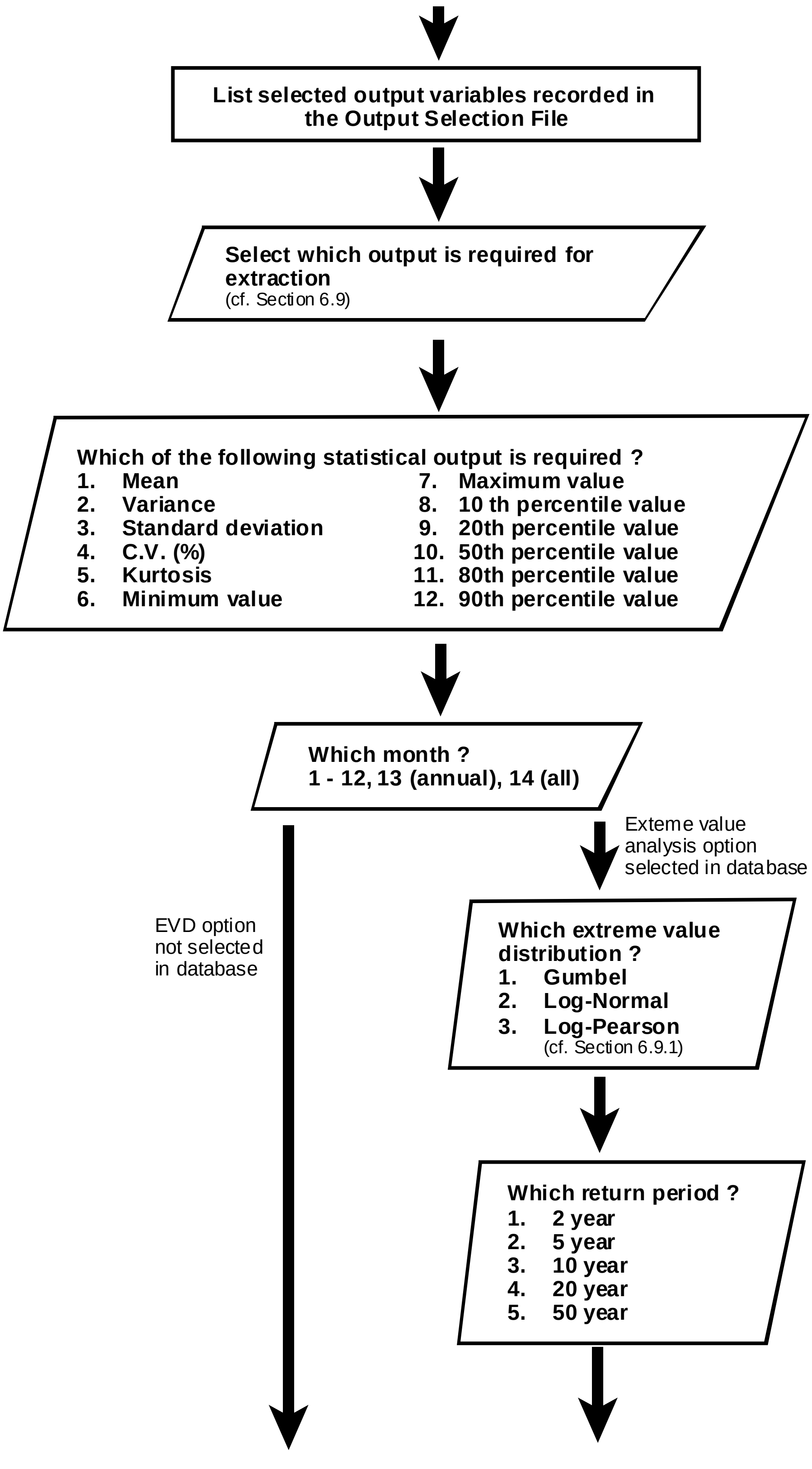


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

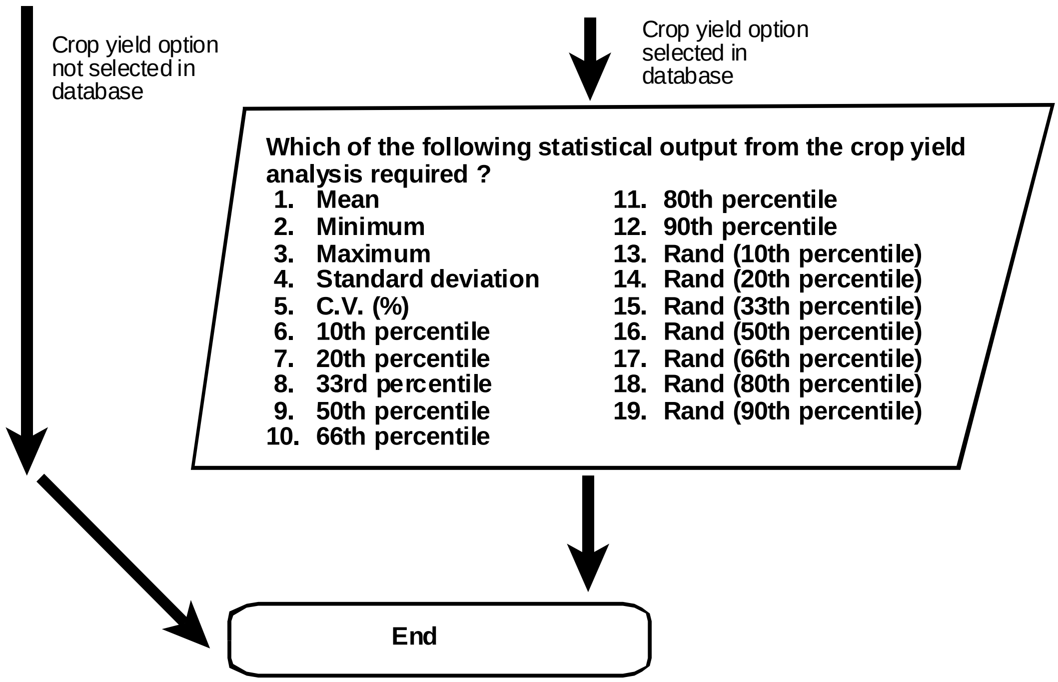


Figure 6.9 Refinements to the linking of the *ACRU* Input Database to the *ACRU* model and GIS

The climate input to be used must also be specified. Agrohydrological responses can then be simulated using *ACRU* for

- present climatic conditions;
- perturbed future climatic conditions, using estimates of temperature and rainfall from the selected GCM for a 2X CO_2 equivalent climate scenario (*cf*. Sections 6.5.1 and 6.5.2);
- a sensitivity analysis where the temperature or precipitation output can be perturbed and with the option to activate CO_2 transpiration suppression only (*cf*. Section 6.5.3); or
- a threshold analysis for different threshold levels (*cf*. Section 6.5.3).

A choice must be made as to whether daily or monthly temperatures are to be used (*cf*. Figure 6.9). If daily temperatures are selected then these temperatures are generated using the methodology described in Section 6.5.4 for the period of simulation.

Next, the catchments required for simulation must be identified. If the Quaternary Catchment Input Database is being used, then the Quaternary Catchments can be selected by choosing a drainage region, a large catchment or a Water Management Area in southern Africa (*cf*. Section 6.6). All the Quaternary Catchments that fall into the selected group will automatically be isolated and the list written to an ASCII file. If the Input Database being used is not the Quaternary Catchment Input Database then an ASCII file needs to be created with a list of the catchments required for simulation.

There is the option for generating the monthly values of the water use coefficient, vegetation interception loss and fraction of roots in the A horizon from minimum temperatures, alternatively the monthly parameter values set in the database can be used.

Various output from an *ACRU* simulation can be stored for analysis, e.g. rainfall, simulated runoff or stormflow. The various options available are listed in the *ACRU* Output Selection File and can be identified depending on the output required (*cf*. Figure 6.9). For each output option selected from this list a file containing monthly and annual statistical information can be derived upon completion of the *ACRU* simulation for each catchment selected via a separate executable program available with the *ACRU* model. Details on the extraction of the statistical output for presentation in a GIS are given in Section 6.9.1.

An *ACRU* input menu is automatically created for each catchment selected containing information (e.g. climate, soils, land cover) pertaining to that catchment, as extracted from the *ACRU* Input Database using a Fortran script. The file containing the daily rainfall information for the simulation period is unzipped in the case of Quaternary Catchments (*cf*. Figure 6.9) using a Fortran program established by Meier (1997). If the option of using daily temperatures was selected, then composite files are created containing the daily rainfall and temperatures for each catchment selected for simulation.

In climate change impact studies reference potential evaporation for both present and future climate simulations is calculated using the Linacre (1991) equation, which is given in Schulze and Kunz (1995).

In this equation potential evaporation is derived using the principles of the physically based Penman (1948) equation, yet it uses only maximum and minimum temperatures (to estimate solar radiation and vapour pressure deficit), together with latitude (to modulate the radiation component for day length) and altitude (which influences the psychometric constant, net radiation and vapour pressure).

The *ACRU* input menu established for each catchment is used for a individual *ACRU* simulation for each catchment required. The selected output from *ACRU* is written to files which are later used for extraction of the required output for display purposes as explained in Section 6.9.

6.8 SIMULATION OF AGROHYDROLOGICAL RESPONSES OF CASCADING CATCHMENTS

Initially, in the School of BEEH, climate change and other impact assessments of water resources had been made using *ACRU* with Quaternary Catchments modelled as individual, catchments which were unconnected hydrologically to other downstream Quaternary Catchments (e.g. Kunz, 1993; Lowe, 1997). In reality, both Quaternary Catchments and Quinary Catchments are, however, hydrologically linked and simulated streamflows should be cascaded from one catchment to the next one downstream, using flow routing procedures available in *ACRU*.

6.8.1 Need to Link Catchments

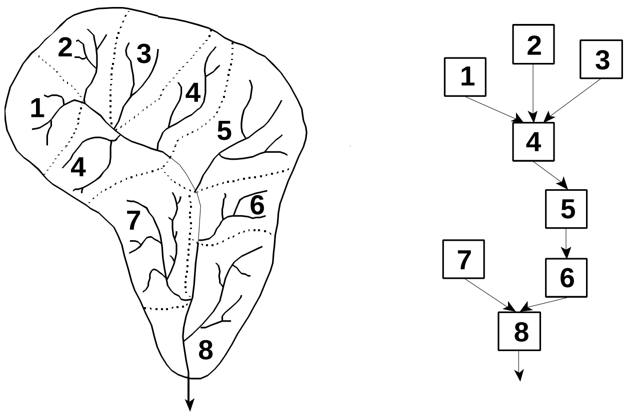
This cascading option in *ACRU* is useful to determine cumulative flows and total available water under different climate or land use scenarios. This option of simulating a cluster of catchments, such that the streamflow from one catchment flows to its immediate downstream catchment, is modelled in *distributed* mode in *ACRU* as opposed to each catchment being modelled individually, termed *lumped* mode. The procedure of linking catchments to determine accumulative flows is described below.

6.8.2 Procedure of Linking Catchments

When modelling catchments in distributed mode in *ACRU* the total number of subcatchments making up the entire catchment needs to be known and used as input into the *ACRU* menu. In addition, each subcatchment has to be assigned an unique numerical identifier, with the number assigned increasing as the catchments cascades downstream, in such a way that a catchment with a smaller numerical identifier always flows into a catchment with a larger numerical identifier. This ordering, or configuration, of the subcatchments is entered into the *ACRU* input menu. Figure 6.10 illustrates how a catchment might be delineated and each subcatchment assigned a numerical identifier. Subcatchment 8 in the figure would be the exiting subcatchment and if only Catchments 1 through 4 are required for simulation, then Catchment 4 would be the end catchment in the simulation.

To enable the modelling of streamflow from catchments to determine cumulative flows for a selected area, an ASCII file needs to be created listing all the catchments on the left-hand side with their respective downstream catchment listed on the right-hand side. This file is termed the Catchment Ordering File. If a catchment flows into the ocean or another country, for example Mozambique, then that is noted on the right-hand side instead of the catchment name. An example of the format of writing the sequence of the cascading Quaternary Catchments is given in Table 6.4.

In the case of the Quaternary Catchments, this Catchment Ordering File has been created and is automatically accessed if the option of using the Quaternary Catchment Input Database for cascading catchments is selected.



(a) Subcatchment delineation (b) *ACRU* Configuration

Figure 6.10 An example of (a) the delineation of a catchment into subcatchments and (b) the configuration of the catchment for distributed mode simulation in *ACRU* (after Schulze, Angus, Lynch and Smithers, 1995)

Table 6.4 Example of list showing the Quaternary Catchments on the left hand side and their downstream Quaternary Catchments or exit on the right hand side

Upstream Quaternary Catchment	Downstream Quaternary Catchment or Exit
M10A	M10B
M10B	M10D
M10C	M10D
M10D	SEA

A similar procedure is followed to model catchments as linked catchments in *ACRU* for climate impact assessment as for individual catchments as described in Section 6.6 (*cf*. Figure 6.9). Once the database has been specified and the level of climate input identified, the end catchment for the simulation needs to be specified. However, if the option of using the Quaternary Catchment Input Database has been chosen, then there is the option of choosing an exiting Quaternary Catchment from a larger Catchment Division, *viz*. Primary, Secondary or Tertiary Catchment. There may be a single exit from the selected catchment cluster or there may be multiple Quaternary Catchments that exit from the selected catchment cluster, as shown in Figure 6.11.

If this option is chosen a list is written to the screen of all the Quaternary Catchments that exit from that selected Primary, Secondary or Tertiary Catchment. Provided with the list are

- the total number of Quaternary Catchments that contribute to that exit;
- the total drainage area of all the Quaternary Catchments that contribute to that exit;
- whether the exiting Quaternary Catchment exits into the sea or another country;
- the total area of all the Quaternary Catchments in the selected range; and
- the total number of Quaternary Catchments in the selected range.

From this information the user can select one exiting Quaternary Catchment, whereby an ASCII file containing a list of all the Quaternary Catchments that feed that exit is automatically established.

Alternatively, any end Quaternary Catchment is entered and through a recursive loop in a Fortran script the catchments that feed that selected end catchment are identified using the Catchment Ordering File. Any end catchment for a group of Quinary Catchments can be selected and the feeding catchments will be identified in a similar manner.

From this list of contributing catchments the total number of catchments that are to be modelled using *ACRU* can be determined and the numerical ordering identity of each catchment, needed for the *ACRU* input menu, can be assigned via a Fortran script.

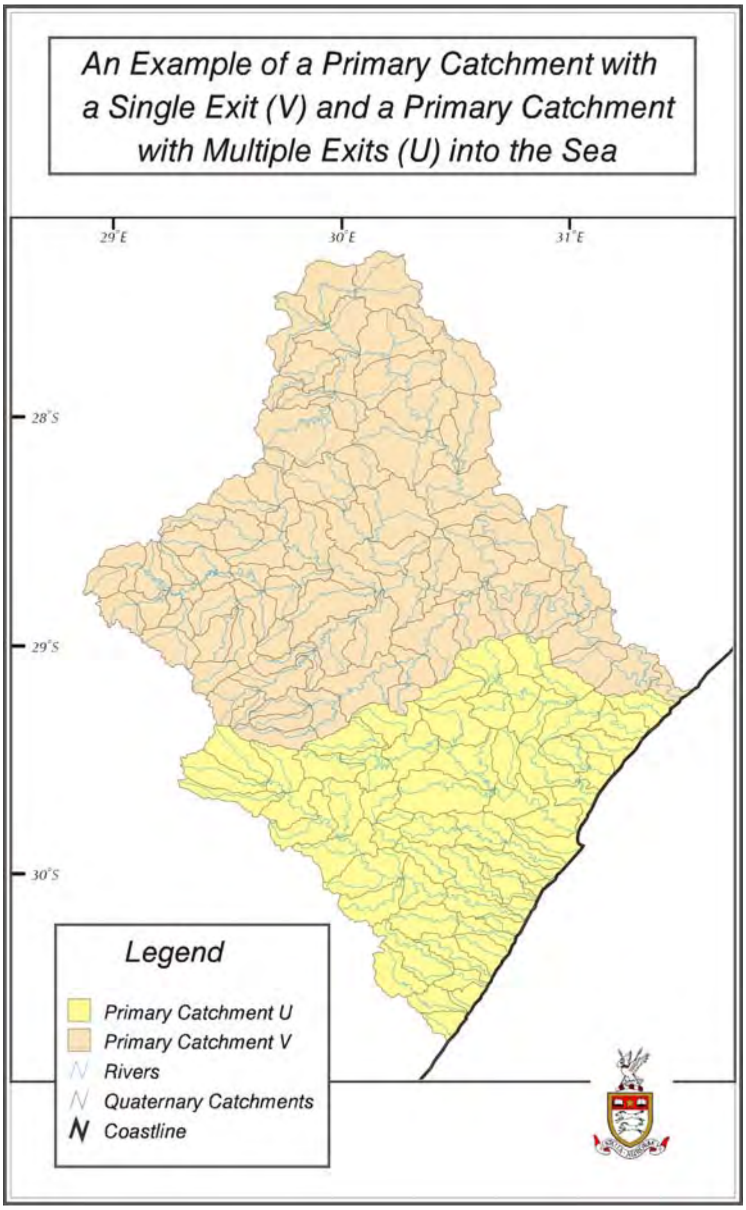


Figure 6.11 An example of a Primary Catchment with a single Quaternary Catchment at the exit into the sea (Primary Catchment V) and a Primary Catchment with multiple Quaternary Catchments exiting into the sea (Primary Catchment U)

The other options available for an *ACRU* simulation described in Section 6.7, such as using assuming a future climate scenario, are available when simulating the catchments as cascading catchments, as shown in Figure 6.9. An *ACRU* input menu is established for each catchment by extracting the relevant information from the *ACRU* Input Database specified. All the rainfall files required for the catchments selected are prepared for use.

To model the isolated catchments with *ACRU* when determining accumulated flows, one distributed *ACRU* menu is established using the individual *ACRU* menus that have been created for each catchment selected. This distributed menu contains the details of all the catchments that feed the selected end catchment and the ordering of the catchments to route the streamflow from one catchment to its downstream catchment. Therefore, the structures are in place to perform *ACRU* simulations on Quaternary or Quinary Catchments with the option of the catchments' cascading from the upstream catchment to their downstream catchments.

Output from a simulation of cascading catchments can also be extracted for import into a GIS or spreadsheet, as detailed in the following section.

6.9 EXTRACTION OF OUTPUT FROM *ACRU* FOR PRESENTATION

Once the *ACRU* simulations have been performed the output that was required from any simulation needs to be extracted and imported into the ARC/INFO GIS or a spreadsheet for display purposes.

6.9.1 Graphical Display of Output from *ACRU* Using the ARC/INFO GIS

The original extraction of output from the *ACRU* model for import into the ARC/INFO GIS for display purposes was time consuming. Routines needed to be written to easily extract output from the *ACRU* model for each catchment for import into GIS for display purposes.

To achieve this, the monthly statistical output generated by *ACRU* is extracted via a Fortran script and is stored in a condensed ASCII file per output variable. The ASCII files are in a column format, with each column representing a statistical output for a month of the year and each row representing a catchment.

A Fortran script was written to read the Output Selection File. This file records which output variables were initially selected. These variables are then written to the screen and information from one of the output variables can be selected. This identifies which stored ASCII file to use to extract the relevant statistical information. Various statistical output is computed by *ACRU*, *viz*.

- mean;
- coefficient of variation CV (%);
- minimum value;
- maximum value;
- 10th percentile value;
- 20th percentile value;
- 50th percentile value;
- 80th percentile value; and
- 90th percentile value

and one of the these statistics can be extracted, in turn, for the output variable selected.

Either the output for any specified month, the annual total or output for all the months can be selected for extraction from the isolated ASCII file.

Similarly, the extreme value analysis output can be extracted for use in the GIS. Output from either the Gumbel, Log-Normal or Log-Pearson analyses can be selected. Consequently, the return period of 2, 5, 10, 20 or 50 years must be chosen. The desired column from the ASCII file for the selected output is extracted and this information can then easily be imported into the GIS using the *JOINITEM* command in ARC/INFO which joins the extracted column of information to the coverage of the catchment under investigation.

The output from a crop yield analysis is also extracted using a similar program. The options for extraction include the same statistical options as available for the hydrological output, as well as the percentiles (10, 20, 33, 50, 66, 80 and 90%) output from the economic analysis, as shown in Figure 6.9.

6.9.2 Graphical Display of a Time Series from *ACRU*

A monthly or daily output file can also be generated from an *ACRU* simulation for the variables selected in the Output Selection File. This information can be imported into a spreadsheet and plotted as a time series to illustrate a temporal change in response of, say, runoff over time.

6.10 FURTHER REFINEMENTS TO THE NATIONAL QUATERNARY CATCHMENTS DATABASE

6.10.1 Porting of the National Quaternary Catchments Database to a Windows Platform

With the closure of the CCWR it was decided to port the Quaternary Catchments Database and the associated programs to the PC based Microsoft Windows platform. The Microsoft's relational Access Database was used for this process. All functionality of the UNIX based system has been preserved and a further option to run the *ACRU* model on a national basis for catchments with Mean Annual Precipitation exceeding 600mm has been integrated into the system.

6.10.2 Development of a Windows Based Front-End for the National Quaternary Catchments Database

MS Access makes provision for the use of "Forms" which allow the user to interact with the database by means of a Graphical User interface (GUI). A GUI has been developed for this purpose which greatly simplifies the process of configuring the model. A screenshot of the main input form of the GUI is shown in Figure 6.12. This facility also enables the user to run the model on catchments that are viable for commercial afforestation (i.e. Quaternary Catchments with MAPs > 600mm). A screenshot of this option is shown in Figure 6.13.

6.11 CONCLUSION

This chapter has described the refinements made up to 2002 to the procedures which previously existed for simulating of agrohydrological responses at a Quaternary Catchment scale. With these refinements the hydrology of both Quaternary Catchments and Quinary Catchments can be simulated as either individual or cascading catchments for both present and future climatic conditions. There are also a greater variety of options that can be specified for the *ACRU* simulations of the Quaternary Catchments. With these structures in place, not only is a greater versatility achieved, but also a more efficient way of obtaining results in assessments of climate change and other impacts for southern Africa. Further refinements are currently underway.

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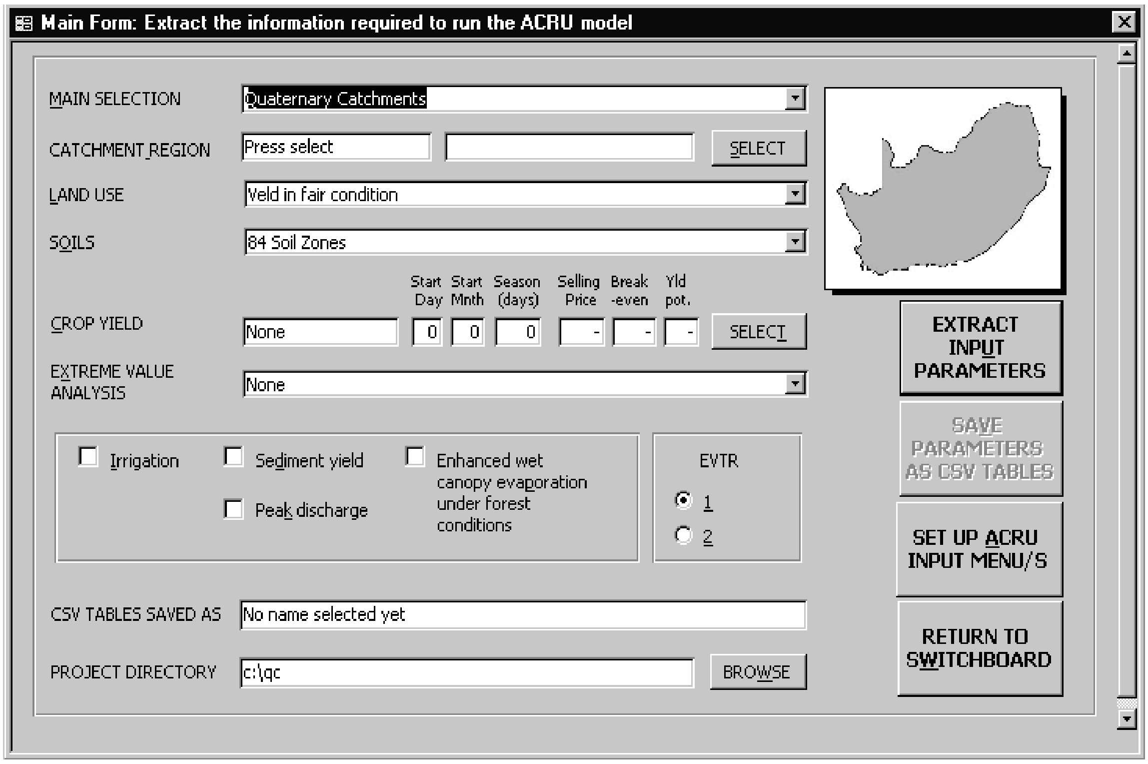

Figure 6.12 Screenshot of the National Quaternary Catchments Database

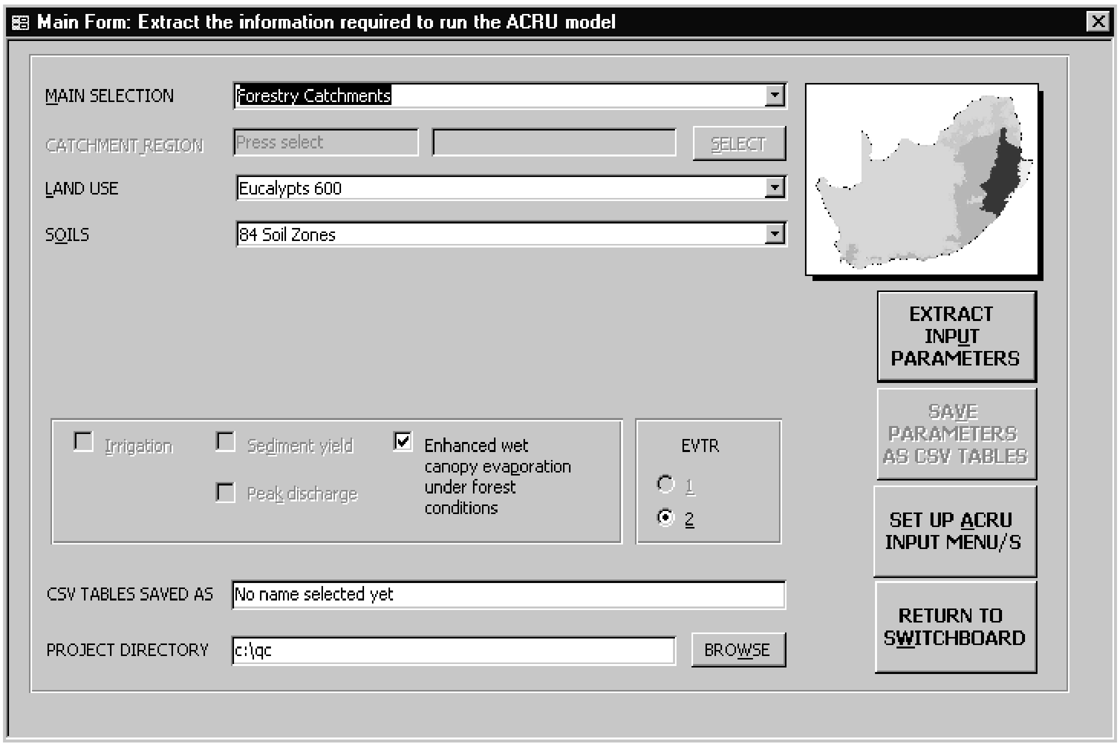

Figure 6.13 Screenshot of the National Quaternary Catchments Database demonstrating the option for simulating catchments with Mean Annual Precipitation exceeding 600 mm (catchments which are viable for commercial forestry)

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CHAPTER 7

INDICATORS OF HYDROLOGIC ALTERATION FOR ASSESSING ENVIRONMENTAL FLOWS FOR HIGHLY VARIABLE RIVERS

Valerie Taylor, Graham Jewitt and Roland Schulze

ABSTRACT

The role of flow on aquatic and riparian ecosystem processes has highlighted the potential of the natural hydrograph in setting environmental flow requirements. Most studies adopt the natural flow paradigm by constructing environmental flow regimes that mimic the full range of natural intra- and inter-annual variation of hydrological regimes. Recognising that hydrological variation plays a major role in structuring the biotic diversity within river ecosystems, the US Conservancy developed the so-called Indicators of Hydrologic Alteration, a methodology to characterise the natural range of streamflow variation. The methodology analyses 33 ecologically relevant characteristics of the hydrological regime. However, it is typically applied to less variable climatic conditions than those experienced in South Africa and other semi-arid countries, where aquatic and riparian ecosystems are influenced by highly variable inter- and intra- annual climatic conditions. Longer than recommended streamflow records may be required to account for the variability associated with these climatic characteristics. The potential of this methodology is explored for its suitability to assess the environmental flows required by highly variable river systems and the identification of alternative indicators. In particular, the hydrological regime of the Mkomazi River in KwaZulu-Natal, South Africa is assessed to ascertain the likely alteration of streamflows by the construction of proposed dams.

KEY WORDS: natural flow paradigm; indicators of hydrological variation; highly variable river systems

7.1 BACKGROUND TO ENVIRONMENTAL FLOWS FOR HIGHLY VARIABLE RIVERS

7.1.1 Setting the Scene

Scientists are challenged by the question of how much water rivers need to maintain river health and to sustain the integrity of aquatic and riparian ecosystems. This has become all the more pressing in South Africa, since, under the provisions of the South African National Water Act (NWA) of 1998 (Act 36 of 1998), some water must be set aside as an environmental Reserve to protect the ecological functioning of rivers and the resource base itself. Nonetheless, the processes to determine the quantity and quality as well as the pattern of flows required to meet the environmental Reserve are relatively well developed. Several different techniques, designed in South Africa and based on the application of historical hydrological records, (*e.g*. the Building Block Methodology, BBM, (King and Louw, 1995) and the Downstream Response to Imposed Flow Transformations, DRIFT, (Brown and King, 2000)) are available for application in the determination of the environmental Reserve. Expertise to assess the environmental flow requirements of South African freshwater systems is based on knowledge of the influence of flow on stream processes (King and Tharme, 1994). The BBM recommends low flows for each calendar month and high flows for wet season months. In the methodology, low flows and high flows are assessed for maintenance (“normal”) years as well as for drought years. The BBM technique defines the management class of representative river reaches and focuses on instream flow requirement sites (IFR Sites) at which flow characteristics required to maintain the integrity of the aquatic ecosystem are evaluated. DRIFT also makes the link between river flow and river condition on the premise that different characteristics of the flow regime produce different responses from the aquatic ecosystem. Unlike the BBM, which “builds” components of a recommended flow regime to sustain a particular aquatic condition, DRIFT assesses biotic responses to potential flow regimes, taking account of any socio-economic implications. While different river ecosystems call for different management decisions, the general consensus amongst environmental flow requirement working groups favours techniques that are based on the response of aquatic organisms to changes in river flow. Despite the differences in approach to the assessment of environmental flows and determination of the environmental Reserve, the most sophisticated techniques acknowledge that the natural variability of flow regimes in South African rivers is an important determinant in the ecological functioning of river systems.

7.1.2 The Role of Flow on Aquatic and Riparian Ecosystems

Hydrological regimes play an important role in determining channel morphology, occurrence and distribution of aquatic and riparian biota, water quality, water temperature, transportation of sediment and organic matter, estuarine inflow and other environmental conditions. Therefore, hydrological regimes play an important role in the environmental regimes of river systems, which in turn influence the composition, structure, and functioning of aquatic and riparian ecosystems (Richter *et al*., 1996, 1997 and 1998). In particular, the response of biota and ecosystems to the hydrological regime is influenced by the variability of streamflows within the regime. The link between hydrological variation and the extent of biotic diversity in aquatic ecosystems is well known (Richter *et al*., 1996, 1997 and 1998; Poff *et al*., 1997; Hughes, 1999). Inter- and intra-annual variation, reflecting all aspects of the hydrological regime, is essential to maintaining the environmental conditions required for the survival of many aquatic and riparian species and for sustaining ecological integrity.

7.1.3 Inter- and Intra-Annual Variation of Hydrological Regimes in Southern Africa

Southern Africa (South Africa, Lesotho and Swaziland) is, generally, a semi-arid region, subject to uneven spatial distribution of rainfall and runoff generation, variability of river flows and droughts as well as flooding, both of which are exacerbated by the impacts of human activity through changes of land use. The runoff to rainfall ratio in the region is low when compared with the world average of 35% and even in the relatively wet province of KwaZulu-Natal the ratio is only 16.5% (Schulze, 1997). The Coefficient of Variation (CV), *i.e*. the standard deviation of daily, monthly or annual flow volume divided by the mean of the particular flow volume, is frequently used as a statistical measure of the variability of streamflows. Even areas with relatively reliable runoff generation have inter-annual CVs close to 40%, whereas some 20% of the region has a CV of runoff greater than 160% (Schulze, 1997).

The inter- and intra-annual variability of runoff presents uncertainties to the assured supply of water for abstractors as well as for instream flows. Water managers are challenged by highly variable river systems and yet, in terms of the NWA, are required to reserve water for environmental functioning before the allocation of water for other uses such as industrial or agricultural use, save for meeting basic human needs. Hydrological simulation modelling of land use impacts, abstractions for domestic, commercial and subsistence use as well as scenarios of management practices is, therefore, pivotal to the reliable assessment of water resources for allocation. However, hydrological simulation modelling is constrained by the uneven spatial distribution and quality of the both the rain gauge and stream gauge networks.

Climatic variability is a critical determinant of streamflow variability. Lynch and Dent (1990) conclude that the rainfall in areas with high Mean Annual Precipitation (MAP) is less variable than in those areas with low MAP. However, the distribution of rain gauges in Southern Africa is low in areas that are characterised by a low MAP and, of the rain gauges capturing a MAP of less than 300mm, only 12% are distributed throughout 32% of the region (Lynch, 1999).

In South Africa, gauged streamflow data is usually available for Quaternary Catchments (QCs) and is not generally available for smaller catchments. Missing streamflow, inaccurate measurement and recording of data, as well as inadequate record length for analysis are some of the problems associated with the assessment of the regions water resources. Most of the regions gauging stations have been automated to record daily streamflows since the 1960s. However, even with automation there are frequently gaps or inaccuracies in the record, especially after extreme flood events when gauging plates require re-calibration and are temporarily out of operation. In-filling or extending daily streamflow records using interpolation techniques and reference gauging stations in catchments with highly variable river systems, or where there are ephemeral rivers, is problematic.

Problems associated with the paucity of useful databases relating to riparian and aquatic biota further compound these difficulties. Consequently, there is limited scope for environmental flow methodologies that require detailed information of the habitat requirements of individual species.

7.1.4 Characterising the Natural Variability of Streamflow Regimes

Hughes *et al*. (1998) investigated the differences in the flow regime characteristics of different river systems within South Africa in an endeavor to derive relationships between the results of past BBM applications and the natural hydrological regimes of rivers. Hughes *et al*. (1998) identified that, according to the BBM, those rivers that have highly variable streamflow regimes (high monthly or annual CVs) require a smaller portion of their natural mean annual flows to sustain ecological functioning than those rivers in which the biota have adapted to more constant streamflow conditions. On this basis, Hughes *et al*. (1998) devised a "flow variability index" comprising the sum of the average CV of the three main wet season months and the average CV of the three main dry season months. Hughes *et al*. (1998), describe the extent of intra-annual variability of streamflow regimes in terms of the proportion of total flows that occur as baseflows and further identified that, according to the BBM, rivers with high constancy of streamflows require a higher proportion of their natural mean annual flows as baseflows, the "baseflow index". Hughes *et al*. (1998) devised a combined index of the flow variability and baseflow indices to relate to the flow components of the BBM. The results of the investigation suggested that there was a stronger relationship between the monthly distribution of low flows than of high flows required for different river systems and that the environmental Reserve requires a higher proportion of the natural mean annual flows in the dry season than in the wet season.

7.2 THE INDICATORS OF HYDROLOGICAL ALTERATION

7.2.1 Background to IHA Methodology

The US Conservancy developed the Indicators of Hydrologic Alteration (IHA) as a method to characterise the natural range of streamflow variability, or the extent to which streamflows have been altered by human activity, based on the analysis of daily streamflow data. The IHA is a statistical analysis of 33 ecologically relevant hydrological attributes that characterise intra-annual variation in the streamflow regime. The hydrological parameters represent five groups of streamflow components, which can be attributed to playing major roles in determining the nature of aquatic and riparian ecosystems (Poff and Ward, 1989). Poff and Ward (1989) and Richter *et al.* (1996) define the five streamflow components as:

- The *magnitude* of water condition, *i.e*. the amount of water passing a point in a river at a point in time, measured in units of $m^3.s^{-1}$. The magnitude of flows is a measure of habitat availability, or suitability, in terms of wetted perimeter area or habitat volume.
- The *timing* of occurrence, *i.e*. the time of year at which particular flow events such as floods or low flow extremes occur. The timing of flow events determines whether certain life-cycle requirements are met and provides variability in ecosystems through environmental stress.
- The *frequency* of occurrence, *i.e*. the number of occurrences of specific conditions such as floods or droughts. The frequency of these flow conditions can be related to reproduction and mortality events for particular species, influencing community population density and distribution.
- The *duration* of occurrence, *i.e.* the length of time over which a particular flow condition lasts. The duration of flow conditions determines whether a particular life cycle can be completed; or the extent of environmental stress within ecosystems.
- The *rate of change* is a measure of how quickly streamflows rise and fall between consecutive days. The rate of change of flow conditions can lead to organisms being stranded in riffles and pools. Additionally, it influences the ability of riparian vegetation to maintain root contact with river channel water.

A summary of the parameters, and their characteristics, used in the IHA is provided in Table 7.1. The IHA analysis statistically characterises inter-annual variation in flow regimes and, because the methodology uses mean daily streamflow rates, it is suitable for detecting the hydrological characteristics relevant to sustaining aquatic ecosystems. Seventeen of the parameters (Groups 2, 3 and 4 in Table 7.1) focus on the magnitude, duration, timing and frequency of *extreme events*, whereas the other 16 parameters (Groups 1 and 5 in Table 7.1) are measures of the *mean* of the magnitude of flows or the rate of change of water conditions. The following sections summarise the descriptions of the five groups and the associated statistical parameters given by Richter *et al*. (1996, 1997 and 1998).

Table 7.1 Summary of hydrological parameters used in the Indicators of Hydrologic Alteration (IHA) and their characteristics (after Richter *et al*., 1996)

IHA Statistics Group	Regime Characteristics	Hydrological Parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means Number of zero-flow days 7-day minimum flow divided by mean daily flow for year (“base flow”)
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day minimum Julian date of each annual 1-day maximum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses each year Number of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values Number of rises Number of falls

- The *magnitude of the monthly mean of daily flows* (Group 1) represents normal daily flow conditions for the month and indicates the general amount of flow required for habitat availability and suitability for each month. The degree to which monthly means vary from month to month indicates the intra-annual variation of streamflow conditions, whereas the extent to which flows vary within a month, from year to year, (the CV of monthly means of flow) indicates the inter-annual variation of streamflow conditions.
- The *magnitude and duration of extreme annual conditions* (Group 2) are a measure of the different environmental disturbances, or stresses that can occur throughout the year. The durations were selected by the developers of the IHA to represent natural or human induced cycles and comprise the 1-day, 3-day, 7-day (weekly), 30-day (monthly) and 90-day (seasonal) extremes. The 1-day events are the maximum and minimum daily flow values that occur in any given year and the multi-day events are the highest and lowest multi-day means occurring in any given year. The number of zero-flow days, characteristic of non-perennial rivers, is also included in this group. The developers of the IHA define “base flow” conditions as the 7-day annual minimum flow divided by the annual mean of daily flows. The inter-annual variation in the magnitude of these extreme conditions influences the extent to which environmental variation occurs within ecosystems.
- The Julian date of the 1-day maximum and minimum flow events represents the *timing of the annual extreme conditions* (Group 3) within annual cycles and provides a measure of the seasonal nature of environmental stresses or disturbances. The timing of these flows can influence the life cycles of aquatic organisms. The inter-annual variation in the timing of these extremes influences the extent to which environmental variation occurs within ecosystems. This may have greater significance in more temperate regimes where snow-melts consistently influence the daily maximum flow and also significantly reduce water temperatures and increase

dissolved oxygen concentration. Alternatively, the timing of cyclones in tropical regions may be environmentally significant.

- The *frequency of conditions* during which the magnitude of streamflows exceeds an upper threshold or falls below a lower threshold within an annual cycle, and the *mean duration of such occurrences* (Group 4) together reflect the pulsing behaviour of environmental variation within a given year. Richter *et al*. (1996, 1997 and 1998) define high pulses as those periods within a year when the daily streamflow rises above the 75th percentile of all daily values, and low pulses as those periods within a year when the daily streamflow falls below the 25th percentile of all daily values.
- The *rate and frequency of change in conditions* (Group 5) measure the number and mean rate of both positive and negative changes in the streamflow between consecutive days. These changes in the hydrograph indicate the fluctuation of the intra-annual cycles of environmental variation and reflect the extent of the rate and frequency of intra-annual environmental change.

7.2.2 Assessing Streamflow Alteration Using the IHA

The goal of the IHA technique is to characterise the temporal variation in streamflow conditions using attributes that are hydrologically and ecologically relevant, yet sensitive to anthropogenic influences such as land use change and modifications such as irrigation abstraction and impoundment. A major benefit of the IHA is that it can be applied to quantify the hydrological alteration associated with the transition from pre-system impacts (natural flow regime or current land use conditions) to post-system impacts (*e*.*g*. as a result land use change). The IHA method of assessing the impacts of land use change or development issues is based on comparing the hydrological attributes of a site before and after the perturbation (Richter *et al*., 1996). Two time series of streamflows, either recorded or simulated using a hydrological model, are required, one for the period before the perturbation and the other initiated after the perturbation. The pre- and post-impact representations of the hydrological regime are then characterised and a statistical comparison between the two time series can be made for any of the 33 IHA parameters. In particular, the methodology highlights the potential use of long-term streamflow records or, alternatively, simulated information, and statistical descriptions of natural flow variability to set ecosystem-based management targets (Richter *et al*., 1996, 1997 and 1998). The developers have published results of the application of the Indicators of Hydrologic Alteration indicating the appropriateness of the this analysis for the Roanoke River, at Roanoke Rapids in North Carolina (Richter *et al*., 1996, 1997) and for the Colorado River at Cisco, Utah, both in the United States of America (Richter *et al*., 1998).

The IHA method was applied by Jewitt *et al*. (1999) to assess the applicability of the approach to South African conditions. Jewitt *et al*. (1999) performed three case studies at the following locations for which adequate data existed, *viz*:

- at streamflow gauging station X2H010 on the Noordkaap River in the Northern Province
- at Schoolplaats streamflow gauging station C9H008 downstream of the Vaalharts Dam and
- at IFR Site 2 on the Mkomazi River, comparing the naturalised streamflow assumed to occur at the IFR site with streamflow generated using the IFR model developed by Hughes *et al*. (1997) for pre- and post-dam construction.

The initial results of the three case studies highlighted the extreme variability of streamflow in South African rivers. Therefore, Jewitt *et al*. (1999) regarded the IHA option of applying non-parametric analysis (based on statistics relating to the percentile data) rather than parametric analysis (based on Gaussian statistics such as the mean) to be more suitable for South African conditions. Furthermore, Jewitt *et al*. (1999) concluded that some of the parameters, such as the Julian date of annual extreme events were not particularly well suited to semi-arid conditions, although that will depend on the concentration of rainfall within the year and its seasonality.

7.2.3 Indicators of Hydrologic Alteration for Highly Variable River Systems

Hydrological information is critical for the effective assessment of the environmental flow requirements of Southern African rivers. Although the IHA is typically applied to less variable streamflow regimes than those experienced in Southern Africa, the identification of relevant hydrological indices appropriate to the region’s highly variable rivers could have great potential towards the determination of the environmental Reserve. The developers of the IHA suggest that a minimum of 20 years of data are required to minimise the effects of inter-annual climatic variation on the IHA parameter statistics (Richter *et al*., 1997). This is based on research by the developers, which showed that the range of estimates of the mean annual 1-day maximum flow from three different stream types in the United States begins to narrow substantially when based on at least 20 years of record. However, for southern African conditions, where statistical analyses can be influenced by a particularly wet or dry spell of years, especially where periodic fluctuations with approximately 20-year oscillations have been identified (Tyson, 1986), longer record lengths may be required (Schulze *et al*., 1995).

7.3 CASE STUDY: THE UPPER MKOMAZI CATCHMENT

7.3.1 Background to the Mkomazi Catchment

The potential of the IHA technique for characterising variation in streamflow regimes is further explored for its suitability to assess the environmental flows required by the Mkomazi River, in KwaZulu-Natal, in South Africa. The Mkomazi Catchment comprises the 12 Department of Water Affairs and Forestry (DWAF) QCs numbered U10A to U10M and covers an area of 4383 km^2. The catchment is situated around 29° 17' 24'' E and 29° 35' 24'' S (Figure 7.1), stretches 170 km from 3300m altitude in the north-west to sea level in the south-east and has MAP ranging from 1283 to 752mm. The MAP is higher in the upper, higher altitude reaches of the Mkomazi Catchment (950 – 1283 mm) and consequently most of the catchment runoff is generated there (DWAF, 1998a). The Mkomazi Catchment is characterised by steep gradients of altitude and rainfall, highly variable land uses as well as highly variable intra- and inter-annual streamflows. Despite the spatial and temporal variability of the streamflows, the Mkomazi River flows throughout the year.

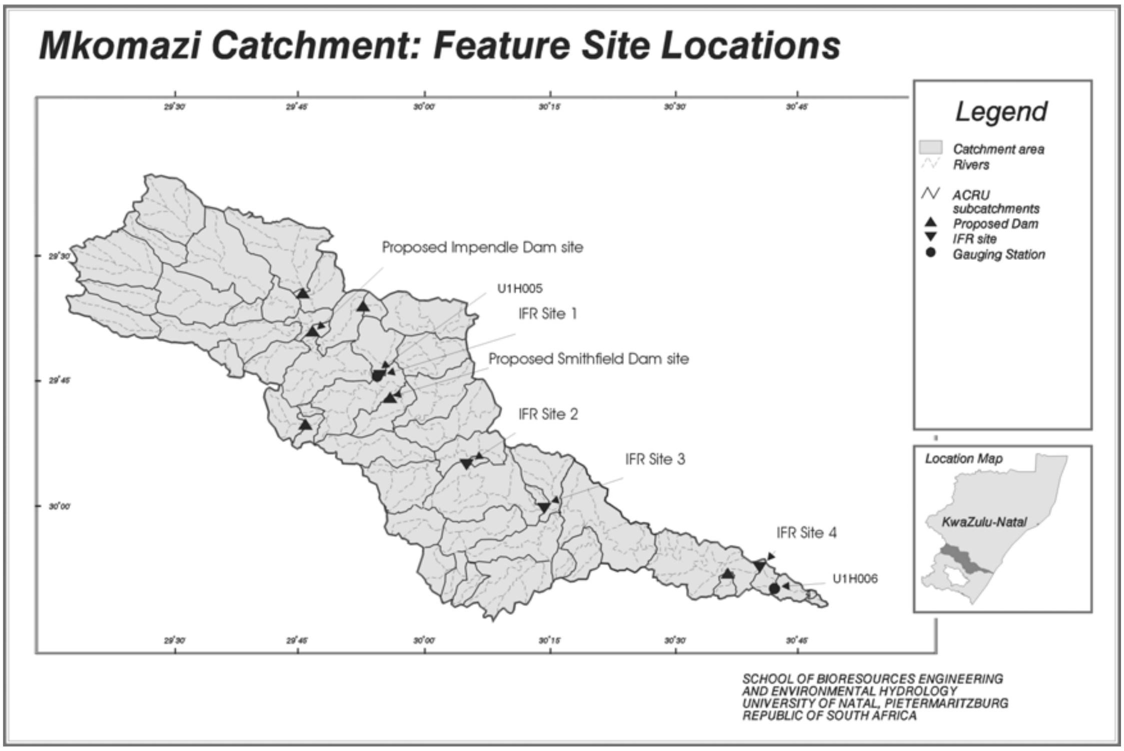


Figure 7.1 Mkomazi Catchment: Feature site locations

The Mkomazi catchment hydrological dynamics were modelled with the *ACRU* agrohydrological model (Schulze, 1995) to assess the impacts of land use and proposed development on the availability of water resources. The Mkomazi Catchment was configured to represent 52 major inter-linked subcatchments, based essentially on a division of the 12 DWAF QCs and focussing on different land use and management practices as well as proposed development concerns. The instream flow requirements for the Mkomazi River were assessed in March 1998 (DWAF, 1998b) by an IFR workshop using the BBM. The workshop participants defined and determined the management class of representative reaches and focussed on four unique sites at which flow characteristics required to maintain the integrity of the aquatic ecosystem were evaluated. IFR Site 1 is upstream of the proposed Smithfield Dam, whereas IFR Sites 2, 3 and 4 are all downstream of the proposed Smithfield Dam site (Figure 7.1).

While the Mkomazi Catchment is spatially complex, only the temporal variation in the climatic and hydrological regimes is discussed in this paper. The natural inter- and intra-annual flow variation of the hydrological regime of the Mkomazi River is investigated to ascertain the pertinence of the indicators of hydrological alteration utilised in the IHA statistical analyses.

7.3.2 The Availability of Adequate Streamflow Record

There are 2 operational DWAF streamflow gauging stations, U1H005 and U1H006 (Figure 7.1), on the Mkomazi River. Automated recording of streamflows at these stations commenced in 1960 for U1H005 and in 1962 for U1H006. However, the recording gauge at U1H006 has a low discharge table and produces unreliable high flow measurements (DWAF, 1998b) and will not be discussed in this paper. The daily streamflow record for the period 1960 to 2001 for U1H005 was accessed from DWAF for this case study. The area upstream from U1H005 is sparsely populated and according to the Thompson's interpretation of the LANDSAT TM 1996 image, the major land use is unimproved grassland (Thompson, 1996). It is, therefore, considered that the record at gauging station U1H005 represents streamflows that are relatively representative of natural conditions.

7.3.3 Streamflow Trends in the Upper Mkomazi Catchment

The IHA technique can be used to analyse a single time series of daily flows. In such instances, the IHA software computes a trend analysis comprising the slope of the linear least-squares fit of the data, y-intercept and significance measures of the regression for the inter-annual distribution of the mean values of each of the 33 parameters. This technique was applied to test the assumption that the streamflow record, from 1960 to 2001, at U1H005 was representative of natural flow conditions. The results were provided as a summary table of the statistics of hydrological parameters on a year by year basis and as graphs of statistical trends of each of the hydrological parameters, all of which are too extensive to include in this paper. However, and in general, streamflows in wetter months have increased slightly over the time period from 1960 to 2000, whereas streamflows in drier months have decreased slightly. These trends are also evident for the minimum and maximum multi-day extreme events. Baseflows have decreased over the time period. The Julian date of the minimum daily flow is later in the year, whereas the date of the maximum daily flow is earlier. The numbers of both high and low pulses have reduced over the time period, whereas the durations of both high and low pulses have increased. While the fall rate of the hydrograph from day to day has been consistent, the rise rate has increased and consequently the number of hydrograph reversals has increased. Therefore, the Mkomazi streamflow record indicates that the hydrological regime has become more variable over the time period from 1960 to 2000. However, Figure 7.2 shows the increasing inter-annual scatter of rainfall as recorded by a nearby South African Weather Bureau rain gauge (0238442) as well as the increasing trend of wetter climatic conditions. Therefore, the increase in variability of streamflows may be attributable to the changes in climatic conditions.

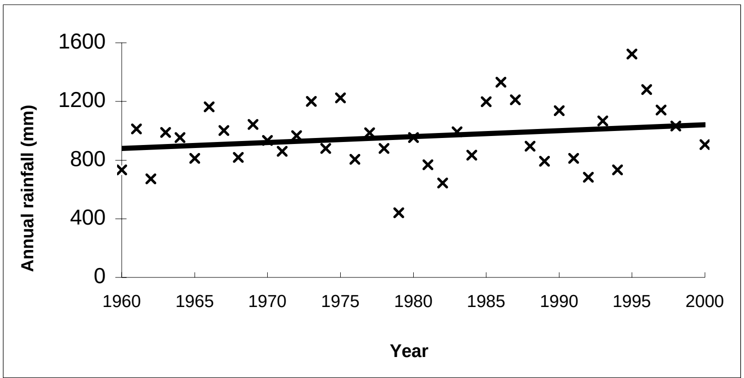


Figure 7.2 Distribution of annual rainfall of Mkomazi Catchment from 1960 to 2000

7.3.4 Pertinence of Record Length to the Assessment of Highly Variable Flow Regimes

The automated daily streamflow flow record at U1H005 is incomplete and there are sporadic months, weeks and days during which there are no recorded data. Although the developers of the IHA state that the IHA program does not object to missing years, long periods of missing data present problems to the statistical analysis of daily time series. Missing days are flagged as such in the program input file and daily flows are interpolated across the gaps by the IHA program. However, interpolation across long gaps can cause anomalies in the statistics and the developers of the IHA advise that such analysis are utilised with caution. Notwithstanding the missing data, there are 41 years of daily streamflows available from gauging station U1H005 for analysis, with the longest gap across the record being only 83 days. The record was checked to ensure that the values interpolated by the IHA program would be realistic and within the natural range for the affected season (13 September 1976 to 4 December 1976).

Schulze *et al*. (1995) produced a map for southern Africa indicating the minimum rainfall record lengths required to ensure that the means of annual rainfall estimates are within 10% of the long term mean 90% of the time. For the Mkomazi Catchment, they suggest a minimum MAP record of 20 years. The daily streamflow record of U1H005 was analysed using the IHA method to determine the flow record length required for the assessment of indicators of hydrologic alteration within Mkomazi streamflow regime. Moving windows of different record lengths comprising 20, 25, 30 and 35 consecutive years of observed data, as well as the 41-year record, were each assessed to ascertain the extent of hydrological variability represented by different record lengths of daily streamflows. The following hypotheses were tested:

- If longer than 20 years of record are required to account for the natural climatic variability of the Mkomazi Catchment, there should be differences between the inter-annual variation of streamflows for record selections at the beginning of the 41-year time series and those at the end of the 41-year time series. Furthermore, there should be greater differences between the comparisons of the 20-year record selections than for the comparisons of the 35-year record selections, and
- There should be greater similarity between the inter-annual variation for the 35-year record and the 41-year record than for any other record length.

The statistical analysis of the selections within each record length category was compared with the statistical analysis of the 41-year record. The IHA was applied using non-parametric statistical analysis and the results were presented in the following formats:

- A Summary Scorecard, an example of which is provided in Table 7.2, for the analysis of comparisons and comprising the following parameters pertaining to the relevant period of analysis:
  - Columns 1 and 2 show the median for each of the two periods.
  - Columns 3 and 4 show the Coefficient of Dispersion (CD) for each period, defined as (75th percentile - 25th percentile) / 50th percentile.
  - Columns 5 and 6 show the deviation of the median and CD values one time period from another, defined as [(α value -β value) / (α value)]. This characterises the alteration of the parameter.
  - Columns 7 and 8 calculate a significance count for the deviation values, based on the probability of the values occurring from randomised recalculations of all years of data.
- Percentile statistics for the analysis of comparisons, showing the 10th, 25th, 50th, 75th and 90th percentile values as well as the CDs for each time series.
- Tables of annual summaries containing all the information given above, on a year by year basis. These tables are particularly useful for analysing the annual variation in the IHA parameter values.
- Graphs for each of the IHA parameters for both time periods showing the median as well as the 25th and 75th percentile levels for each period.

7.3.5 Characterising the Streamflow Regime of the Upper Mkomazi River

The results of the statistical analysis of daily streamflows for the 41-year record are shown as the first time period (extreme values “included”) in Table 7.2. The distribution of median values in the 41-year record indicates that there is greater constancy of the Mkomazi streamflows for the low flow season (*e.g.* 4.0 $m^3.s^{-1}$, 3.0 $m^3.s^{-1}$ and 2.6 $m^3.s^{-1}$ for June July and August) than for the high flow season (*e.g.* 34.6 $m^3.s^{-1}$, 49.3 $m^3.s^{-1}$ and 32.2 $m^3.s^{-1}$ for January, February and March). There is also a greater degree of inter-annual variation for high flow months (CDs of 1.02, 1.21 and 1.31 for December, January, February) than for low flow months (CDs of 0.65, 0.60 and 0.62 for May, June and July). Extreme rainfall events in late September 1987 have influenced the inter-annual variation of streamflows at the end of the low flow season, resulting in October having the highest inter-annual CD of streamflows. The large differences between the medians of the minimum (all less than 3 $m^3.s^{-1}$) and the maximum (ranging between 225 $m^3.s^{-1}$ and 46 $m^3.s^{-1}$) 1-day and multi-day extreme events indicates the degree of intra-annual variation of streamflow events in the upper Mkomazi. The extent of inter-annual variation is similar for both minimum and maximum events with greater variation associated with the shorter multi-day and 1-day events. On average, there are 128 days between the occurrence of the annual minimum daily flow event and that of the maximum daily flow event, however, this statistic does not provide information on the duration of either the low flow or high flow seasons. Moreover, the low CD associated with the dates indicates that the timing of these events, from one year to another, is a fairly predictable characteristic of the upper Mkomazi streamflow regime. Over the 41-year record, there are, on average, more high pulse events (9) than low pulse events (5) within a year, but the high pulses are much shorter (9 days compared to 18 days for low pulses). This pulsing behaviour of the streamflow regime characterises the intra-annual "flashiness" associated with the high flow season, as well as the persistence of the low flow season. Both high

Table 7.2 Comparison of time series at U1H005, with and without extreme daily flows

	Medians		**Coeff. of Dispersion.**		**Deviation Factor**		**Significance Count**	
	included	**excluded**	**included**	**excluded**	**Medians**	**C.V.**	**Medians**	**C.V**
Parameter Group 1								
October	4.60	4.50	1.45	1.51	0.03	0.04	0.82	0.79
November	14.50	13.70	0.62	0.54	0.05	0.12	0.88	0.71
December	27.50	27.00	1.02	0.86	0.02	0.15	0.73	0.58
January	34.60	32.10	1.21	0.62	0.07	0.49	0.34	0.11
February	49.30	40.10	1.31	0.59	0.19	0.55	0.26	0.12
March	32.20	30.90	0.82	0.66	0.04	0.19	0.61	0.57
April	16.20	16.20	0.93	0.92	0.00	0.01	1.00	0.96
May	6.50	6.50	0.65	0.65	0.00	0.00	1.00	1.00
June	4.00	4.00	0.60	0.60	0.00	0.00	1.00	1.00
July	3.00	3.00	0.62	0.61	0.02	0.02	0.82	0.96
August	2.60	2.70	0.79	0.74	0.02	0.07	0.86	0.89
September	3.20	3.50	1.19	1.02	0.10	0.14	0.59	0.60
Parameter Group 2								
1-day minimum	1.10	1.30	0.80	0.35	0.20	0.57	0.01	0.13
3-day minimum	1.10	1.40	0.83	0.36	0.26	0.57	0.00	0.11
7-day minimum	1.20	1.50	0.74	0.37	0.28	0.51	0.00	0.16
30-day minimum	1.80	1.90	0.58	0.53	0.06	0.10	0.58	0.80
90-day minimum	2.70	2.80	0.51	0.48	0.03	0.07	0.86	0.82
1-day maximum	224.60	84.00	0.76	0.07	0.63	0.91	0.01	0.02
3-day maximum	173.80	78.20	0.90	0.13	0.55	0.86	0.00	0.06
7-day maximum	119.60	68.40	0.86	0.25	0.43	0.71	0.00	0.13
30-day maximum	71.50	50.00	0.75	0.32	0.30	0.57	0.00	0.16
90-day maximum	45.80	37.10	0.64	0.33	0.19	0.48	0.04	0.06
Number of zero days	0	0	0	0	0	0	0	0
Base flow	0.10	0.10	0.65	0.39	0.37	0.40	0.00	0.30
Parameter Group 3								
Date of minimum	270.50	259.00	0.11	0.13	0.06	0.17	0.25	0.41
Date of maximum	32.00	35.00	0.13	0.14	0.02	0.02	0.54	0.95
Parameter Group 4								
Low pulse count	5.00	4.00	0.60	1.00	0.20	0.67	0.32	0.04
Low pulse duration	18.30	18.40	0.73	0.71	0.01	0.03	0.94	0.89
High pulse count	9.00	9.00	0.64	0.64	0.00	0.00	0.69	0.98
High pulse duration	8.80	8.80	0.68	0.67	0.01	0.02	0.90	0.98
The low pulse threshold is	*3.25*							
The high pulse level is	*21.29*							
Parameter Group 5								
Rise rate	9.40	4.70	0.59	0.53	0.50	0.09	0.00	0.89
Fall rate	-3.80	-2.30	-0.52	-0.34	0.40	0.34	0.00	0.36
Number of reversals	93.50	81.50	0.26	0.27	0.13	0.05	0.04	0.85

and low pulsing events are characterised by similar inter-annual variability. The average rate of hydrograph rise (9.40 $m^3.s^{-1}.d^{-1}$) is greater than the rate of hydrograph fall (3.80 $m^3.s^{-1}.d^{-1}$), again demonstrating the flashy characteristic of the upper Mkomazi River during the high flow season. With the exception of the timing of the annual minimum and maximum daily flows (Group 3) the streamflow characteristics comprising Group 5 are more predictable, from year to year, than any of the other Groups of hydrological parameters.

7.3.6 Comparison of Different Record Lengths of the Upper Mkomazi Streamflows

The comparison of different record lengths of the upper Mkomazi streamflows, using the IHA technique, resulted in extensive quantities of statistical information being produced. Over the 41-year record, there is little difference (similar medians and CDs) in the intra- and inter-annual variation of the hydrological parameters between overlapping periods of 20 years. Table 7.3 indicates this relationship for the mean daily streamflows ($m^3.s^{-1}$) for each calendar month of Group 1, when comparing 1963 to 1982 with 1964 to 1983. However, there are greater differences in the intra- and inter annual variation between periods of 20 years at the start of the 41-year record to those at the end of the record. These differences, also for the mean daily flows for each month, are indicated in Table 7.3 for 1980 to 2000. Record lengths longer than 20 years reveal greater similarity in both intra- and inter-annual variation of the hydrological parameters when samples at the beginning of the 41-year record are compared to those at the end of the record. Notwithstanding the variation associated with different time periods, water managers and researchers are more likely to focus on recent climatic and hydrological events. The results of the comparison of record length within the 41-year period are shown for the last 35 years (1966 to 2000) and for the last 20 years (1981 to 2000) in Figures 7.3, 7.4, 7.5, 7.6 and 7.7.

Table 7.3 Differences in medians and coefficients of dispersion, for three different 20-year samples within the 41-year streamflow record of stream gauge U1H005 on the Mkomazi River

Hydrological parameter	1963-1982		1964-1983		1981-2000	
	Median	**CD**	**Median**	**CD**	**Median**	**CD**
October	4.40	1.81	4.40	1.61	4.70	0.86
November	12.50	0.59	12.50	0.59	14.30	1.00
December	21.10	0.94	21.10	0.94	28.70	1.00
January	26.20	1.78	26.20	1.20	34.20	0.85
February	50.80	1.28	50.60	1.37	30.40	2.13
March	32.50	0.77	37.00	0.75	31.00	0.80
April	16.80	0.94	17.80	1.40	11.70	1.01
May	6.50	0.79	6.50	0.89	5.30	0.69
June	4.10	0.60	4.10	0.60	3.60	0.58
July	3.10	0.63	3.10	0.62	2.70	0.71
August	2.80	0.80	2.80	0.80	2.30	0.73
September	3.80	1.13	3.60	1.00	1.80	1.76

There are similarities in the intra-annual distribution of median flows for the different record lengths, particularly for low flow months and at the start of the high flow season (Figure 7.3), indicating some seasonal predictability of the Mkomazi streamflows. However, there is greater inter-annual variation in high flow months than in low flow months. While there is similarity in the extent of inter-annual variation for the different record lengths during low flow months, there are differences during high flow months. There is, however, no clear pattern to indicate which record length has the greatest, or least, inter-annual variation for a given season. The 35-year record is more similar to the 41-year record, yet in February and March there is greater inter-annual variation associated with the 35-year record than for the 41-year record. These features suggest that while 20 years of record may be sufficient to statistically analyse the monthly statistics (Group 1) of the upper Mkomazi streamflows in the low flow season, more than 20 years may be required for high flow months. When the climatic regime includes a greater extent of high rainfall events, even 35 years of record may not be adequate to analyse the monthly statistics.

The variation of annual minimum events is shown in Figure 7.4 for different record lengths. There are differences among the median streamflows and the CDs associated with different record lengths for each of the annual minimum events of Group 2, indicating the intra- and inter-annual variation associated with these events. There is, again, least difference between the 35-year record and the

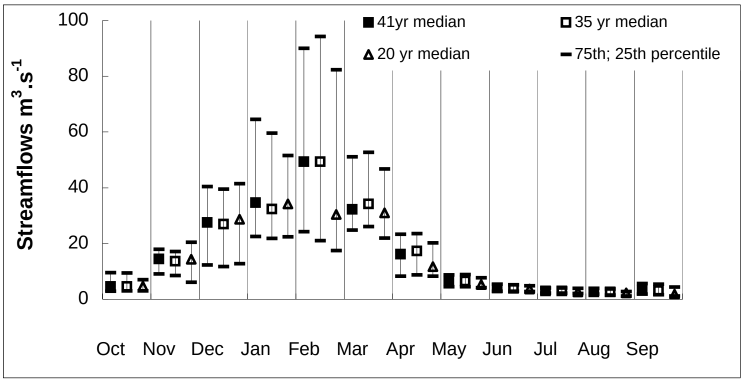


Figure 7.3 Variation of monthly means of water condition (representing the hydrological parameters of Group 1 of the IHA) of the upper Mkomazi River for three different record lengths backdated from 2000. Median values for different record lengths are shown, together with the 25th and 75th percentiles of each to indicate the extent of inter-annual variation

41-year record for these hydrological parameters suggesting that at least for the short duration extreme events, the 35 year-record may be sufficient to statistically analyse the extreme low flow events (of Group 2) of the upper Mkomazi River. However, the downward trend in the magnitude of annual minimum events over the 41-year record length may counter the assumption of stationarity of land use (representative natural conditions) over the time period. The Mkomazi River flows throughout the year. Therefore, the number of days of zero flow included as an indicator of hydrologic alteration in Group 2 is not relevant to this case study. The analysis of baseflows, defined by Richter *et al*. (1996; 1997) as "the 7-day minimum flow divided by the annual mean of daily flows" produced very low medians (0.10) for all record lengths, with no discernible differences in inter-annual variation and were, therefore, excluded from Figure 7.4.

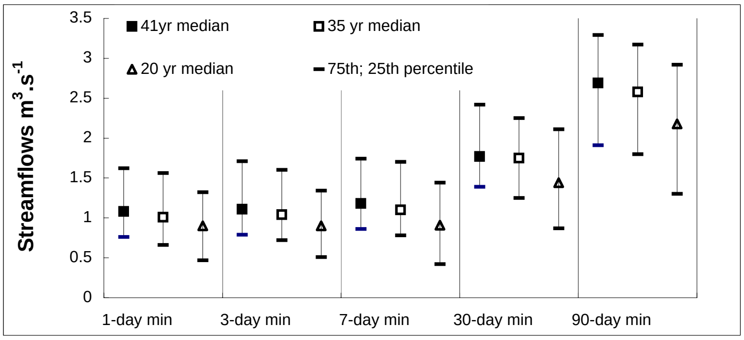


Figure 7.4 Variation of extremes of low flow events (representing the annual minimum day and multi-day events of the hydrological parameters of Group 2 of the IHA) of the upper Mkomazi River for three different record lengths backdated from 2000. Median values for different record lengths are shown, together with the 25th and 75th percentiles of each to indicate the extent of inter-annual variation

Figure 7.5 indicates the variation of the annual maximum events for different record lengths. There is no discernible difference among the median values of extreme high streamflows events for the record lengths. However, there are differences in the inter-annual variation, particularly for the shorter duration high flow events. With the exception of the 3-day maximum, the greatest inter-annual variation for the annual maximum events of Group 2 is associated with the 35-year record. This suggests that even 35 years may be insufficient to statistically analyse the extreme high flow events of the upper Mkomazi streamflow regime.

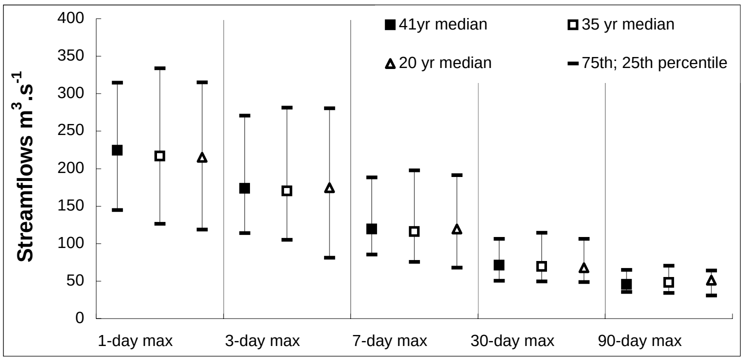


Figure 7.5 Variation of extremes of high flow events (representing the annual maximum day and multi-day events of the hydrological parameters of Group 2 of the IHA) of the upper Mkomazi River for three different record lengths backdated from 2000. Median values for different record lengths are shown, together with the 25th and 75th percentiles of each to indicate the extent of inter-annual variation

The median Julian date of the minimum flow is constant regardless of the record length investigated and there are only 10 days between the timing of the annual maximum flow in the 20-year record compared with 41-year record. Moreover, there is least inter-annual variation (0.06 to 0.15) associated with these hydrological parameters (Group 3) than any of the other parameters.

There is greater similarity among the different record lengths for the median number of low pulses than any other parameter in Group 4 (Figure 7.6) and 20 years of record may be adequate to indicate the number of *both* high and low pulses which characterise the upper Mkomazi River. However, there is much lower inter-annual variation associated with the 20-year record for the duration of both high and low pulses and longer records may be required for these parameters.

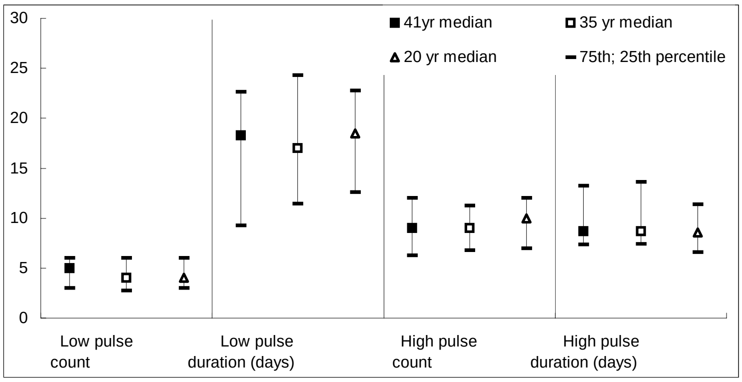


Figure 7.6 Pulsing characteristics (representing the hydrological parameters of Group 4 of the IHA) of the upper Mkomazi for three different record lengths backdated from 2000. Median values for different record lengths are shown, together with the 25th and 75th percentiles of each to indicate the extent of inter-annual variation

There are strong similarities among the record lengths for the hydrological parameters of Group 5. Figure 7.7 shows that 20 years of record would be just as reliable as 41 years to statistically analyse the rates of daily hydrograph rise and fall, together with number of hydrograph reversals, within the streamflow regime of the upper Mkomazi. Additionally, there is fairly low inter-annual variation (0.25 in all record lengths investigated) associated with the number of hydrograph reversals confirming the predictability of this parameter within the streamflow regime of the upper Mkomazi River.

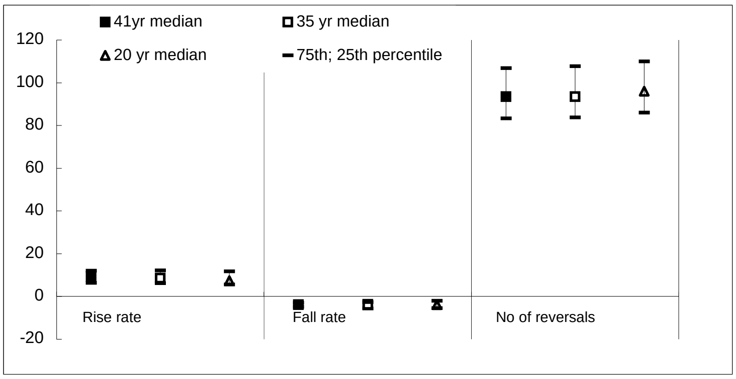


Figure 7.7 Rate and change in water conditions (representing the hydrological parameters of Group 5 of the IHA) of the upper Mkomazi for three different record lengths backdated from 2000. Median values for different record lengths are shown, together with the 25th and 75th percentiles of each to indicate the extent of inter-annual variation

7.3.7 The Impact of Extreme Events on the Streamflow Characteristics of the Upper Mkomazi River

A further study was undertaken to assess the impact of extreme daily flows on the streamflow characteristics of the upper Mkomazi River. The magnitude of each of the daily streamflow values for the 41-year record was ranked and the 95th percentile as well as the 5th percentile values of streamflows were determined to represent extreme high and low streamflow conditions respectively. Any daily values greater than the 95th percentile value of 86.850 $m^3.s^{-1}$ as well as any daily values less than the 5th percentile of 1.230 $m^3.s^{-1}$ were replaced in the IHA statistical analysis with a "missing day". This resulted in the exclusion of 300 values between 86.850 $m^3.s^{-1}$ and 637 $m^3.s^{-1}$ together with 300 values between 1.230 $m^3. s^{-1}$ and 0 $m^3.s^{-1}$ from the analysis. The IHA program replaced the excluded values with values interpolated across the gaps in the record. This had the effect of moderating the variability of the streamflow regime. The longest gap of "missing days" across in the record increased from 83 to 124 and this period (4 August to 4 December 1976) was checked to ensure that the interpolated values would be realistic and within the natural range for the season.

The results of the assessment of the impact of extreme flows on the hydrological regime of the upper Mkomazi River, using the IHA statistical analysis, are shown as the second time period (extreme values "excluded") in Table 7.2. Table 7.2 shows that extreme flows influence the intra-annual variation of streamflows by increasing the monthly means of streamflows from October to March (essentially the high flow season) and by reducing the monthly means of streamflows at the end of the low flow season (August and September). The influence of extreme high flows on the inter-annual variation of the monthly means of streamflows (Group 1) is greater (*e.g*. CD of 1.31 compared to 0.59 in February) than that of extreme low flows (*e.g*. little to no change in CDs for April to July). There is also a higher occurrence of high flows in October than for any other low flow month. The impact of the extreme flows characteristic of the Mkomazi River is greatest on the inter-annual variation of the shorter minimum and maximum day and multi-day events and the difference in the date of the minimum and maximum day events results in the lengthening of the low flow season. At the thresholds for the pulsing behaviour of the upper Mkomazi streamflows, set by the IHA program (low pulse is 3.25; high pulse is 21.29), extreme flows have little impact on the average number of low pulses, but they do reduce the extent of inter-annual variation of these occurrences. The impact of extreme flows on the characteristics of the high pulses is negligible. Extreme flows have a greater influence on the inter-annual variation of the hydrograph fall rate than rise rate.

7.3.8 Likely Alteration of Mkomazi Streamflows as a Result of Catchment Development

The proximity of the Durban-Pietermaritzburg metropolitan area is expected, in time, to impact on the Mkomazi Catchment water resources. Potential dam sites have been identified for inter-basin transfer and rural water supply (Figure 7.1) and to meet increased water demands for commercial as well as subsistence agriculture. There are also plans to barrage the Mkomazi River to augment year-round productivity at the Sappi-Saicorr paper mill on the Mkomazi estuary. The indicators of hydrologic alteration identified by Richter *et al*. (1996, 1997) were utilised to assess the impacts of likely development on the Mkomazi streamflows. Richter *et al*. (1996; 1997 and 1998) highlight the potential of the indicators of hydrologic alteration to set preliminary ecosystem management targets for river systems for which there is limited ecological or habitat information, but where adequate streamflow records or simulated streamflows exist, using a technique called the "range of variability approach" (RVA).

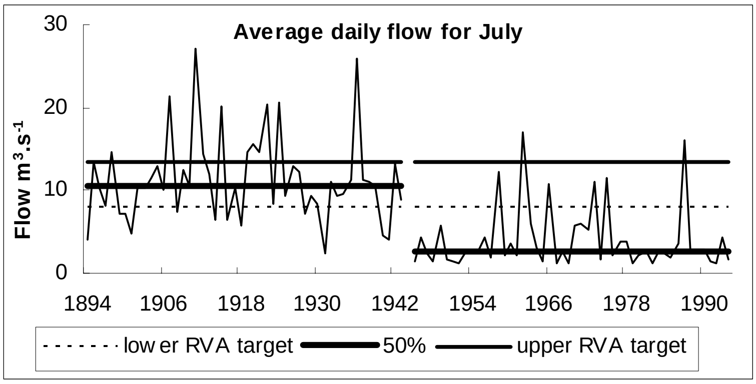
The *ACRU* agrohydrological model was applied to simulate daily streamflows for each of the four IFR sites (Figure 7.1) identified by the Mkomazi BBM workshop held in 1998 (DWAF, 1998b). A 51-year time series of daily rainfall was applied using *ACRU* to simulate streamflows resulting from different scenarios for the Mkomazi Catchment. The IHA technique was applied to statistically compare the *ACRU* streamflows simulated to represent "natural" conditions (using the water use coefficients of Acocks' veld types; Acocks', 1988), with those streamflows simulated to represent different catchment development scenarios. The 25th and 75th percentile values of each of the 33 hydrological parameters for the pre-impact (Acocks') time series of streamflows were assessed as hypothetical lower and upper management targets.

There is a development proposal to transfer water by pipeline from the Mkomazi Catchment to augment the adjacent Mgeni Catchment. Several transfer phases have been considered, one being the construction of the proposed Smithfield Dam (shown in Figure 7.1) downstream of gauging station U1H005 and the first of four IFR sites on the Mkomazi River. Examples of the likely alteration of the hydrological regime at the second IFR site downstream of the proposed Smithfield Dam are shown in Figure 7.8. After the construction of the Smithfield Dam, the decrease in July streamflows shifts the majority of yearly values of flows to below the 25th percentile (lower RVA target) of pre-impact streamflows for July. The average length of low pulses is much longer after the construction of the dam, with most durations being above the 75th percentile (upper RVA target) of pre-impact low pulse durations. Based on the RVA analysis, management plans for this river reach should clearly look to efficient reservoir operating rules for the Smithfield Dam in order to ameliorate the impacts of inter-basin transfer on the hydrological regime.

7.4 DISCUSSION

The statistical analyses of the different record lengths of Mkomazi streamflows identified that a period of wet conditions was absent from the 20-year record, yet was statistically tempered by the 41-year record. This resulted in the 35-year record displaying the greatest inter-annual variation for several of the hydrological parameters relating to high flow events, in particular the streamflows assessed for February and March and the annual maxima multi-day flows. Despite relatively low differences between the 41-year record and the 35-year record for median values, longer than 35-years of record may be needed to statistically analyse the inter-annual variability of high flow events in the Mkomazi streamflow regime. In contrast, 20 years of record appears to be sufficient to statistically analyse the inter-annual variation associated with low flow events. These features are indicative of the problems associated with the characterisation of flows for highly variable rivers, even when daily flows are available for statistical analyses. In Southern Africa, it is more often the case that streamflows are available at only monthly and annual time steps and as such any meaningful statistical analysis of the characterisation of streamflow regimes becomes even less clear.

The monthly means of streamflows (Group 1) are a suitable indicator of the seasonality of the low flows and start of high flow season of the Mkomazi River, with particular relevance attached to the first of season flushing flows for October. This concurs with the work of Hughes *et al*. (1998) relating to possible hydrological indices for rivers within Southern Africa, who found that there was a stronger relationship between the monthly distribution of low flows than of high flows required for different river systems. The low impact of extreme flows in low flow months substantiates the rigor of the monthly means of streamflows as suitable indicators of hydrologic alteration. However, it is practical to surmise that since these flows represent general flow conditions, they may not be as suitable as indicators of alteration as other components of the highly variable streamflow regimes. The inter-annual variability associated with high flow months indicates a much greater degree of environmental



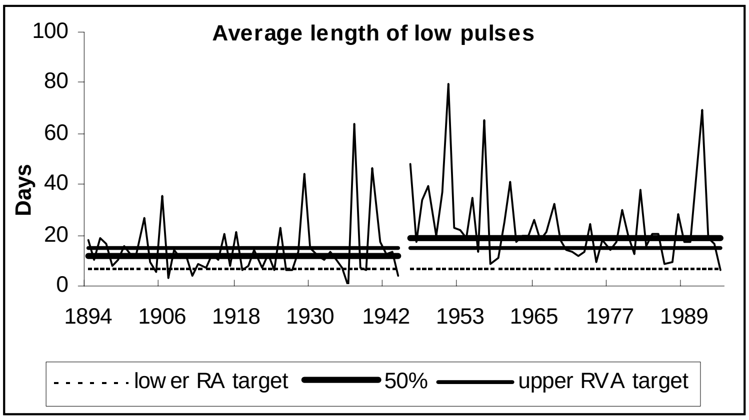


Figure 7.8 Examples of changes in the hydrological regime at IFR Site 2, downstream from the proposed Smithfield Dam on the Mkomazi River, together with potential upper (75th percentile) and lower (25th percentile) RVA management targets

uncertainty and as such the magnitudes of flows in these months are less suitable as indicators of hydrologic alteration.

The annual minimum day and multi-day events are more appropriate as indicators of hydrologic alteration than the annual maximum extremes of flow for similar reasons as those given above. There is more predictability associated with minimum extreme events, especially for the longer multi-day events making these the most suitable indicators within Group 2. This study has shown that the baseflows (also Group 2) as defined by Richter *et al*. (1996, 1997), are not pertinent as an indicator of hydrologic alteration of highly variable rivers, since the 7-day minimum flow is such a small proportion of the annual mean of daily flows. As discussed by Hughes and Münster (2000) a more suitable definition of a baseflow index lies in the traditional separation of the hydrograph to isolate the low amplitude "baseflow" response to climatic conditions. Smakhtin and Toulouse (1998) found a consistent relationship between low flow indices extracted from flow duration curves of daily flows and the baseflow proportion of total flow. In addition, Hughes and Münster (2000) found a strong relationship between the Q75 (the flow equalled or exceeded for 75% of the time) and the baseflow proportion of total flow. The Q75 would seem a more suitable parameter to use as an indicator of baseflows for highly variable rivers.

Jewitt *et al*. (1999) found in a previous study, that for highly variable river systems, there was limited usefulness associated with the Julian date of minimum and maximum flows in Group 3. However, the present study indicates that these parameters are reasonably predictable in the Mkomazi streamflow regime, and as such are suitable indicators of alteration.

Extreme flows have little impact on the pulsing behaviour of the Mkomazi streamflows in Group 4. This suggests that these parameters are suitable indicators of hydrologic alteration. The appropriateness of the parameters in Group 5 as indicators of hydrologic alteration of the Mkomazi streamflows is less clear. However, of these, the number of hydrograph reversals is the most suitable, since it experiences least change as a result of extreme flows.

Notwithstanding the usefulness of the deviation factor and significance counts output by the IHA program when comparing one time series with another, comparative statistical tests would be required to test whether the differences exhibited between the different record lengths and hydrological parameters are significant. Furthermore, although the Mkomazi streamflows are highly variable when compared to streamflows of rivers in more temperate climates, the Mkomazi Catchment is, at times, relatively wet by Southern African catchment standards. Therefore, additional studies should be carried out for catchments in other eco-regions to test the findings of this case study.

Nonetheless, the major benefit of the indicators of alteration is that preliminary targets for streamflow events, designed to protect natural aquatic biodiversity and aquatic ecosystems, can be set using either historical hydrological data or simulated hydrological information. The absence of adequate aquatic ecosystem and climatic data, as well as for observed streamflow, is common for South African catchments and rivers. Consequently, there is great scope for the application of the RVA in South African catchments where river management objectives for the Reserve are still being defined. The indicators of hydrologic alteration provide a link between river flow and river condition by identifying critical variations in magnitude, timing, duration, frequency and rate of change of streamflows. The uncomplicated approach could offer water resources managers considerable potential as a preliminary assessment of the range of flows required for aquatic ecosystem functioning.

7.5 ACKNOWLEDGEMENTS

Mr Steven Lynch of the School of Bioresources Engineering and Environmental Hydrology provided guidance on the experimental design of the investigation of the hydrological parameters as suitable indicators of hydrological alteration described in this chapter.

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CHAPTER 8

PLANNING FOR THE ENVIRONMENTAL RESERVE OF THE MKOMAZI CATCHMENT

Valerie Taylor, Roland Schulze and Graham Jewitt

ABSTRACT

Hydrological regimes play a major role in structuring the biotic diversity within river ecosystems and hydrological variation is recognised as a primary driving force within those ecosystems. The US Nature Conservancy developed a method known as the Indicators of Hydrological Alteration, IHA, for assessing the degree of hydrological alteration attributable to human induced changes within an ecosystem. The method is based on the statistical analyses of 33 hydrological parameters representing five components of streamflow characteristics that can be attributed to playing major roles in determining the nature of aquatic and riparian ecosystems (Richter *et al*., 1996, 1997 and 1998). The Range of Variability Approach, RVA, (Richter *et al*., 1997) is an application of the IHA, incorporating the concepts of hydrological variability and river ecosystem integrity, and was developed to enable river managers to define and adopt preliminary flow management targets before conclusive, long-term ecosystem research results are available. This paper presents an application of the RVA to simulated streamflows at two of the four Instream Flow Requirements (IFR) Sites on the Mkomazi River in KwaZulu-Natal in order to assess the extent of alteration caused by human induced changes to the hydrological regime. The assessment was achieved by comparing the range of variation of the hydrological regime simulated under natural catchment conditions (pre-impact) with the variation resulting from catchment development (post-impact). The 25th and 75th percentile values of each of the 33 parameters were selected as the lower and upper thresholds within which streamflow management targets could be set. By setting preliminary streamflow management thresholds which can be modified and refined when ecological data and information becomes available, the RVA incorporates flexibility and adaptability.

KEY WORDS: hydrological regime; indicators of variation; aquatic and riparian ecosystems; preliminary flow management targets

8.1 INTRODUCTION

Scientists are challenged by the question of how much water rivers need to maintain aquatic health and to sustain the integrity of aquatic and riparian ecosystems. This has become all the more pressing in South Africa, since, under the provisions of the South African National Water Act (NWA) of 1998 (Act 36 of 1998), some water must be set aside as an environmental Reserve to protect the ecological functioning of rivers and the resource base itself. However, the process for determining the Reserve is not due for publication until 2003 and in the interim the Department of Water Affairs and Forestry (DWAF) has initiated the setting of a preliminary ecological Reserve for water resources planning projects. Expertise to assess the environmental flow requirements of South African freshwater systems is based on knowledge of the influence of flow on stream processes (King and Tharme, 1994) and the most sophisticated techniques acknowledge that the natural variability of flow regimes is an important determinant in the ecological functioning of river systems.

Recognising that hydrological variation plays a major role in structuring the biotic diversity within river ecosystems, the US Nature Conservancy developed the Indicators of Hydrologic Alteration, IHA, Richter *et al*. (1996, 1997), to characterise the natural range of streamflow variation, based on the analysis of daily streamflow data. The IHA is a statistical analysis of 33 ecologically relevant hydrological attributes that characterise intra-annual variation in the streamflow regime. The IHA method comprises the statistical analyses of computations of the central tendency (mean or median) and dispersion (standard deviation or coefficient of variation) for each of the 33 hydrological parameters for each year of record to characterise the inter-annual streamflow variation (Richter *et al*. 1996). The development of the Range of Variability Approach, RVA, (Richter *et al*., 1997) arose from the application of the IHA and is intended for use in setting streamflow based aquatic management targets, based on the statistical analysis of the 33 hydrological parameters. The RVA was developed to enable river managers to define and adopt preliminary flow management targets before conclusive, long-term ecosystem research results are available. In this paper the RVA is presented as an approach for setting streamflow based aquatic ecosystem management targets for the Mkomazi Catchment in KwaZulu-Natal.

8.2 RANGE OF VARIABILITY APPROACH

The fundamental premise of the RVA is to guide efforts to restore or maintain the natural streamflow regime of a river using a range of the natural inter-annual variability in 33 ecologically relevant flow parameters (cf, Table 8.1) as the basis for setting streamflow management targets. The RVA recognises the relationship between the characteristics of river flow and river habitat condition and addresses the critical role of hydrological variability in the natural flow regime. The methodology considers the magnitude, timing, frequency, duration and rate of change of streamflows (Table 8.1) required to sustain aquatic ecosystems. The developers consider that the approach will be most appropriate when protection of the natural aquatic biodiversity and aquatic ecosystem are the primary management objectives. To this extent the approach addresses the issues identified by DWAF in its assessment of the preliminary ecological Reserve.

Table 8.1 Summary of hydrological parameters used in the Indicators of Hydrologic Alteration (IHA) and their characteristics (after Richter *et al*., 1996)

IHA Statistics Group	Regime Characteristics	Hydrological Parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means Number of zero days 7-day minimum flow divided by mean daily flow for each year ("base flow")
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day minimum Julian date of each annual 1-day maximum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses each year ("high pulse" being defined as those periods within a year when the daily streamflow rises above the 75th percentile of all daily values) Number of low pulses each year ("low pulse" being defined as those periods within a year when the daily streamflow falls below the 25th percentile of all daily values) Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values Number of rises Number of falls

8.3 THE RVA METHODOLOGY

The developers of the RVA methodology identify six fundamental steps for setting, implementing and refining management targets and rules for specific rivers or river reaches (Richter *et al*., 1997). The following sections summarise the salient points of each step described by Richter *et al*. (1997).

The first step is to characterise the natural range of streamflow variation using the IHA method described by Richter *et al*. (1996). Where daily streamflow records representing natural conditions are inadequate or incomplete, existing records may be infilled or extended using regression relationships between the site of interest and other less perturbed streamflow-gauging sites (Richter *et al*., 1997). Where no streamflow records exist, the records of reference catchments with adequate record lengths and with similar climate and geology as well as minimal anthropogenic effects can be used. This will require adjustment to the streamflow data or statistical characteristics to account for differences in catchment area and driving variables such as rainfall. Alternatively, a simulation model such as the *ACRU* agrohydrological model (Schulze, 1995) could be applied to generate a daily time series of flows to represent defined baseline natural conditions. However, it is imperative that adequate verification of the simulation output is performed to validate the use of the generated time series. The developers suggest that a minimum of 20 years of data is required to minimise the effects of inter-annual climatic variation on the IHA parameter statistics Richter *et al*. (1997). This is based on research by the developers that showed that the range of estimates of the mean annual 1-day maximum from three different stream types in the United States begins to narrow substantially when based on at least 20 years of record. However, for southern African conditions, where statistical analyses can be influenced by a particularly wet or dry spell of years, especially where periodic fluctuations with approximately 20-year oscillations have been identified (Tyson, 1986), longer record lengths may be required (Schulze *et al* 1995).

The second step comprises the selection of management targets that fall within the natural range of each of the 33 IHA parameters, based on the inter-annual measure(s) of dispersion used in Step 1. Ideally, the management targets should be based on available ecological information. There is, however a paucity of such information in southern Africa and in such instances the developers recommend that the ± 1 standard deviation from the mean or the 25th to 75th percentile range of each of the 33 IHA parameters are selected for preliminary flow-based management targets (RVA targets).

Using the RVA targets as guidelines, the third step requires that river managers design a management system comprising a set of rules that allow the targets to be met. A management system could include a viable set of reservoir operating rules, including restrictions on abstractions, or restorative land use practices.

The fourth step involves the application of a monitoring and ecological research programme to assess the response of ecosystems to the management system described in Step 3. Catchment management strategies in the form of restorative land use programmes (e.g. the removal of alien invasive riparian vegetation) and modifications to dam operating rules can be assessed at this stage.

The fifth step is to apply the IHA methodology to characterise the actual streamflow alteration. Comparison is made of the values of each of the 33 parameters with the RVA targets to identify whether targets resulting from the implementation of any management system (Step 3) are met. This should be performed on an annual basis to assess the previous year's management system.

The final step is a reiteration of steps 2 to 5, incorporating the results of the preceding years' management system and any additional ecological research or monitoring information required to refine the management system or the RVA targets.

8.4 MKOMAZI RIVER CASE STUDY

It has been projected that by 2008 some form of impoundment of the Mkomazi River will be required to augment the water supply in the neighbouring Mgeni Catchment to meet the water demand of the Durban-Pietermaritzburg region (DWAF, 1998a). The hydrological dynamics of the Mkomazi catchment were modelled with the *ACRU* model to assess the impacts of land use changes and proposed developments on the availability of water resources. The Mkomazi Catchment was configured to represent 52 major inter-linked subcatchments, based essentially on a division of the 12 DWAF Quaternary Catchments and focusing on different land uses and management practices as well as proposed development concerns. The final configuration includes, inter alia, 2 major proposed dam sites (Impendle and Smithfield) and 4 instream flow requirement (IFR) sites, all on the Mkomazi River (Figure 8.1). Impact-of-land use and development scenario studies, using the *ACRU* model, were performed to simulate the impacts of first, baseline land cover, secondly, present land use and thirdly, present land use, but with the first phase of the Mkomazi-Mgeni Transfer Scheme (MMTS). For the purposes of this study:

- baseline land cover conditions were defined as Acocks' Veld Types (Acocks'1988)
- present land use conditions were defined in accordance with Thompson's (1996) land classification and the interpretation of the 1996 LANDSAT TM image and
- *ACRU* simulated daily streamflows were generated with the assumption that under Phase 1 of the MMTS, the total dam storage capacity is 137 x $10^6 m^3$ with a daily draft of 604.8 x $10^3 m^3$ out of the Mkomazi system (DWAF, 1998a). In the absence of defined reservoir operating rules, legal flow releases, assumed to be 91.33 x $10^3 m^3$, i.e. 1/1500 x the full capacity, each day, for downstream use were simulated, on two conditions incorporated in the *ACRU* model, viz.
  - if the total streamflow into the reservoir on a given day was less than the normal flow releases, the releases were reduced to equal those of the total inflows
  - if the storage volumes were below dead storage level, no normal flow releases were made.

The instream flow requirements for the Mkomazi River were assessed in March 1998 (DWAF, 1998b) by an IFR workshop using a technique known as the Building Block Methodology (BBM). The workshop participants defined and determined the management class of representative reaches and focused on four unique sites at which flow characteristics required to maintain the integrity of the aquatic ecosystem were evaluated. IFR Site 1 is upstream of the proposed Smithfield Dam, whereas IFR Sites 2, 3 and 4 are all downstream of the proposed Dam site (Figure 8.1). In this paper, the hydrological alteration and preliminary management targets of streamflows at the upper 2 sites will be discussed since these sites represent alteration resulting from present land use (IFR Site 1) and from inter-basin transfer (IFR Site 2 being the uppermost of the 3 downstream IFR Sites). The upper part of the Mkomazi Catchment is largely undeveloped, and the upper reach of the river is in good condition.

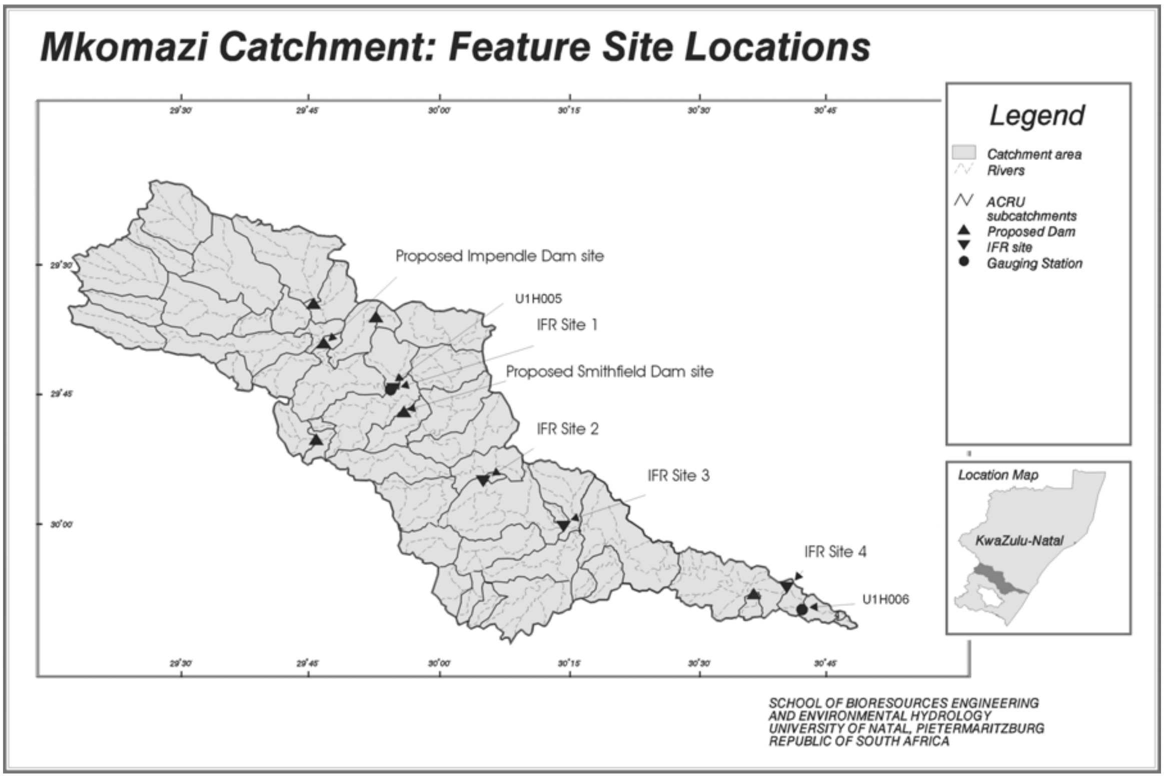

Figure 8.1 Mkomazi Catchment: Feature site locations

Therefore, the BBM workshop participants attributed a category C/B (where A represents pristine conditions and D represents degraded conditions) to the present state class of the macro-reaches in which both IFR Sites 1 and 2 are situated. However, the workshop participants considered it important that the habitat, instream and riparian integrity of these macro-reaches be protected from degradation. Therefore, the workshop set a protective management class of category B for the macro-reaches upstream of both IFR Sites 1 and 2.

8.5 APPLICATION OF THE RVA FOR THE MKOMAZI STREAMFLOWS

The RVA was applied as a preliminary assessment of management targets for the Mkomazi Catchment streamflows at IFR Sites 1 and 2. This comprised the comparison of the hydrological regime at both IFR sites under baseline land cover conditions (pre-impact conditions) with post-impact conditions. The hydrological regimes for both pre- and post-impact conditions, at both sites, were simulated using the *ACRU* model to generate time series of daily flows. Schulze *et al*. (1995) have show a map for Southern Africa indicating the minimum rainfall record lengths required to ensure that the means of annual rainfall estimates are within 10% of the long term mean 90% of the time. For the region comprising the Mkomazi Catchment, they suggest a minimum MAP record length of 20 years. Furthermore, Schulze *et al*. (1995) surmise that for a daily model such as *ACRU*, the ideal minimum record lengths require to be double those for MAP as given in the map. A 51-year time series of daily rainfall was applied using the *ACRU* model to simulate daily streamflows resulting from different scenarios.

For IFR Site 1 the comparison was made with *ACRU* simulated daily streamflows from present land use. For IFR Site 2 the comparison was made with the streamflow regime after the construction of Phase 1 of the MMTS. Comparisons were made assuming a hypothetical continuous time span from October 1894 to September 1996, separating the two time series of simulated streamflows with “the impact”. Each RVA analysis was performed using non-parametric (i.e. percentile) statistics and the programme output was provided in the form of a summary scorecard, percentile statistics, an annual summary and graphs. Typically, the RVA scorecards provide the following information (Richter *et al*., 1997):

- Columns 1 – 4 show the median, coefficient of variance, and low and high extreme values for each parameter during the pre-impact period.
- Columns 5 – 8 show the same information for the post-impact period.
- Columns 9 – 10 show the low and high RVA targets. These percentiles are used to set preliminary ecosystem management targets. The user may define different RVA targets, based on appropriateness to local management plans or as additional hydrological and ecological information becomes available. If the target falls outside the range of the pre-impact data, it is replaced by the pre-impact range limit.
- Column 11 shows the hydrological alteration, defined as

$$\frac{\text{Observed} - \text{Expected}}{\text{Expected}}$$

where: Expected = the frequency (i.e. number of years) with which annual statistics fall within the RVA limits in the pre-impact period, and

Observed = the frequency (i.e. number of years) with which annual statistics fall within the RVA limits in the post-impact period.

The second panel of the table provides a comparison of the data within, above and below the RVA range for the pre- and post-impact periods. Expected and observed frequencies, and the RVA range of alteration (= observed – expected) are shown for the values above the RVA limits, below and within the limits. Where the calculated frequency is equal to either threshold limit, the RVA analysis places the occurrence within the range limits. Where this occurs, warnings are printed at the bottom of the table.

In the absence of river management plans for the Mkomazi, the upper and lower thresholds of the target range were set at the 75th and 25th percentiles of the range of natural variation for each of the 33 parameters.

8.6 RESULTS OF RVA APPLICATION AT MKOMAZI IFR SITE 1

The statistics in Table 8.2 show that management plans to enhance the hydrological regime at IFR Site 1 should focus on attempts to increase flows in low flow months. Of these months, streamflows resulting from present land use in the winter months of July through to September show the highest alteration from the set RVA target range and the greatest number of below range years (i.e. monthly mean of daily flows less than the lower RVA target of the 25th percentile). This is illustrated in Figure 8.2 (a) for July. Correspondingly, the alteration from the RVA range for the extreme flows, shown in Table 8.2, is greatest for the shorter minimum day and multi-day flows, with a substantial increase in the number of years in which the 1-, 3- and 7-day minimum flows do not meet the lower threshold. Table 8.2 shows that there is also some depression of baseflows. However, most of the seasonal flows remain within the target range, as shown in Figures 8.2 (b) and (c). Table 8.2 shows that the frequency of low pulses increases as a result of present land use, with 21 yearly values of counts (compared with the pre-impact count of 11) being above the upper RVA target. This is exacerbated by the shortening of low pulse durations, more of which (17 post-impact compared to 12 pre-impact) now occur below the lower RVA target set (Figure 8.2 (d) and Table 8.2), further substantiating the need for management plans to address the performance of present low flows. High pulse counts and their durations are less impacted by present land uses, but together with the alteration in low pulse counts and their durations, result in alteration in the hydrograph rise and fall rates. This results in all numbers of hydrograph reversals occurring above the upper RVA target, indicating an increase in intra- and inter-annual environmental variation. Summer high flow months show less alteration than winter low flow months, with only slight increases in the occurrence of flows below the target range. Moreover, the daily and multi-day maximum extreme flows are, generally, very similar to those under natural conditions.

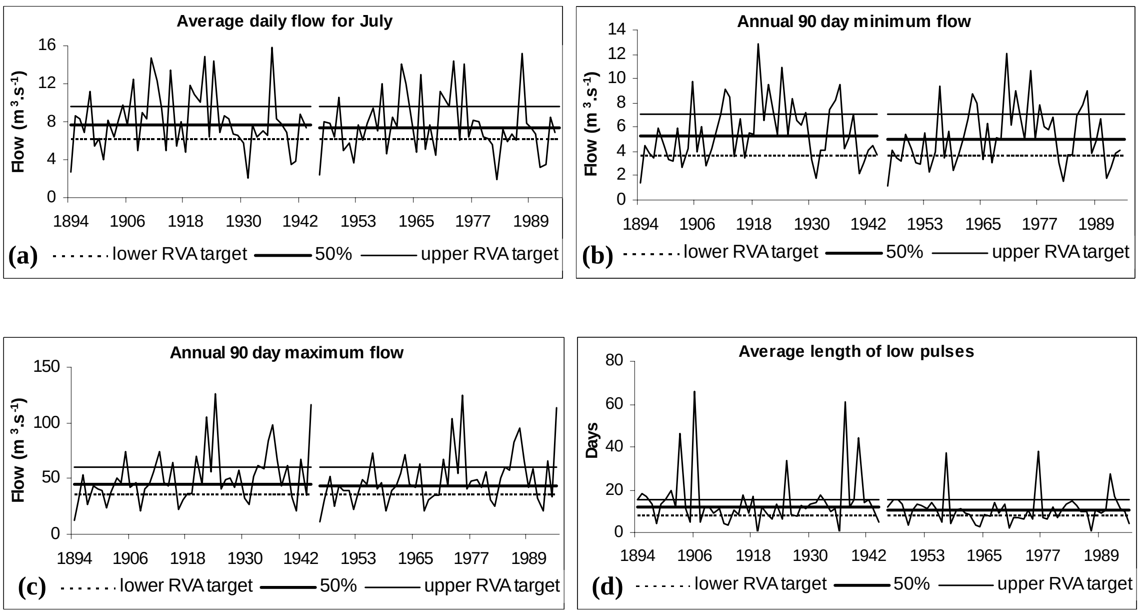

Figure 8.2 Examples of changes in the hydrological regime, with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 1 on the Mkomazi River

The RVA analysis of hydrological variation generated warnings regarding the yearly values of the low and high pulse counts and number of hydrograph falls equal to either the upper or lower RVA limits. These occurrences, for both pre- and post-impact analysis, have been included as being within the target range limits. For example, over the entire record period, 9 of the yearly values of low pulse counts are equal to the lower target of 4, and 7 yearly values are equal to the upper target of 8. The RVA analysis places these occurrences as being within the management range. The statistical relevance associated with this warning is that 3 of the yearly values of low pulse counts under natural flow conditions were equal to the upper RVA limit and 8 were equal to the lower RVA limit. While thresholds for statistical analysis have to be set, the RVA table results should be viewed with caution where the warnings are generated by the calculation. However, the results do not detract from the

Table 8.2 RVA score card: Mkomazi IFR Site 1

Parameter	Units	Pre-impact period October 1894 - September 1945 (51 years) Medians	Coefficient of Variance	Range Limits Low	Range Limits High	Post-impact period October 1945 - September 1996 (51 years) Medians	Coefficient of Variance	Range Limits Low	Range Limits High	RVA TARGETS Low	RVA TARGETS High	HYDROLOGIC ALTERATION
Group 1	**Units**											
October	$m^3.s^{-1}$	6.50	1.29	1.50	81.60	6.00	1.34	1.20	79.50	3.45	11.75	-0.04
November	$m^3.s^{-1}$	13.70	0.88	3.00	43.70	13.30	0.89	2.70	42.80	8.67	20.71	-0.08
December	$m^3.s^{-1}$	22.40	0.84	4.30	89.10	21.80	0.83	4.00	86.50	14.76	33.52	-0.08
January	$m^3.s^{-1}$	37.00	0.70	6.80	118.20	35.90	0.71	6.30	115.90	25.25	51.29	-0.08
February	$m^3.s^{-1}$	44.30	0.64	8.40	120.60	42.90	0.67	8.20	119.30	30.48	58.95	-0.12
March	$m^3.s^{-1}$	42.00	0.52	13.90	153.60	40.40	0.53	13.10	151.60	31.27	53.06	-0.04
April	$m^3.s^{-1}$	27.60	0.53	5.50	72.00	27.20	0.54	5.40	71.70	19.84	34.55	0.00
May	$m^3.s^{-1}$	16.40	0.57	3.40	95.00	16.00	0.56	3.20	93.40	12.67	21.98	0.04
June	$m^3.s^{-1}$	11.10	0.45	2.30	25.20	10.60	0.46	2.10	24.80	8.55	13.58	0.00
July	$m^3.s^{-1}$	7.70	0.42	2.10	44.50	7.40	0.43	1.90	43.20	6.30	9.57	-0.15
August	$m^3.s^{-1}$	5.80	0.68	1.80	29.40	5.40	0.69	1.60	28.30	4.52	8.45	-0.08
September	$m^3.s^{-1}$	5.20	1.04	1.40	113.70	4.80	1.06	1.20	111.90	3.57	8.94	-0.12
Group 2												
1-day minimum	$m^3.s^{-1}$	2.40	0.51	0.70	7.30	1.80	0.60	0.50	6.60	1.96	3.18	-0.58
3-day minimum	$m^3.s^{-1}$	2.40	0.54	0.80	7.30	2.00	0.61	0.60	6.80	1.99	3.29	-0.38
7-day minimum	$m^3.s^{-1}$	2.60	0.52	0.80	7.50	2.30	0.61	0.60	7.00	2.18	3.55	-0.38
30-day minimum	$m^3.s^{-1}$	3.10	0.83	1.10	9.00	2.80	0.92	0.80	8.40	2.25	4.78	-0.04
90-day minimum	$m^3.s^{-1}$	5.30	0.65	1.40	12.90	5.00	0.67	1.20	20.70	3.67	7.08	0.04
1-day maximum	$m^3.s^{-1}$	134.20	0.81	48.20	1168.90	130.60	0.81	45.80	1166.90	102.15	211.18	0.00
3-day maximum	$m^3.s^{-1}$	114.10	0.77	43.50	882.10	109.50	0.78	41.10	873.10	85.76	173.45	-0.19
7-day maximum	$m^3.s^{-1}$	85.70	0.79	38.20	568.40	82.10	0.80	37.50	560.90	65.60	133.12	0.04
30-day maximum	$m^3.s^{-1}$	60.60	0.58	16.90	182.20	58.90	0.58	16.00	176.10	45.75	81.04	-0.08
90-day maximum	$m^3.s^{-1}$	45.20	0.53	12.00	126.60	43.50	0.53	11.40	124.40	36.04	59.90	-0.04
Number of zero days	number	0	0	0	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.45	0.05	0.31	0.12	0.44	0.04	0.30	0.10	0.16	-0.04
Group 3												
Date of minimum	day	274	0.08	227	340	274	0.07	224	339	268.75	297.5	0
Date of maximum	day	39.5	0.15	2	361	39.5	0.15	2	361	33.75	163.5	0
Group 4												
Low Pulse Count	number	5.50	0.73	0.00	17.00	7.00	0.57	1.00	18.00	4.00	8.00	-0.17
Low Pulse Duration	days	11.80	0.58	0.00	66.00	10.30	0.56	1.00	38.00	8.65	15.46	0.15
High Pulse Count	number	7.50	0.53	2.00	24.00	8.00	0.66	2.00	23.00	6.00	10.00	-0.19
High Pulse Duration	days	9.80	1.31	2.20	46.50	9.50	1.13	2.00	46.00	5.42	18.19	0.08
Group 5												
Rise rate	$m^3.s^{-1}.day^{-1}$	8.30	0.51	3.40	25.70	5.40	0.47	2.20	17.10	6.17	10.38	-0.58
Fall rate	$m^3.s^{-1}.day^{-1}$	-2.30	-0.50	-6.50	-1.00	-2.70	-0.55	-7.40	-1.30	-2.95	-1.79	-0.08
Number of reversals	number	103.00	0.12	84.00	128.00	164.50	0.27	118.00	211.00	96.75	109.50	-1.00

Comparison of Statistics Within, Above and Below RVA Range

Parameter	Within Expected	Within Observed	RVA Range Alteration	Above Expected	Above Observed	RVA Range Alteration	Below Expected	Below Observed	RVA Range Alteration
Group 1									
October	26	25	-0.04	13	12	-0.08	12	14	0.17
November	26	24	-0.08	13	13	0	12	14	0.17
December	26	24	-0.08	13	13	0	12	14	0.17
January	26	24	-0.08	13	13	0	12	14	0.17
February	26	23	-0.12	13	13	0	12	15	0.25
March	26	25	-0.04	13	13	0	12	13	0.08
April	26	26	0	13	12	-0.08	12	13	0.08
May	26	27	0.04	13	11	-0.15	12	13	0.08
June	26	26	0	13	12	-0.08	12	13	0.08
July	26	22	-0.15	13	12	-0.08	12	17	0.42
August	26	24	-0.08	13	11	-0.15	12	16	0.33
September	26	23	-0.12	13	10	-0.23	12	18	0.5
Group 2									
1-day minimum	26	11	-0.58	13	12	-0.08	12	28	1.33
3-day minimum	26	16	-0.38	13	12	-0.08	12	23	0.92
7-day minimum	26	16	-0.38	13	12	-0.08	12	23	0.92
30-day minimum	26	25	-0.04	13	12	-0.08	12	14	0.17
90-day minimum	26	27	0.04	13	10	-0.23	12	14	0.17
1-day maximum	26	26	0	13	12	-0.08	12	13	0.08
3-day maximum	26	21	-0.19	13	13	0	12	17	0.42
7-day maximum	26	27	0.04	13	11	-0.15	12	13	0.08
30-day maximum	26	24	-0.08	13	12	-0.08	12	15	0.25
90-day maximum	26	25	-0.04	13	12	-0.08	12	14	0.17
Number of zero days	51	51	0	0	0	0	0	0	0
Base flow	26	25	-0.04	13	10	-0.23	12	16	0.33
Group 3									
Date of minimum	26	26	0	13	11	-0.15	12	14	0.17
Date of maximum	26	26	0	13	13	0	12	12	0
Group 4									
Low Pulse Count	30	25	-0.17	11	21	0.91	10	5	-0.5
Low Pulse Duration	26	30	0.15	13	4	-0.69	12	17	0.42
High Pulse Count	31	25	-0.19	9	13	0.44	11	13	0.18
High Pulse Duration	26	28	0.08	13	10	-0.23	12	13	0.08
Group 5									
Rise rate	26	11	-0.58	13	5	-0.62	12	35	1.92
Fall rate	26	24	-0.08	13	5	-0.62	12	22	0.83
Number of reversals	26	0	-1	13	51	2.92	12	0	-1

general trend of the hydrological alteration and are therefore still valuable for assessing whether the management targets can be achieved.

Based on the RVA analysis, it can be recommended that catchment management plans to enhance the conditions of the river reaches upstream of IFR site 1 on the Mkomazi River to a class B ecological management category from a present state class C/B should include objectives to:

- maintain historical winter low flows,
- elevate the baseflow regime,
- decrease the frequency of low pulses and increase their duration,
- decrease the frequency of hydrograph reversals resulting from the increased number of shifts between rising and falling flow levels and
- adjust the rate at which daily flows rise or fall.

The following Best Management Practices (BMP) could be adopted in catchment management strategies to meet these objectives for the upper Mkomazi:

- The removal of alien riparian vegetation to restore the baseflow regime: Alien riparian vegetation is assumed to use more water than the indigenous vegetation with which it competes. In a study on the impacts of the removal of this vegetation, Jewitt *et al*. (2000) found that the most significant improvements in streamflow generation were obtained in the drier winter months.
- The initiation of more water use efficient agriculture in periods of low flow, including irrigation scheduling systems (e.g. Schulze *et al*., 1999).
- The rehabilitation of degraded land to increase infiltrability of water into the soil thereby allowing the timing and duration of surface and subsurface flow reaching the stream channel to become more natural.

If the ecological management category of the Mkomazi River is to be enhanced, careful consideration should be given to the implications of issuing any new afforestation permits or additional licenses for irrigation abstraction. The adoption of any management strategy would benefit greatly from the initiation of a monitoring and research programme to determine the biotic responses to the implementation of the management system (Richter *et al*., 1997).

8.7 RESULTS OF RVA APPLICATION AT MKOMAZI IFR SITE 2

Given the assumptions of legal flow releases described above, Table 8.3 indicates that the hydrological alteration from the RVA target range set for post-dam streamflows at IFR Site 2 for the winter low flow months is greatest from June through to October. However, the impact of catchment development with present land use and Phase 1 of the MMTS is such that the low flow season is extended to include May and November, and with a substantial alteration of December flows. Figure 8.3 (a) shows that the decrease in July streamflows shifts the majority of yearly values to below the lower target range (25th percentile), from 12 occurrences under natural land cover conditions to 44 in post-dam conditions (*cf*. Table 8.3). For all winter low flow months there are substantial reductions in streamflows within the RVA target range, yet only slight reductions in summer high flow months, e.g. January and February both decrease from 26 occurrences to 24 and 22 occurrences respectively, whereas the number for March remains the same at 26 occurrences (Table 8.3).

The alteration of the magnitude of minimum flows as a result of catchment development with present land use and Phase 1 of the MMTS is considerable, with all occurrences of the 1-, 3-, 7- and 30- day minimum flows falling below the lower RVA target. Figure 8.3(b) illustrates this for the 30-day minimum flow. The 1-day and multi-day maximum flows are far less impacted and most still fall within the RVA target range. Table 8.3 also indicates the extent of suppression of the baseflow regime after the construction of the dam, with most occurrences appearing below the lower RVA threshold.

With present land use and the operation of Phase 1 of the MMTS, the number of years in which low pulse counts are within the RVA range is increased (change from 28 to 33, Table 8.3) at the expense of those below the lower target (change from 11 to 4). Furthermore, the average length of low pulses is much longer, with most durations being above the upper RVA threshold (Figure 8.3,c), (viz. 38 occurrences, as shown in Table 8.3). This concurs with the findings described above, that the low flow season is considerably extended under post-dam conditions.

Table 8.3 RVA score card: Mkomazi IFR Site 2

		Pre-impact period October 1894 - September 1945 (51 years)				Post-impact period October 1945 - September 1996 (51 years)				RVA TARGETS		HYDROLOGIC ALTERATION
				Range Limits				Range Limits				
Parameter		Medians	Coefficient of Variance	Low	High	Medians	Coefficient of Variance	Low	High	Low	High	
Group 1	**Units**											
October	m^3.s^{-1}	10.10	0.90	2.40	143.60	2.50	1.10	1.20	127.50	5.69	14.81	-0.77
November	m^3.s^{-1}	21.70	0.70	5.40	67.90	6.70	2.02	1.30	54.00	13.24	28.44	-0.62
December	m^3.s^{-1}	30.90	0.84	5.40	145.10	19.80	1.59	1.50	125.40	22.22	48.28	-0.42
January	m^3.s^{-1}	52.80	0.83	8.00	161.20	42.00	1.05	1.60	147.40	31.97	75.95	-0.08
February	m^3.s^{-1}	62.40	0.64	10.60	174.60	47.70	0.80	2.30	160.40	38.68	78.72	-0.15
March	m^3.s^{-1}	59.60	0.65	20.80	218.50	48.40	0.76	3.20	203.90	41.39	80.20	0.00
April	m^3.s^{-1}	37.00	0.52	7.00	100.50	27.00	0.72	2.00	90.10	26.60	45.88	-0.27
May	m^3.s^{-1}	22.20	0.47	3.80	219.60	12.60	0.79	1.40	206.30	18.04	28.37	-0.69
June	m^3.s^{-1}	15.20	0.47	2.60	33.70	6.10	0.98	1.10	24.00	11.45	18.55	-0.81
July	m^3.s^{-1}	10.50	0.52	2.50	78.00	2.60	1.01	1.10	66.00	7.92	13.32	-0.85
August	m^3.s^{-1}	8.40	0.82	2.30	45.00	2.10	1.42	1.10	29.40	6.14	13.08	-0.85
September	m^3.s^{-1}	7.70	1.03	2.30	220.10	2.00	1.17	1.20	208.60	5.13	13.07	-0.85
Group 2												
1-day minimum	m^3.s^{-1}	3.30	0.72	1.00	10.70	1.20	0.15	0.60	2.30	2.45	4.79	-1.00
3-day minimum	m^3.s^{-1}	3.30	0.74	1.00	10.70	1.30	0.15	0.80	2.40	2.48	4.97	-1.00
7-day minimum	m^3.s^{-1}	3.80	0.56	1.10	10.40	1.30	0.17	0.90	2.50	3.01	5.15	-1.00
30-day minimum	m^3.s^{-1}	4.60	0.67	1.40	11.60	1.50	0.24	1.00	3.00	3.79	6.88	-1.00
90-day minimum	m^3.s^{-1}	7.10	0.71	1.80	15.80	1.80	0.87	1.10	24.50	5.29	10.29	-0.88
1-day maximum	m^3.s^{-1}	222.30	0.75	61.10	2362.70	201.80	0.75	15.30	2435.70	146.11	312.59	-0.08
3-day maximum	m^3.s^{-1}	181.80	0.87	56.90	1757.30	164.90	0.73	11.80	1731.00	117.03	275.51	-0.04
7-day maximum	m^3.s^{-1}	129.00	0.85	51.20	1128.30	113.60	0.78	7.60	1100.30	92.96	203.00	-0.15
30-day maximum	m^3.s^{-1}	87.30	0.73	26.60	340.50	74.20	0.83	4.30	323.00	62.02	126.13	-0.15
90-day maximum	m^3.s^{-1}	65.60	0.64	21.90	180.10	52.80	0.80	7.00	165.20	49.74	91.52	-0.19
Number of zero days	number	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Base flow	fraction of total flow	0.13	0.46	0.05	0.28	0.07	0.67	0.02	0.58	0.10	0.16	-0.65
Group 3												
Date of minimum	day	278.5	0.08	227	339	274	0.06	227	340	268.75	297.5	0.27
Date of maximum	day	28.5	0.21	2	365	36	0.18	6	365	26	272.75	0.11
Group 4												
Low Pulse Count	number	6	0.83	0	20	7	0.71	2	16	4	9	0.18
Low Pulse Duration	days	11.6	0.68	0	64	19	0.76	6.6	79.5	7	14.89	-0.56
High Pulse Count	number	8	0.63	2	19	9	0.69	0	21	6	11	-0.35
High Pulse Duration	days	9.6	1.1	2	63.5	5.7	1.21	0	54	4.98	15.55	-0.08
Group 5												
Rise rate	m^3.s^{-1}.day^{-1}	12.30	0.49	5.50	38.20	6.80	0.51	0.70	24.00	9.66	15.68	-0.85
Fall rate	m^3.s^{-1}.day^{-1}	-3.70	-0.45	-10.10	-1.60	-4.00	-0.65	-13.40	-0.40	-4.49	-2.83	-0.31
Number of reversals	number	104.50	0.14	84.00	132.00	169.50	0.12	135.00	207.00	99.00	114.00	-1.00

Comparison of Statistics Within, Above and Below RVA Range

		Within		RVA Range	Above		RVA Range	Below		RVA Range
Parameter		Expected	Observed	Alteration	Expected	Observed	Alteration	Expected	Observed	Alteration
Group 1										
October		26	6	-0.77	13	5	-0.62	12	40	2.33
November		26	10	-0.62	13	7	-0.46	12	34	1.83
December		26	15	-0.42	13	8	-0.38	12	28	1.33
January		26	24	-0.08	13	9	-0.31	12	18	0.5
February		26	22	-0.15	13	11	-0.15	12	18	0.5
March		26	26	0	13	6	-0.54	12	19	0.58
April		26	19	-0.27	13	8	-0.38	12	24	1
May		26	8	-0.69	13	6	-0.54	12	37	2.08
June		26	5	-0.81	13	5	-0.62	12	41	2.42
July		26	4	-0.85	13	3	-0.77	12	44	2.67
August		26	4	-0.85	13	2	-0.85	12	45	2.75
September		26	4	-0.85	13	3	-0.77	12	44	2.67
Group 2										
1-day minimum		26	0	-1	13	0	-1	12	51	3.25
3-day minimum		26	0	-1	13	0	-1	12	51	3.25
7-day minimum		26	0	-1	13	0	-1	12	51	3.25
30-day minimum		26	0	-1	13	0	-1	12	51	3.25
90-day minimum		26	3	-0.88	13	1	-0.92	12	47	2.92
1-day maximum		26	24	-0.08	13	9	-0.31	12	18	0.5
3-day maximum		26	25	-0.04	13	7	-0.46	12	19	0.58
7-day maximum		26	22	-0.15	13	10	-0.23	12	19	0.58
30-day maximum		26	22	-0.15	13	9	-0.31	12	20	0.67
90-day maximum		26	21	-0.19	13	6	-0.54	12	24	1
Number of zero days		51	51	0	0	0	0	0	0	0
Base flow		26	9	-0.65	13	3	-0.77	12	39	2.25
Group 3										
Date of minimum		26	33	0.27	13	9	-0.31	12	9	-0.25
Date of maximum		27	30	0.11	13	10	-0.23	11	11	0
Group 4										
Low Pulse Count		28	33	0.18	12	14	0.17	11	4	-0.64
Low Pulse Duration		27	12	-0.56	13	38	1.92	11	1	-0.91
High Pulse Count		34	22	-0.35	12	13	0.08	5	16	2.2
High Pulse Duration		26	24	-0.08	13	6	-0.54	12	21	0.75
Group 5										
Rise rate		26	4	-0.85	13	6	-0.54	12	41	2.42
Fall rate		26	18	-0.31	13	15	0.15	12	18	0.5
Number of reversals		29	0	-1	12	51	3.25	10	0	-1

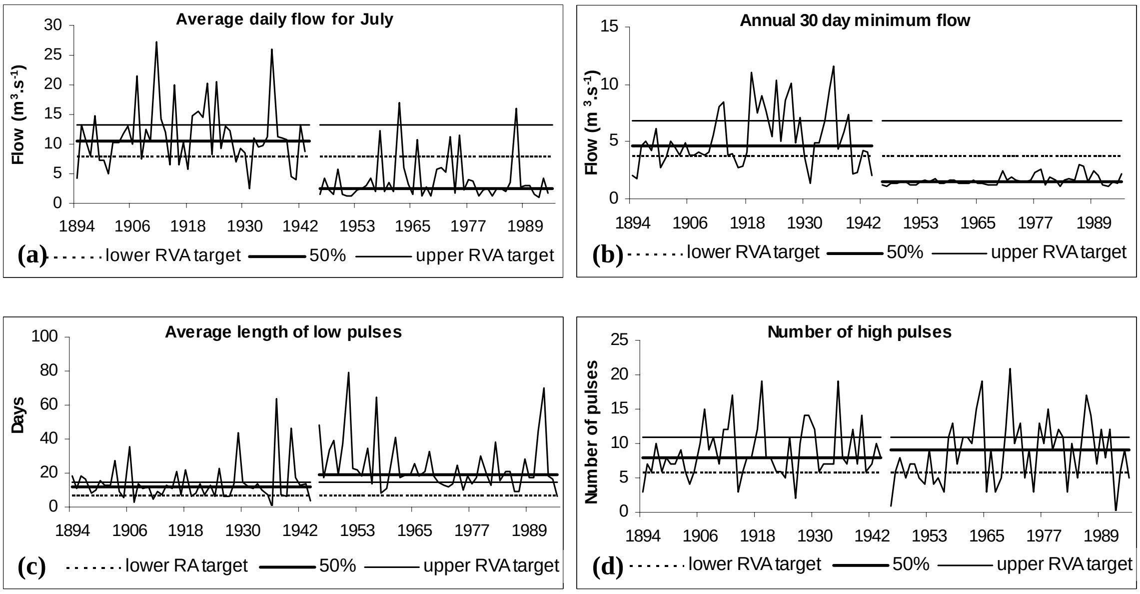

Figure 8.3 Examples of changes in the hydrological regime, with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 2 on the Mkomazi River

The reverse can be shown in Table 8.3 for high pulses and their durations and in Figure 8.3(d), where the number of years in which pulse counts are below the lower RVA target increases from 5 to 16 after the construction of the dam. The number of years in which high pulse durations are below the lower threshold increases from 12 to 21 (Table 8.3). The decline in high pulses and their durations can be attributed principally to the attenuation of high flows by the dam, the inter-basin transfer and to the restrictions imposed by the legal flow releases for downstream use assumed in the *ACRU* model simulation as described above. The extent of alteration of the low and high pulses and their durations, under post-dam conditions results in high alteration in the hydrograph rise and fall rates. Under such conditions, all yearly numbers of hydrograph reversals occur above the upper RVA target, indicating that the modified regime is characterised by substantial changes.

The RVA analysis generated warnings regarding the interpretation of the occurrences both high and low pulses, duration of low pulse counts, number of hydrograph falls and reversals as well as the date of the maximum daily flow. For example, of the 34 yearly values of pre-impact high pulse counts calculated to be within the target range of 6 to 11, nine counts were equal to the lower threshold (6). However, as discussed above, this factor does not detract from the general trend of reductions in high pulses following the construction of the Smithfield Dam for inter-basin transfer.

Similarly to Mkomazi IFR Site 1, river management plans for the river reach upstream of the Mkomazi IFR Site 2 require the ecological management category to be enhanced from a present state class C/B to class B. The impact of present land use with the proposed Smithfield Dam clearly exerts more influence on downstream flows than present land use conditions on flows at IFR Site 1. Notwithstanding the influence of land use practices on flows upstream of IFR Site 2, management plans for this river reach should look to efficient reservoir operating rules for the Smithfield Dam in order to ameliorate the impacts of the inter-basin transfer on the streamflow regime. Based on the RVA analysis, operating rules should particularly address:

- maintenance of the historical winter low flows,
- increased releases at the start and end of the low season, to limit the low flow season to a more natural duration,
- elevation of the baseflow regime,
- decreasing the frequency of low pulses and their duration,
- increasing the frequency of high pulses and their duration,

- decreasing the frequency of hydrograph reversals attributable to the current operating rule of legal flow releases, and
- adjustment of the rate at which legal flows are released.

Despite the fact that this scenario is somewhat artificial or inadequate in terms of the requirements of the NWA, it does illustrate some important features of the impacts of potential impoundment on the Mkomazi streamflow regime. In particular, curtailment of releases for inter-basin transfer may be required at pre-determined levels in the winter low flow season. Lower releases for transfer should also be considered in periods before low flow periods and after water stress months to ensure greater semblance to the natural flow regime. Additionally, restrictions to river abstractions for irrigation in low flow months could be applied. A number of short releases from the Smithfield Dam made in March (when there is no hydrological alteration within the target range from pre-dam conditions) for off-channel irrigation storage downstream may compensate for abstraction losses in periods of low flows and increase the high pulses and durations to within the RVA target range. However, this would be effective only so far as to the point of off-take for off-channel storage.

8.8 CONCLUSIONS

The major benefit of the RVA is that, in the absence of extensive biological data or ecological expertise, preliminary targets designed to protect natural aquatic biodiversity and aquatic ecosystems, can be set using either historical hydrological data or simulated hydrological information. The absence of adequate aquatic ecosystem and climatic data, as well as for observed runoff, is common for South African catchments and rivers. Consequently, there is great scope for the application of the RVA in South African catchments where river management objectives for the Reserve have yet to be ascertained. By setting preliminary flow management thresholds which can be modified and refined when ecological data and information becomes available, the approach incorporates flexibility and adaptability. These attributes could prove to be instrumental to resolving water resource management issues.

The approach embraces the theory that the full range of natural variation of a hydrological regime is required to sustain the full natural biodiversity and integrity of aquatic ecosystems. The RVA addresses this concept by focusing on ecologically relevant hydrological parameters that characterise natural streamflow regimes. However, the developers of the RVA acknowledge that the reliance of natural aquatic biota on the 25th to 75th percentile range of the hydrological parameters used in the analysis has not been widely tested for statistical soundness. Furthermore, any statistical analysis of the causal link between flow and the organisms dependent on it, are inherently limited. This could well be construed to be a shortcoming of the approach. However, as a link between river flow and river condition, by virtue of identifying critical variations in the magnitude, timing, frequency, duration and rate of change of flows, it represents a feasible and practical methodology towards the preliminary assessment of the ecological reserve of the Mkomazi River.

8.9 ACKNOWLEDGEMENTS

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CHAPTER 9

MESO-SCALE INDICATORS OF WATER POVERTY IN THE THUKELA CATCHMENT, SOUTH AFRICA, UNDER BASELINE LAND COVER CONDITIONS

Dennis Dlamini and Roland Schulze

ABSTRACT

The value of the results of water resources assessments is minimal if they are not linked to, or viewed in the light of, human welfare. Several global initiatives have highlighted the strategic importance of the water sector in poverty alleviation. Suitable methods or indices of water stress and poverty, in addition to having to be multi-disciplinary and having to link physical water availability (supply) with requirements of human population (demand), need to accommodate the population's capacity to access water and adapt to its shortage.

The Centre for Ecology and Hydrology Wallingford in the UK co-ordinated a multi-phased and multi-institutional research project aimed at deriving a tool for addressing the needs highlighted above. The tool is known as a Water Poverty Index (WPI).

The WPI has evaluated in the Thukela catchment. Within the Thukela catchment two communities, at Kate's Drift and Wembezi, were identified for more site-specific research on household water use.

The objectives of this study were: to provide an overview of the background hydrology of the Thukela catchment assuming baseline land cover conditions in regard to water availability at the meso-scale, i.e. at the operational subcatchment level of 10s to 100s km^2 in area in order to identify where, how much and how variable individual subcatchment flows as well as accumulated flows are; and furthermore to provide more specific detail on the background water availability at the two selected field sites within the Thukela, *viz*. at Keate's Drift and Wembezi by configuring the entire Thukela into relatively homogeneous operational subcatchments in order to undertake hydrological simulations under baseline land cover conditions using the *ACRU* agrohydrological simulation model; and to undertake preparatory work for an envisaged follow up phase.

9.1 PREAMBLE

The value of the results of water resources assessments is minimal if they are not linked to, or viewed in the light of, human welfare. Since the 1992 World Summit in Rio de Janeiro, several global initiatives (e.g. The 5th Global Forum of Water Supply and Sanitation Collaboration Council, 2000; 6th Session of the Commission for Sustainable Development) have highlighted the strategic importance of the water sector in poverty alleviation and the promotion of regional stability. This has resulted in the classification of countries and regions on the basis of water stress in order to implement interventions in crisis areas. At regional and national scales, Falkenmark's (1989) water stress index (while mindful of its limitations) has been used with considerable success for these categorisations. However, this method is too coarse for sub-national (provincial, small catchment or community) classification programmes. Furthermore, suitable methods or indices of water stress and poverty, in addition to having to be multi-disciplinary and having to link physical water availability (supply) with requirements of human population (demand), need to accommodate the population's capacity to access water and adapt to its shortage.

The Centre for Ecology and Hydrology (CEH) at Wallingford in the UK co-ordinated a multi-phased and multi-institutional research project aimed at deriving a tool for addressing the needs highlighted above. The tool is known as a Water Poverty Index (WPI), and its utility includes:

- enabling the classification of regions on the basis of a quantifiable methodology which reflects both the physical availability of water and the human adaptive capacity to access it,
- facilitating an assessment of progress towards water related development targets,
- contributing towards prioritisation of water related needs, and
- monitoring the effectiveness of water related development projects.

The WPI, the derivation of which was also identified during the 5th Global Forum of Water Supply and Sanitation Collaboration Council (2000) as a research need, was evaluated and tested by partner institutions in three countries, *viz*. South Africa, Sri Lanka and Tanzania. For the South African evaluation, the Thukela catchment of 29 035.9 km^2 in the province of KwaZulu-Natal was selected for a regional WPI study (Figure 9.1). Within the Thukela catchment two communities, at Kate's Drift and Wembezi, were identified for more site-specific research on household water use.

The University of Natal's School of Bioresources Engineering and Environmental Hydrology (SBEEH) was one of the partner institutions in the research project. For the SBEEH, the objectives of Phase 1 of this study were:

- to provide an overview of the background hydrology of the Thukela catchment assuming baseline land cover conditions, i.e. land cover not influenced by human activities;
- in regard to water availability at the meso-scale, i.e. at the operational subcatchment level of 10s to 100s km^2 in area;
- in order to identify where, how much and how variable individual subcatchment flows as well as accumulated flows are; and furthermore
- to provide more specific detail on the background water availability at the two selected field sites within the Thukela, *viz*. at Keate's Drift and Wembezi;
- by configuring the entire Thukela into relatively homogeneous operational subcatchments in order to undertake hydrological simulations under baseline land cover conditions using the *ACRU* agrohydrological simulation model; and
- to undertake preparatory work for an envisaged Phase 2 of this WPI study.

Section 9.2 presents background information on the Thukela catchment, focusing on aspects of its hydroclimatology, but also introducing elements of human influences on the landscape by briefly assessing present land use patterns as well as discussing the general poverty status within the catchment. The configuration of the *ACRU* model for hydrological simulations is discussed in Section 9.3, while overall and site-specific results are presented in Sections 9.4 and 9.5 respectively. The case study concludes with recommendations of work proposed for Phase 2 of the project.

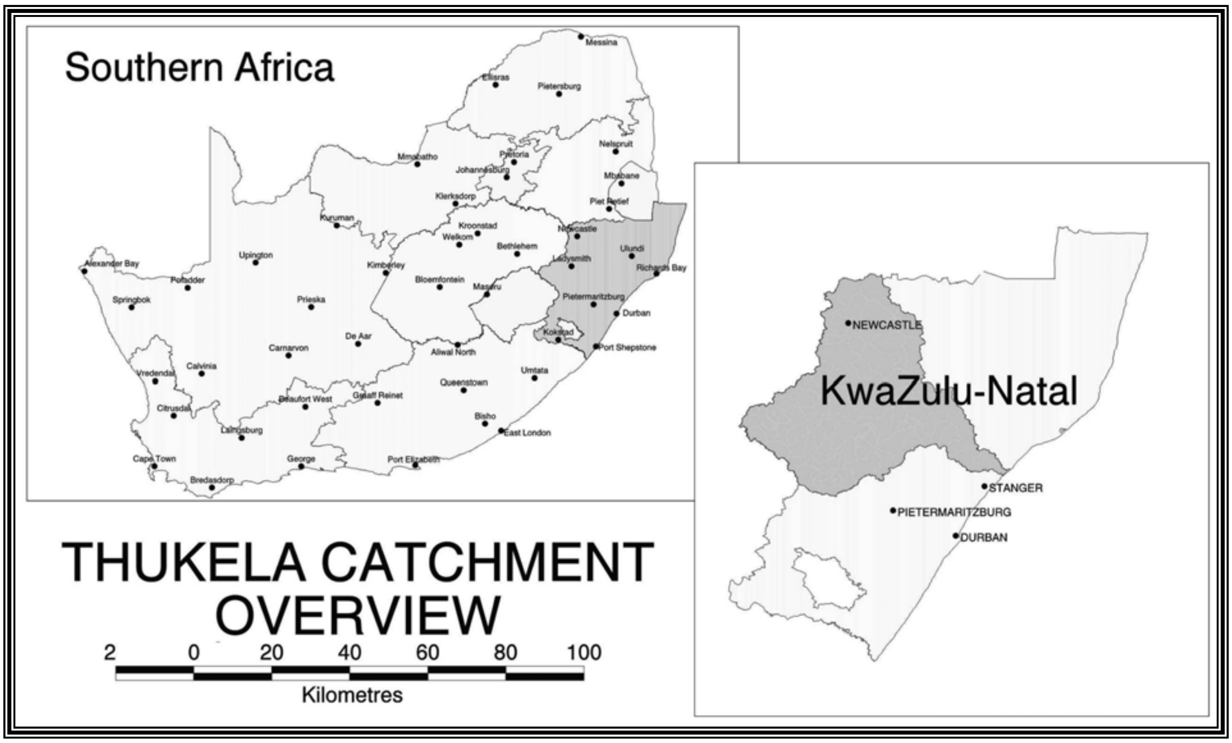

Figure 9.1 Location of the Thukela catchment

9.2 THE THUKELA CATCHMENT: BACKGROUND

9.2.1 Location and Physical Features

The Thukela catchment extends latitudinally from 27°25' to 29°24'S and longitudinally from 28°58' to 31°26'E (Figure 9.1). It covers an area of 29 035.9 km^2. The Thukela River has its source in the Drakensberg mountain range in the west. The Drakensberg is a declared World Heritage Site which, in places, has altitudes exceeding 3000 m (Figure 9.2). It then flows eastward from a steep escarpment across low mountains of high relief, open hills of high relief and lowlands of low relief and thereafter through a deeply incised valley until it reaches the Indian Ocean approximately 85 km north of the city of Durban. The mainstem Thukela's major tributaries are the Little Thukela, Mooi and Bushman's Rivers which join from the southwest, and the Klip, Sundays and Buffalo Rivers flowing from the north.

9.2.2 Hydroclimatic Features

Mean annual precipitation (MAP) in the Thukela ranges from around 2000 mm in the Drakensberg to as low as 550 mm in the drier central regions (Figure 9.3). Most of the rainfall is received during the mid-summer months from December to February. Significant from the water poverty perspective is the relatively high inter-annual variability of rainfall, generally in the range of 20 – 30% (Figure 9.4).

The driest year in 10 records is only about 60% of MAP. Equally as important for WPI studies as its variability is the strong concentration of rainfall in the summer months. January's rainfall means range from 100 – 300 mm (mostly 120 – 150 mm) against July's means which over most of the catchment are < 5 mm (Schulze, 1997).

Monthly means of daily maximum temperatures of the hottest month, January, are generally between 26°C and 28°C with the highest means, (around 32°C), occurring in the incised eastern valleys and the lowest (below 20°C) in the high Drakensberg mountains (Figure 9.5). Winter (July) means of daily minimum temperatures range from 0°C in the Drakensberg mountains to 10°C at the coast (Figure 9.6). Illustrated in Figure 9.7 is the distribution of average annual potential evaporation (E_p) using the A-pan as a reference. E_p is relatively high at between 1600 and 2000 mm per annum (Schulze, 1997). Highest monthly means of E_p (200 – 220 mm) coincide with high means of maximum temperatures in January and similarly the lowest values, still around 100 – 110 mm per month, occur in July (Schulze, 1997). In regard to a WPI, it is significant to note that the ratio of annual E_p to annual rainfall in the Thukela is 2- 4, which classifies most of the area as semi-arid, despite the rainfall *per se* not necessarily being low everywhere.

Physiographically and climatologically the Thukela catchment is, thus, a highly diverse catchment, with first indications of water poverty already evident in the strong seasonality and inter-annual variability of its rainfall, exacerbated by a very high atmospheric demand which is expressed through the high values of potential evaporation.

9.2.3 Human Imprints on the Thukela Catchment

The Thukela catchment's natural land cover of mainly grasslands and savanna type bushveld (*cf*. Section 3) has been highly modified and impacted upon by humans. This is illustrated clearly by the map of current land uses (Figure 9.8), which shows activities such as mining and urbanisation, as well as commercial agriculture, subsistence agriculture, irrigation and impoundments to be important. However, with regard to water poverty, the substantial areas of degraded grasslands, thickets and bushveld (mainly through overgrazing) are first indicators of lack of sufficient water in certain areas.

That large tracts of the Thukela catchment are socio-economically not well endowed becomes evident from the perusal of an overall (not specifically water) poverty index, which is made up of indicators such as income, levels of education and access to adequate sanitation (Figure 9.9). The above two examples of 'human imprints' on the Thukela catchment already point to a complex juxtapositioning of developed vs underdeveloped elements in the catchment, partially determined by the strong biophysical diversity described in Sections 9.2.1 and 9.2.2, but largely influenced also by the socio-political history of the area.

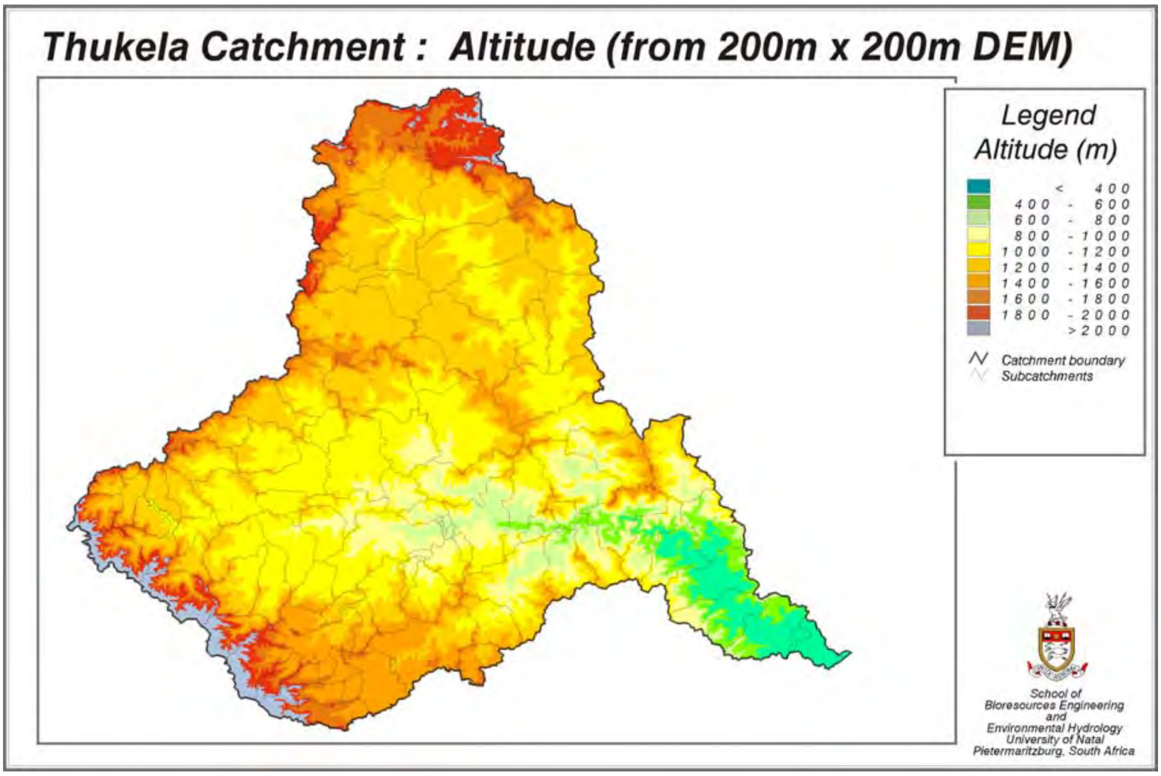

Figure 9.2 Topography of the Thukela catchment

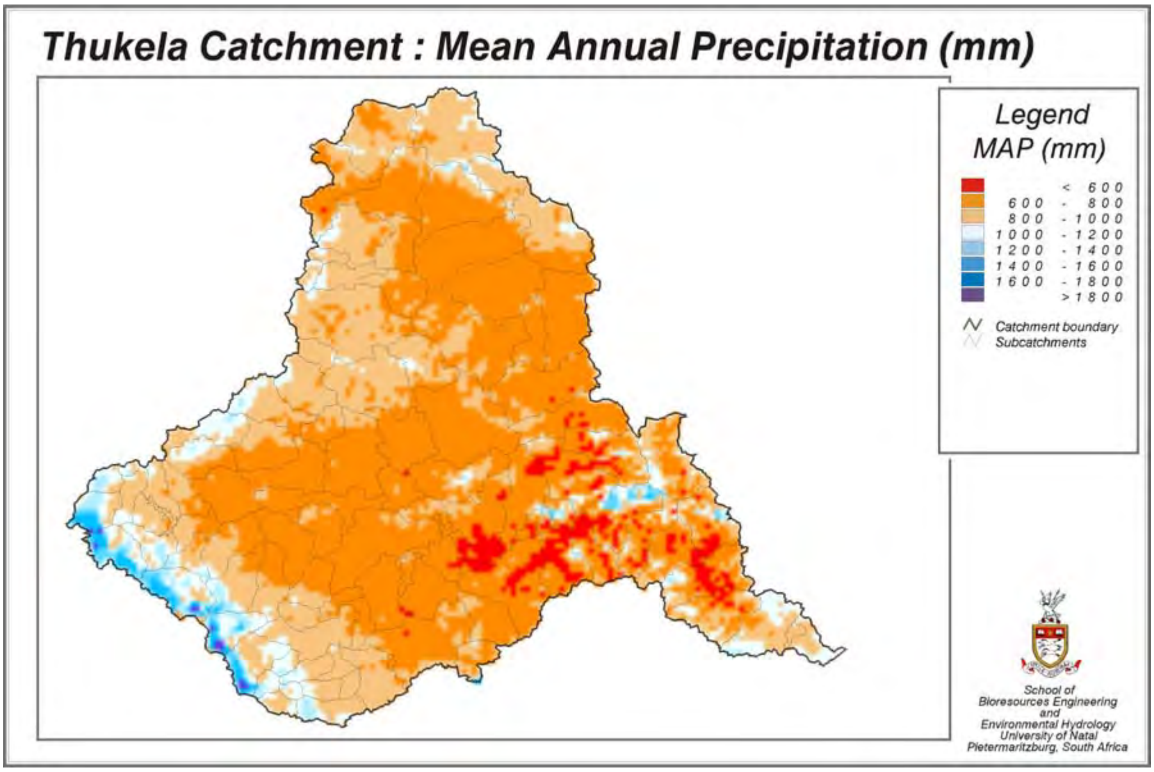

Figure 9.3 Mean annual precipitation (mm) in the Thukela catchment (after Dent, Lynch and Schulze, 1989)

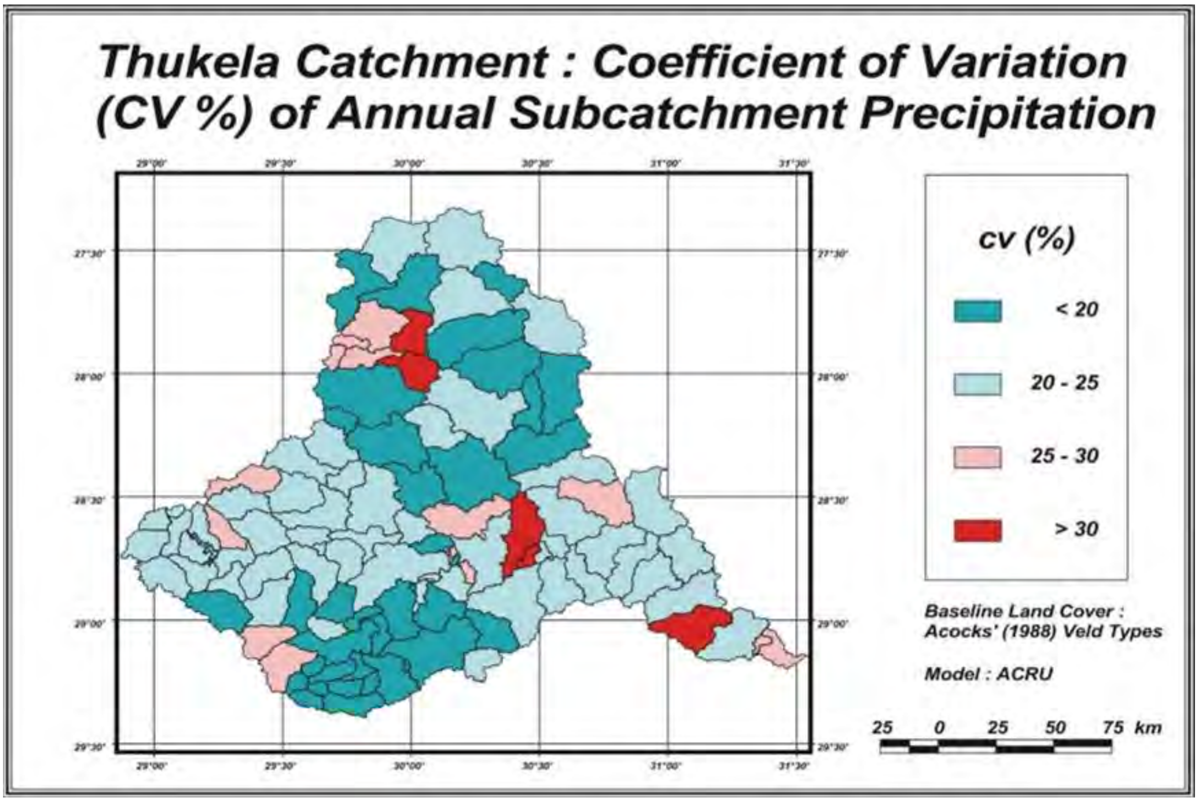

Figure 9.4 Inter-annual coefficient of variation (CV %) of rainfall in the Thukela catchment (Schulze, 1997)

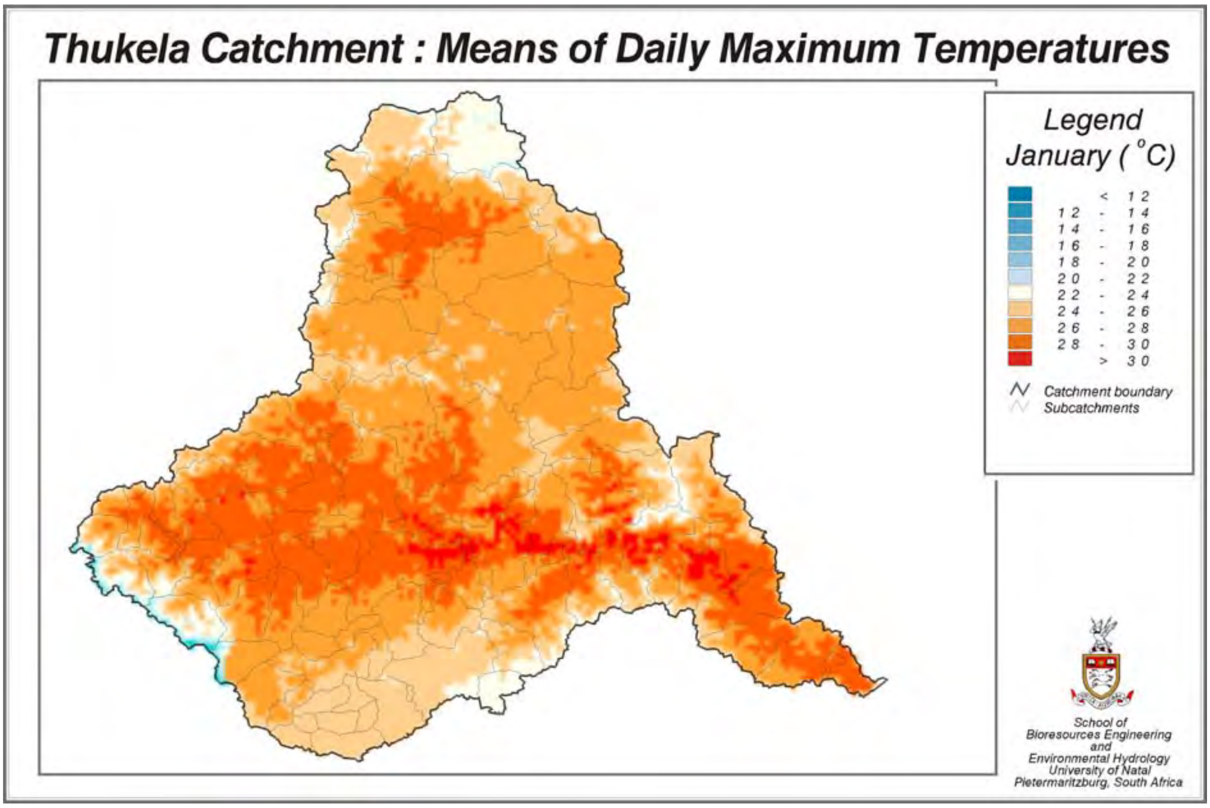

Figure 9.5 January means of daily maximum temperatures (°C) in the Thekula catchment (after Schulze, 1997)

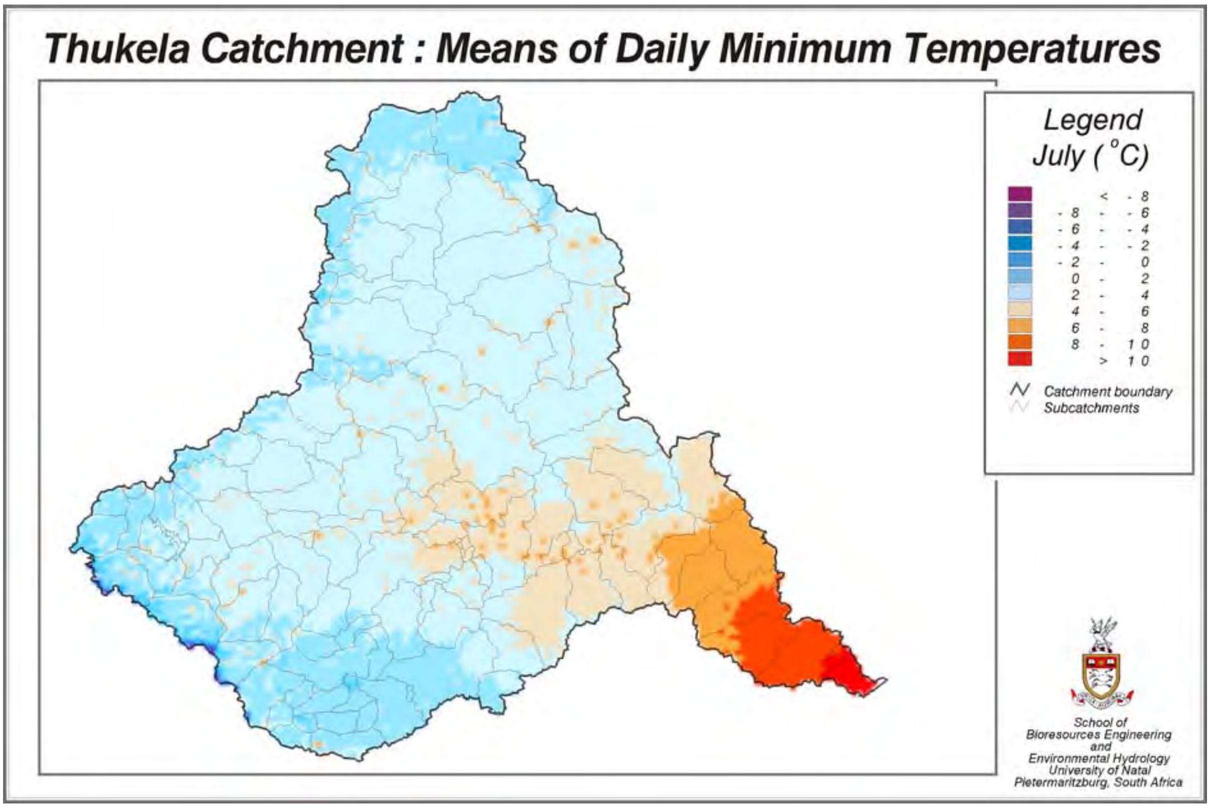

Figure 9.6 July means of daily minimum temperatures (°C) in the Thukela catchment (after Schulze, 1997)

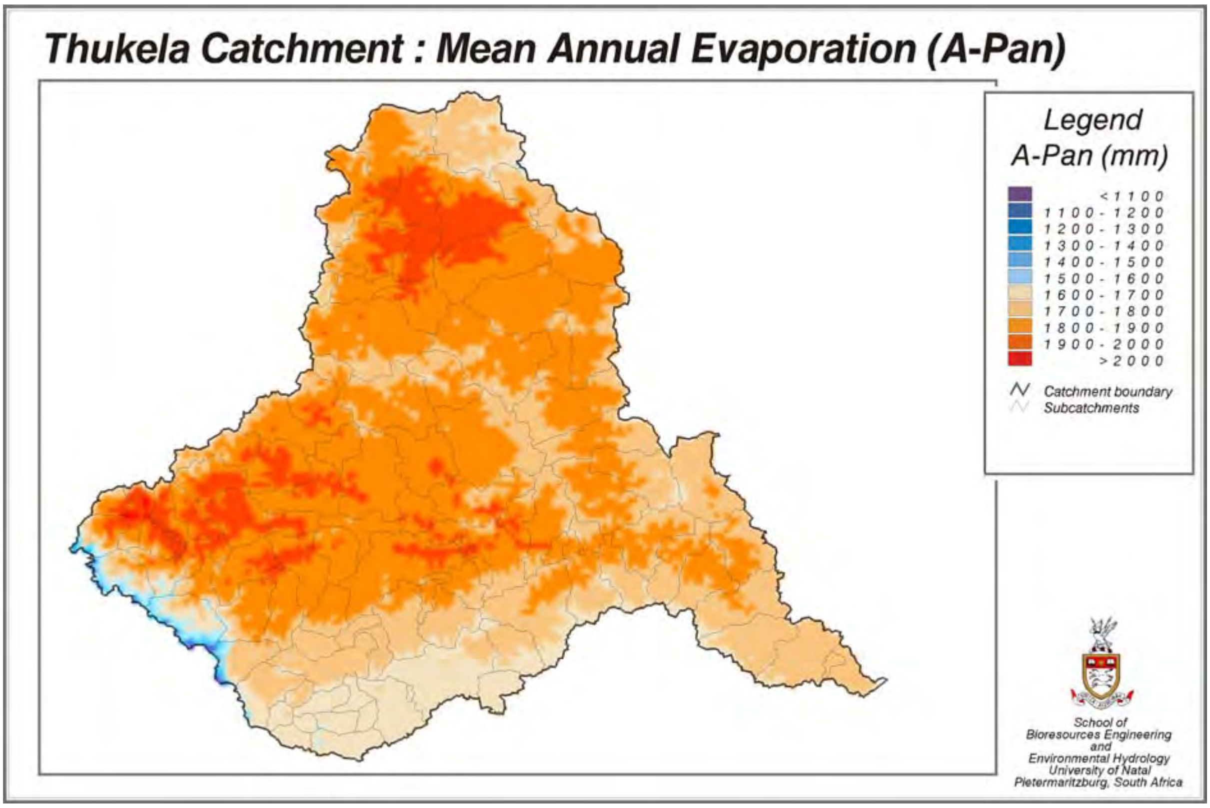

Figure 9.7 Mean annual potential evaporation (mm), using A-pan equivalent values as the reference, in the Thukela catchment (after Schulze, 1997)

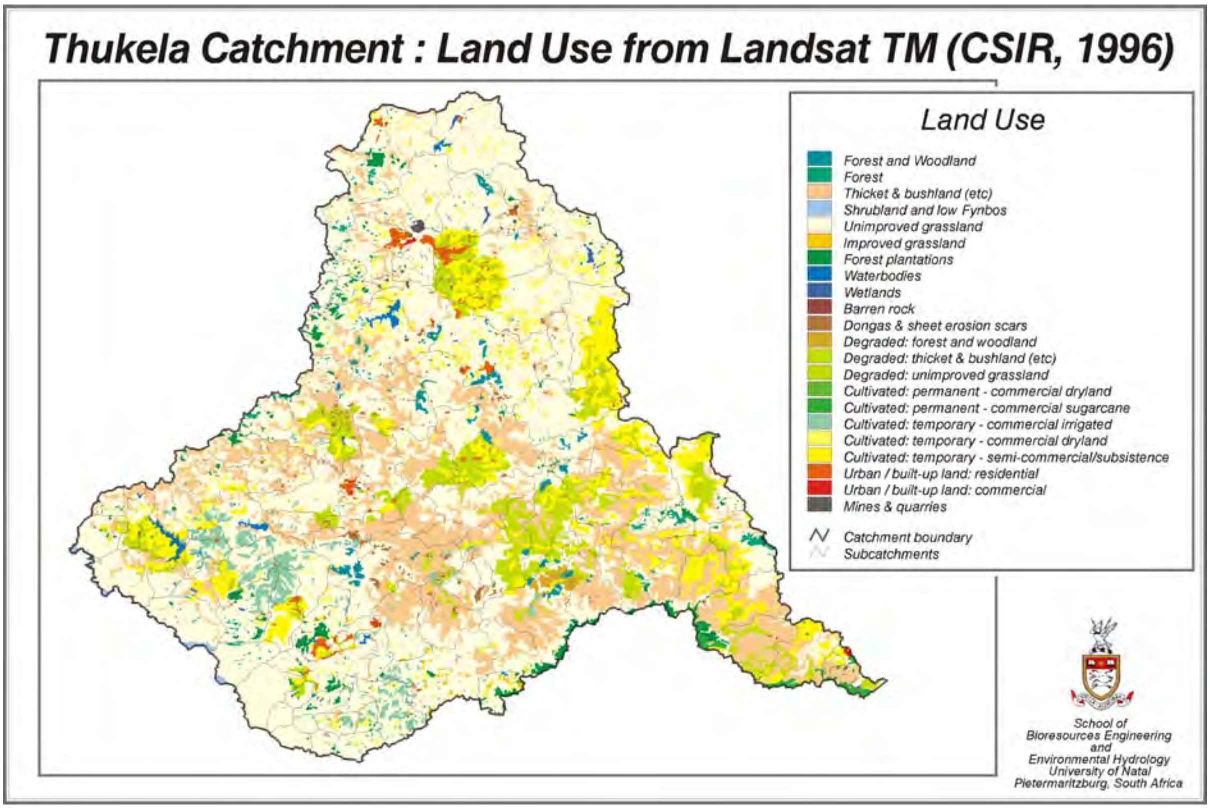

Figure 9.8 Present land use in the Thukela catchment (Source: CSIR, 1996)

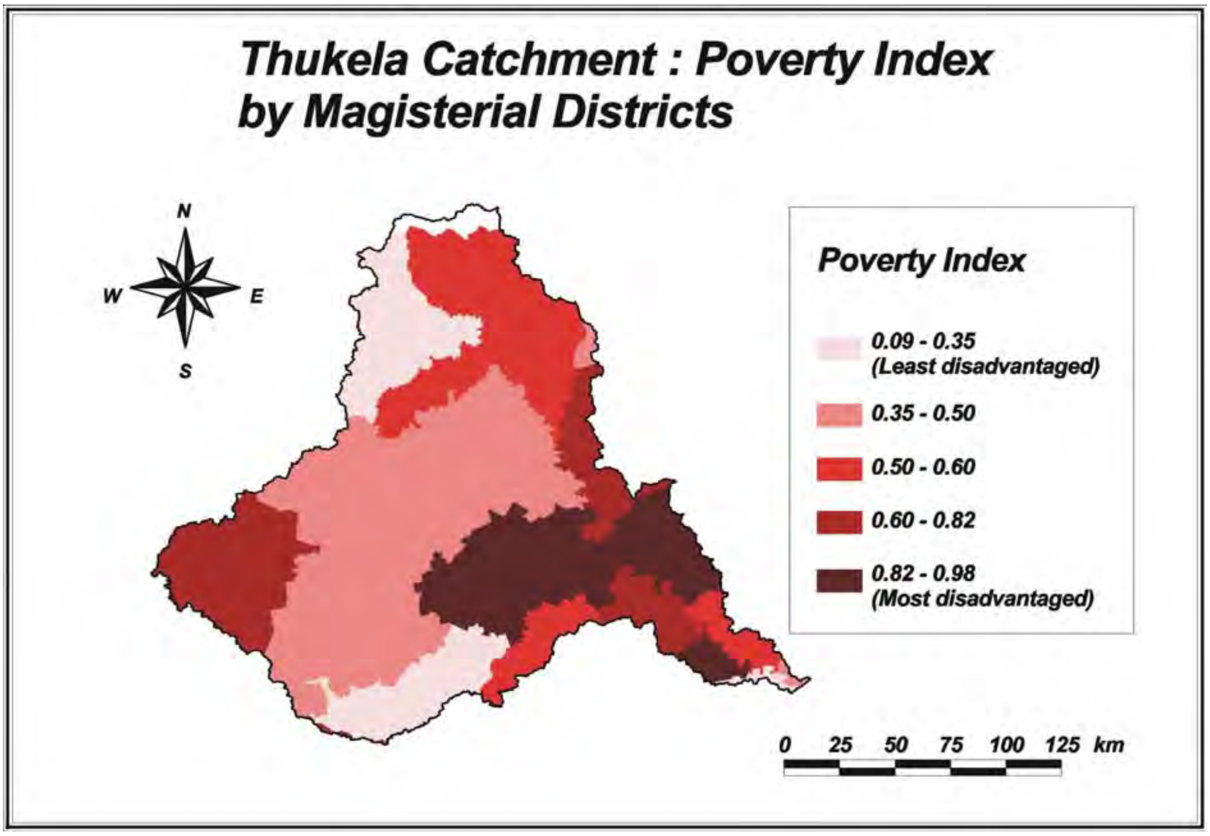

Figure 9.9 An overall index of poverty in the Thukela catchment (after Wilson, 2001)

However, Phase 1 concerns itself with the availability of water under baseline (i.e. non-anthropogenically influenced) land cover conditions; without taking cognisance of the 'human imprints', as an indicator of an area's natural endowment of water when quantifying a WPI. This brief is achieved by modelling streamflow characteristics at the meso-scale within the Thukela catchment. The meso-scale identifies subcatchments of 10s to 100s km^2 in area which are used as individual or as interlinked operational hydrological units in the planning and implementation of rural and small urban water supplies.

9.3 THE HYDROLOGICAL MODELLING SYSTEM

Owing to unavailability of observed records of pre-development streamflows over most of the Thukela catchment, simulation modelling was applied to estimate the catchment's baseline hydrological responses. The *ACRU* agrohydrological modelling system (Schulze, 1995; Smithers and Schulze, 1995; Schulze, 2001) was selected for this task.

9.3.1 The ACRU Agrohydrological Modelling System

ACRU is a daily time step, physical-conceptual and multi-purpose agrohydrological modelling system (Schulze, 1995) with options to output, *inter alia*, daily values of stormflow, baseflow, peak discharge, reservoir status, recharge to groundwater, sediment yield, as well as irrigation water supply/demand and additionally having the facility to output seasonal yields of selected crops at any location within the catchment, either with or without irrigation (Figure 9.10).

The model revolves around multi-layer soil water budgeting concepts (Figure 9.11). It is structured to be hydrologically sensitive to impacts of different catchment land uses and changes thereof, including the impacts of reservoirs operations, run-of-river abstractions, irrigation practices, urbanisation, afforestation and of enhanced greenhouse gas induced climate change on catchment streamflow and sediment generation.

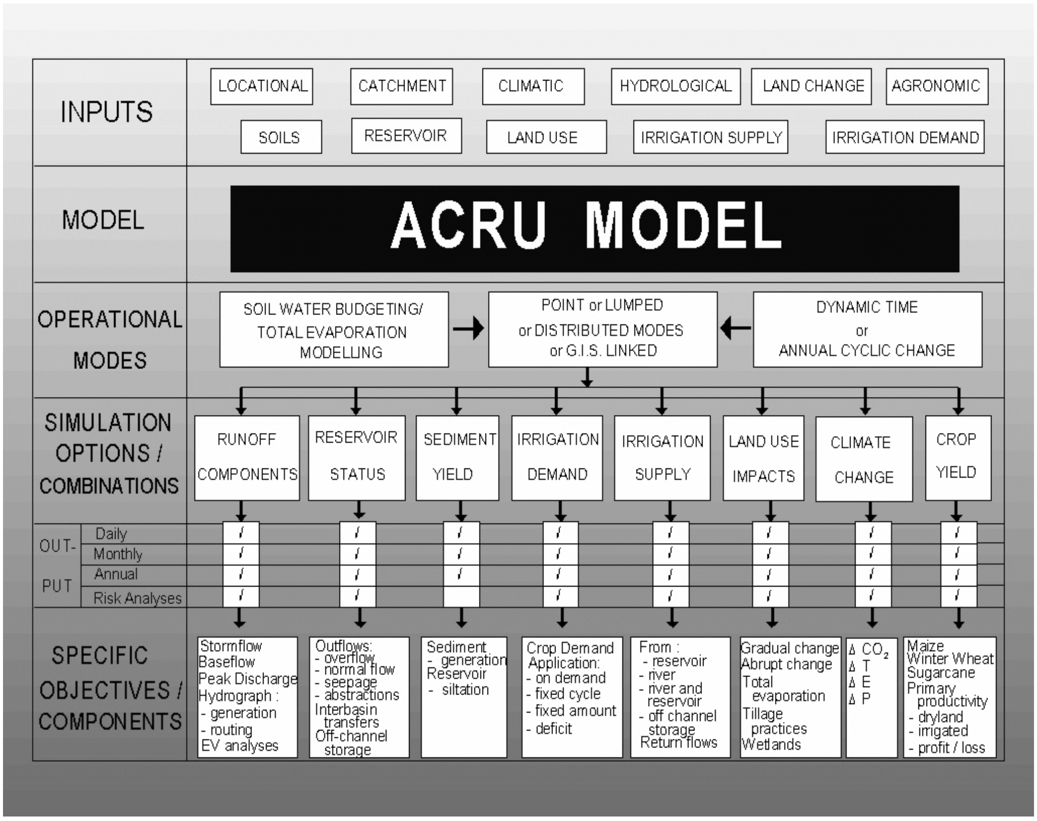

Figure 9.10 The *ACRU* agrohydrological modelling system: Concepts (Schulze, 1995)

For large areas, or where complex land uses and hydrologically variable soils occur, or where streamflows in the channel have been modified by reservoirs/abstractions, the catchment is discretised into relatively homogeneous response zones, and *ACRU* then operates as a hydrologically cascading distributed cell-type model.

The *ACRU* model requires input of known and measurable spatial and temporal variables which characterise the catchment's hydrological behaviour. Catchment information may be classified by:

- climate, e.g. daily rainfall, temperature, potential evaporation;
- physical attributes, e.g. area, slope, hydrological soil properties;
- bio-physical characteristics, i.e. baseline land cover and present rainfed land uses and their hydrological properties; and other
- land use/management practices, including irrigation demand and supply, as well as domestic, industrial and livestock water abstractions from river runoff, as well as from reservoirs, and return flows.

Within the model, the input information is transformed to produce the eventual responses through the routines which represent the processes of each sub-system of the hydrological cycle (e.g. the rainfall, interception, infiltration, stormflow generation or groundwater recharge sub-systems) and the manner in which they interact and are linked. The model also calculates thresholds at which catchment responses occur and response rates change.

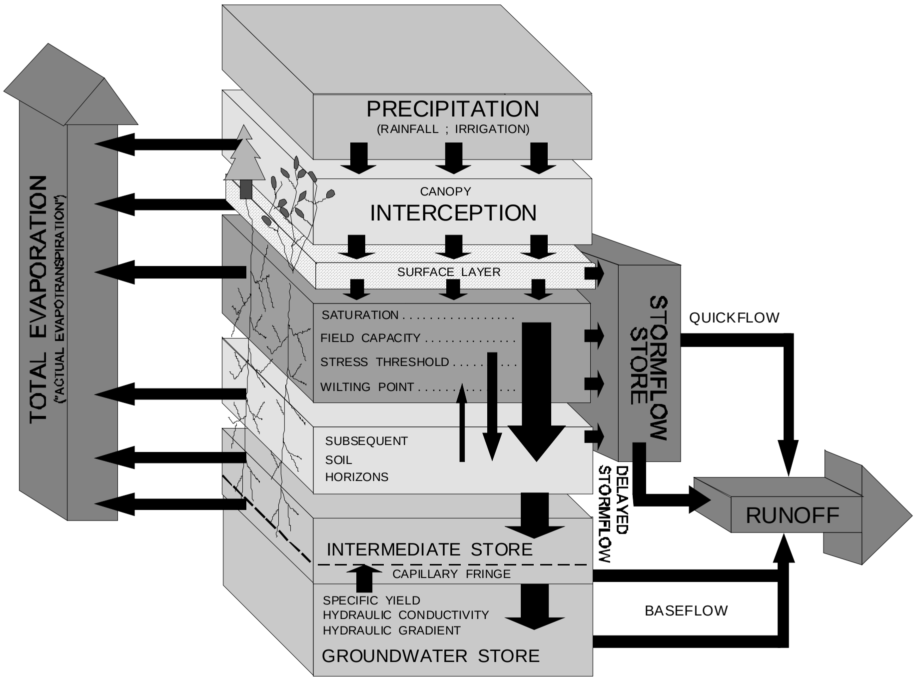

Figure 9.11 The *ACRU* agrohydrological modelling system: Structure (Schulze, 1995)

9.3.2 Preparation of *ACRU* Model Input and Sources of Information

9.3.2.1 Layout and configuration of the Thukela catchment system for simulation purposes

At 29 035.9 km^2, the Thukela catchment is a large system with marked spatial and hydrological heterogeneity. For simulation modelling purposes, the catchment was therefore discretised into 113 hydrologically relatively homogeneous subcatchments, or management units (Figure 9.12), on the basis of the Department of Water Affairs and Forestry's (DWAF) operational Quaternary Catchment

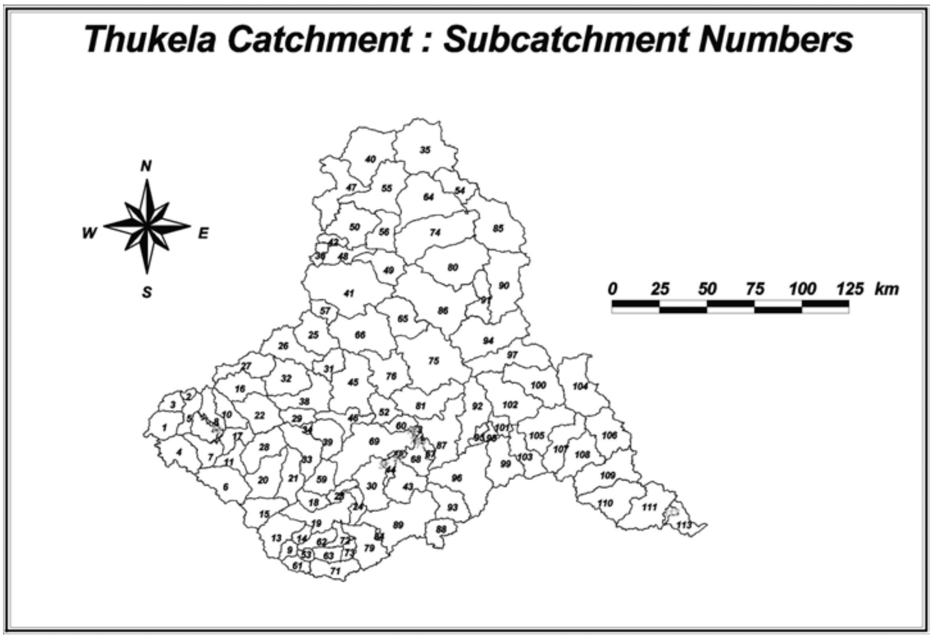

Figure 9.12 The 113 subcatchments, i.e. management units delimited within the Thukela and their numbering system (after DWAF and Jewitt *et al*., 1999)

(QC) delimitation which uses uniformity of soils, land uses and topography, as well as present reservoirs as criteria.

DWAF's initial official subcatchment delimitation of 86 QCs within the Thukela was extended by Jewitt *et al*. (1999), who considered Instream Flow Requirement (IFR) monitoring sites, critical reach sites as well as other locations in the channel such as water abstractions points and locations of proposed major dams where streamflows may be significantly modified; hence 113 subcatchment outlets. The manner in which the subcatchments were arranged and configured such that the simulated runoff would be routed through the system in a downstream direction is illustrated in Figure 9.13.

9.3.2.2 Climatic variables

Minimum climatic information required per subcatchment by the model is a time series of daily rainfall together with monthly means of daily maximum and minimum temperature and monthly totals of reference potential evaporation. Rainfall stations, in and adjacent to the Thukela catchment, with long records of daily rainfall were selected from the database maintained in the former Computing Centre for Water Research (CCWR) for an initial assessment of their data to "drive" the catchment's hydrological responses. Using a recently developed sophisticated technique (Smithers, 1998), missing daily records were in-filled for each of the rainfall stations before they were further screened using a utility known as CalcPPTCor (Pike, 1999) to choose the most appropriate so-called "driver" station for each subcatchment. The CalcPPTCor utility also calculates a precipitation adjustment factor which, when applied as a multiplier with the driver station's daily rainfall, is used to estimate a representative daily areal rainfall for each subcatchment. Using this selection procedure, 57 driver stations were eventually assigned to the 113 management units (Figure 9.14), implying that many of the rainfall stations determined will "drive" the hydrological responses of more than one unit, albeit with a different daily adjustment.

For each subcatchment, representative values of monthly A-pan equivalent reference potential evaporation and means of daily minimum and maximum temperatures (*cf*. Figures 9.5, 9.6 and 9.7) were determined, based on input derived from one minute latitude by one minute longitude gridded surfaces that were developed by Schulze (1997). These are converted to daily values within the model by using a Fourier Analysis.

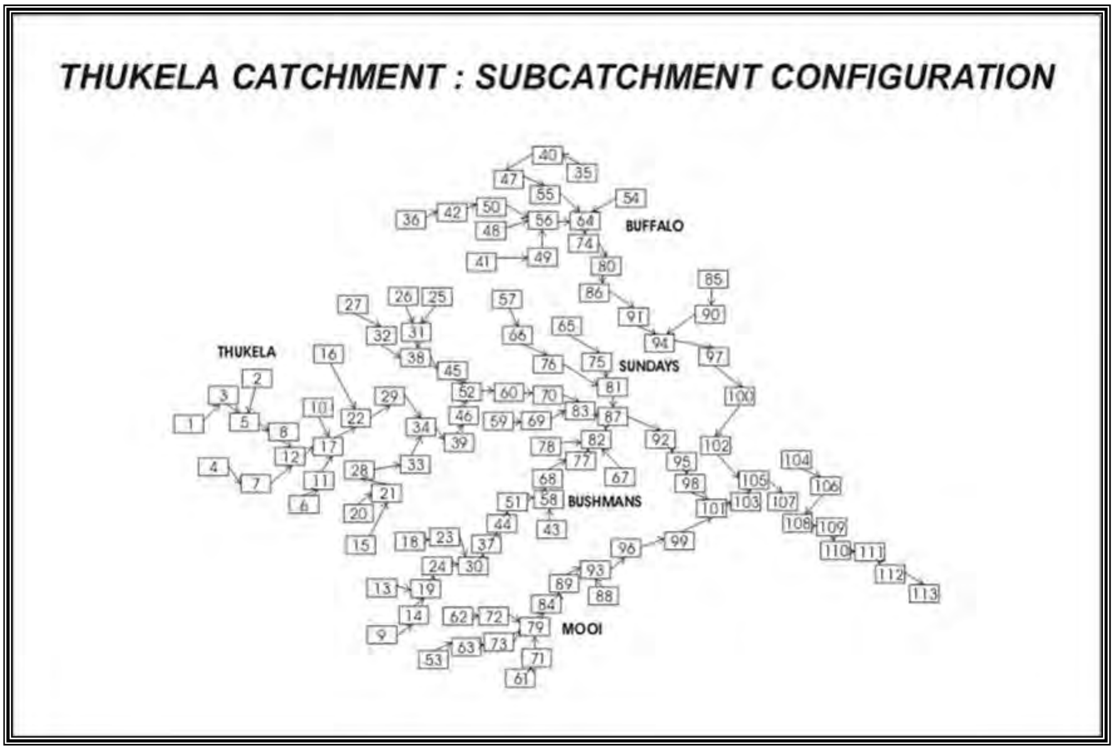

Figure 9.13 Subcatchment, i.e. management unit, configuration and the routing of flows within the Thukela catchment

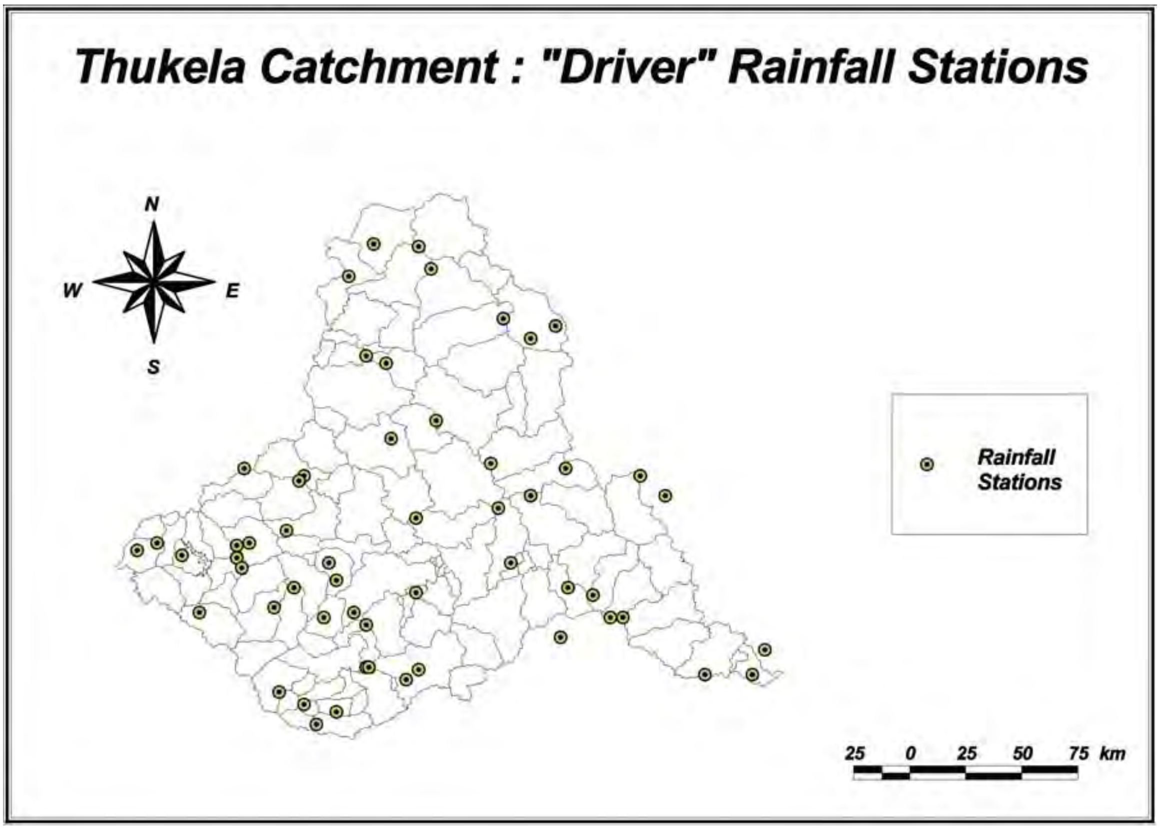

Figure 9.14 Locations of the “driver” rainfall stations selected for this study

9.3.2.3 Soils information

Soils play an important role as regulators of the rate and manner in which a catchment responds, hydrologically, to a rainfall event by

- influencing the rate of infiltration, thus dictating the timing and rate of stormflow generation;
- providing storage for soil water, which may become available for evapotranspiration;
- redistributing soil water, both within and out of the soil profile;
- controlling rates of soil water evaporation and transpiration processes; and
- influencing rates and amounts of drainage beyond the root zone and eventually into the intermediate/groundwater zone, which feeds baseflow.

A GIS coverage of soil mapping units called Land Types was obtained for the Thukela catchment from the Institute of Soil, Climate and Water (ISCW). The coverage provides detailed information on percentages of soil series making up individual terrain units, together with certain physical characteristics, for each Land Type. Using a soils decision support system known as *AUTOSOILS* (Pike and Schulze, 1995), these properties were translated into hydrological variables for a two-horizon soil profile, as required by *ACRU* (e.g. horizon thickness, critical water retention constants, drainage rates and saturated overflow areas).

9.3.2.4 Land cover information

Like soils, land cover and land use/management systems have profound influences on hydrological responses through seasonally variable canopy and litter interception amounts, surface water detention, evapotranspiration rates, provision of protective cover against soil particle detachment and loss from direct raindrop impact, as well as extraction of soil water by plant roots. For this Phase 1 of the WPI study, hydrological modelling is undertaken to evaluate streamflows under baseline land cover conditions to enable the estimation of primary water endowment, or natural water availability per subcatchment. Acocks' (1988) so-called Veld Types (Figure 9.15), which are assumed to represent natural vegetation classes, have become the standard land cover used for baseline hydrological studies in South Africa. The *ACRU*-related attributes of the Veld Types have been determined by Schulze (2001). The hydrological variables and associated values for the Veld Types found in the Thukela catchment are given in Table 9.1. Monthly values corresponding to each Veld Type were weighted according to the percentage areas of the Veld Types found in each subcatchment. For this Phase of the WPI study, therefore, no land and water resources development was assumed to have taken place, and hence the impacts of land uses and abstractions/return flows of water from streams and reservoirs on streamflows were not considered.

9.3.3 Verification and Validation Studies of Streamflow Responses

To engender confidence in the *ACRU* model's output of hydrological responses from baseline land cover conditions, verification studies have been undertaken on catchments under pre-development land cover conditions. An example from the Cathedral Peak hydrological research station's Catchment II (1.94 km^2), which is under natural grassland, is given in Figure 9.16.

However, owing to the unavailability of observed streamflow data from other catchments in the Thukela under baseline land cover conditions, a validation task was undertaken to visually check the overall plausibility of the model output. The results are illustrated in Figure 9.17, where simulated mean annual runoff, MAR, is plotted against MAP for each of the 113 subcatchments.

In accordance with hydrological theory, MAR increases curvilinearly with increasing mean annual rainfall. The trend is clearly evident in Figure 9.17. A map of subcatchments' rainfall-runoff ratios in Figure 9.18 further highlights the above curvilinear trend. The trends in this validation are in accord with results from other studies conducted in the Thukela catchment (e.g. Schulze, 1979; Jewitt *et al*., 1999). The above results are interpreted as an indication that representative results are produced by the *ACRU* model, thus lending credibility to the conclusions drawn from the simulation results, which are assessed in the next two chapters.

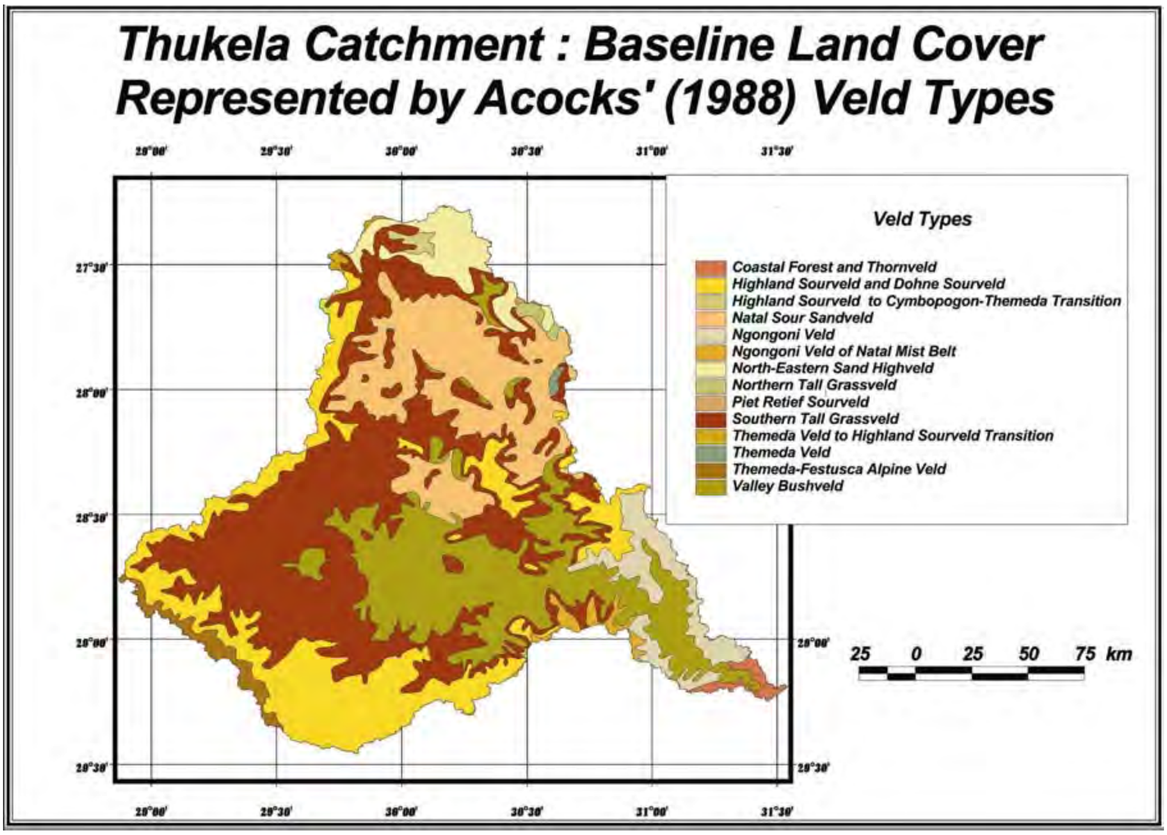

Figure 9.15 Baseline land cover in the Thukela catchment as represented by Acocks' (1988) Veld Types

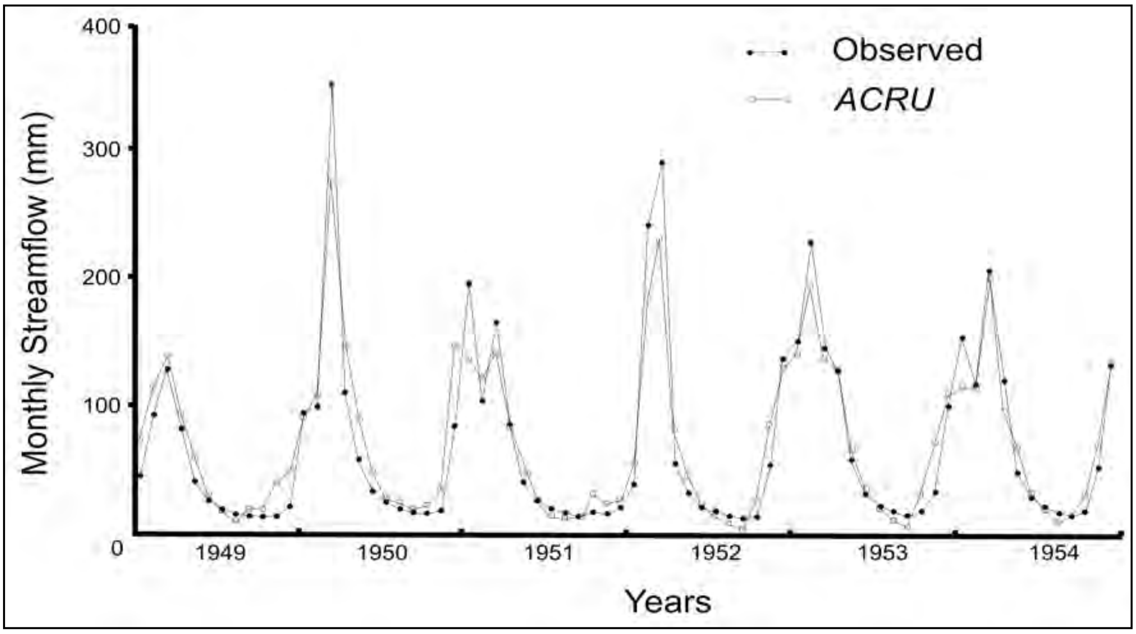

Figure 9.16 An example of an *ACRU* model verification from Catchment II at the Cathedral Peak hydrological research station (after Schulze and George, 1987)

Table 9.1 Hydrological attributes of the Acocks' (1988) Veld Types, which represent baseline land cover in the Thukela catchment (Schulze, 2001)

Veld Type	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coastal Forest and Thornveld	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85
	VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10
	ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Ngongoni Veld - Zululand	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70
	VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40
	ROOTA	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40
	COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
Highland Sourveld and Döhne Sourveld	CAY	0.70	0.70	0.70	0.50	0.30	0.20	0.20	0.20	0.50	0.65	0.70	0.70
	VEGINT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.30	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Natal Mist Belt Ngongoni Veld	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	0.70
	VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Themeda Veld or Turf Highveld	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65
	VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Turf Highveld to Highland Sourveld Veld Transition	CAY	0.60	0.60	0.60	0.52	0.40	0.20	0.20	0.20	0.35	0.50	0.60	0.60
	VEGINT	1.30	1.30	1.30	1.20	1.00	0.90	0.90	0.90	1.10	1.20	1.30	1.30
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
North-Eastern Sandy Highveld	CAY	0.62	0.62	0.60	0.50	0.35	0.20	0.20	0.20	0.35	0.50	0.62	0.62
	VEGINT	1.30	1.30	1.30	1.20	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.30
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Piet Retief Sourveld	CAY	0.70	0.70	0.70	0.55	0.45	0.20	0.20	0.20	0.50	0.60	0.70	0.70
	VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.20	1.30	1.30	1.30
	ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Southern Tall Grassveld	CAY	0.75	0.75	0.75	0.50	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75
	VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Natal Sourveld	CAY	0.75	0.75	0.70	0.50	0.35	0.20	0.20	0.20	0.50	0.65	0.70	0.75
	VEGINT	1.80	1.80	1.80	1.80	1.60	1.40	1.40	1.40	1.50	1.70	1.80	1.80
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15

CAY = water use (i.e. crop) coefficient
ROOTA = fraction of roots in the topsoil horizon
VEGINT = canopy interception (mm/rainday)
COIAM = coefficient of initial abstraction (i.e. infiltrability index)

9.4 SPATIAL VARIATIONS OF STREAMFLOW CHARACTERISTICS WITHIN THE THUKELA CATCHMENT

The success of the verification and validation studies presented in Section 9.3 provides the all important confirmation of the *ACRU* model's output being considered realistic under baseline land cover conditions. The results of this study are presented in two sections. In this section an analysis of baseline streamflow characteristics in the Thukela catchment in its entirety is presented, followed in Section 9.5 by an assessment of baseline streamflow characteristics at the selected WPI case study locations, *viz*. at Keate's Drift and Wembezi.

9.4.1 Spatial Variations of Subcatchment MAR within the Thukela Catchment

Figure 9.19 shows the spatial variations of individual subcatchment MAR within the Thukela catchment. The average MAR for the catchment is 136 mm. MAR values per subcatchment vary widely, from less than 25 to over 250 mm. High runoff values are simulated in the southwest and northern sections of the catchment which make up parts of the high Drakensberg range of mountains. Other high values occur in the southeastern tail of the catchment along the Indian Ocean, which has a

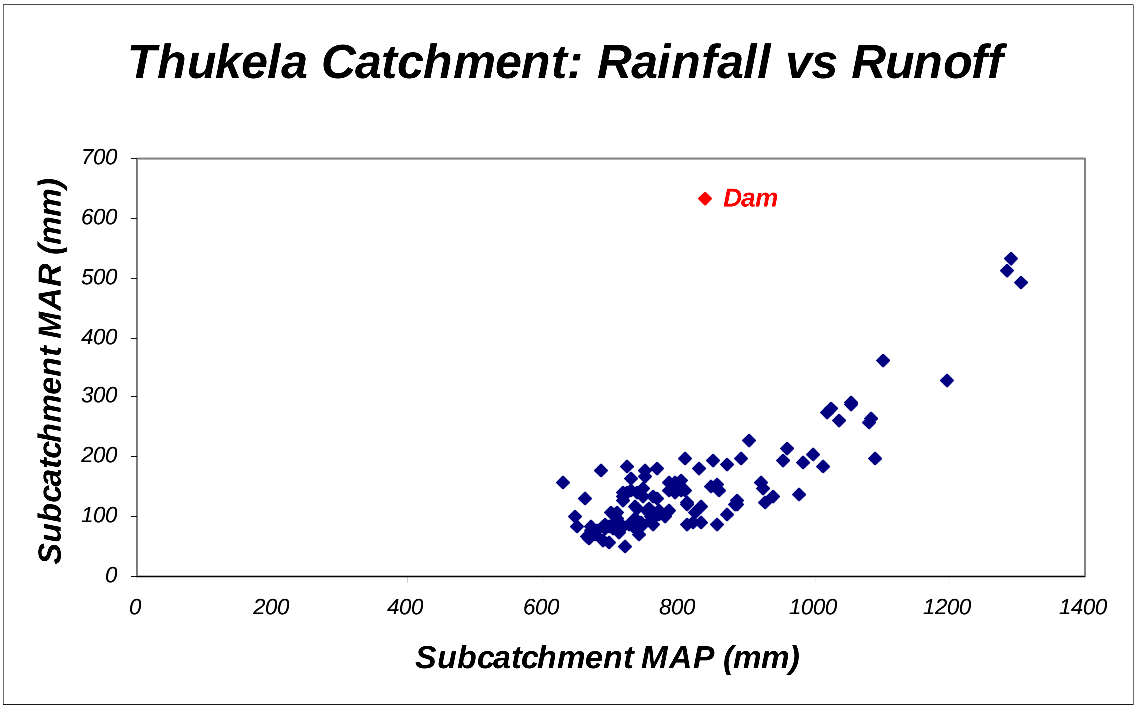

Figure 9.17 Relationship between *ACRU* model simulated MAR (mm) and MAP (mm) for the individual subcatchments, i.e. management units, within the Thukela

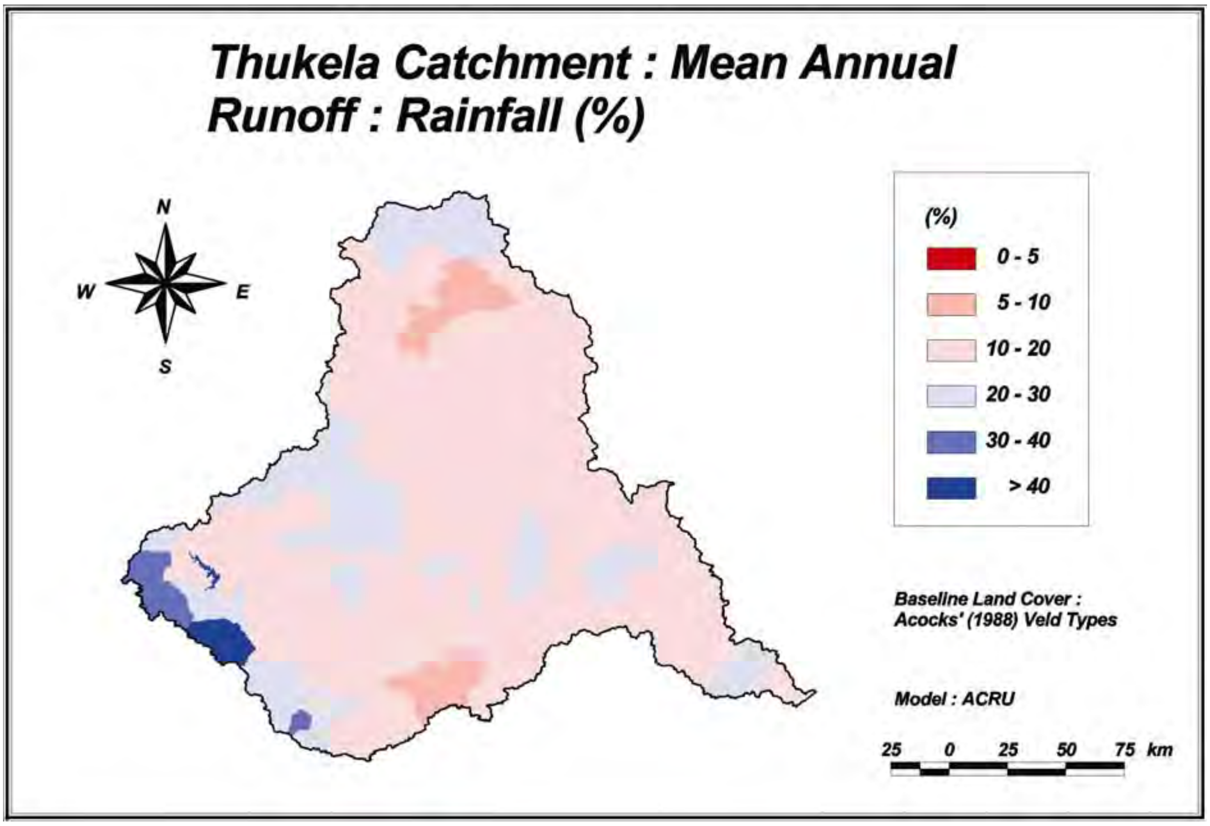

Figure 9.18 *ACRU* model simulated subcatchment MAR (mm) in the Thukela as percentage of MAP (mm)

maritime climate. Save for a few patches of MAR > 150mm, values ranging from 25 to 150 are simulated in the relatively dry central parts of the catchment.

These patterns have important implications on water resources development and water poverty. With most of the streamflows generated in the high altitude, rugged and sparsely inhabited western fringes, and less being produced in the lower lying plains and valleys which contain most of the farmlands, towns and especially the poor rural communities, it has become imperative that the mountain-fed main streams be impounded, also as a result of the strong seasonal nature of the flows, to ensure year-round sustained water supplies. Implications on rural communities will be discussed in the section outlining results at the two specific WPI survey sites.

9.4.2 Inter-Annual Coefficients of Variation (CVs) of Streamflows from Individual Subcatchments

Low CV values depict small year-to-year variations of annual runoff from the mean while the converse holds for high CVs. The spatial patterns of the CVs in the Thukela catchment (Figure 9.20) inversely mimic those of MAR. Subcatchments for which high MAR values are simulated portray correspondingly low values of CV, and vice-versa. The coastal stretch is an exception, as values of both MAR and CV are high. These high CVs of annual streamflows present a major challenge to planners in poor communities, many of whom are, as yet, without any reticulated water. The above picture of high inter-annual variability is exacerbated by the fact that

- most of the rural poor communities within the Thukela live in those areas with high CVs,
- both intensification and extensification of land uses have been shown, to amplify streamflow variabilities in the Thukela catchment (Schulze *et al*., 1997; Schulze, 2000), and
- the CVs depicted in Figure 9.20 are of the “mildest” form because CVs of streamflows for individual months are several times higher than those of annual flows (Schulze, 2000; also Section 9.5)

9.4.3 Spatial Variations of Mean Annual Accumulated Streamflows

Figure 9.21 shows means of annual accumulated streamflows in the Thukela catchment, where accumulated flows incorporate the (usual dampening) effects of all upstream flows, as well as flows from the subcatchment under consideration.

High streamflows are once again simulated in the Drakensberg region and also along internal subcatchments, i.e. those subcatchments that receive streamflow contributions from upstream subcatchments. These high runoff internal subcatchments are clearly those along the mainstem of the Thukela River and its major tributaries such as the Mooi, Sundays, Bushmans and Buffalo rivers. Other than in the Drakensberg, external subcatchments generally have the lower streamflow values than internal ones.

The implication of this pattern is that, although the Thukela catchment appears to have abundant available water, most of that water is concentrated along the major tributaries and the mainstem Thukela itself. It should, furthermore, already be noted at this juncture that most of the rural poor communities do not, however, live along mainstem rivers with high accumulated flows. There is a further constraint to indigenous rural communities not having ready access to available water, other than not being located along internal/mainstem rivers, and that is that within a subcatchment the communities/households tend to be located close to watershed boundaries where their supply of surface water would come from first order headwater streams which are frequently ephemeral in flow, rather than from second or third order streams with more consistent flows.

9.4.4 Inter- Annual Coefficient of Variation of Accumulated Streamflows

The CVs of accumulated flows (Figure 9.22) display inverse patterns to those of the accumulated flows themselves. Low CVs occur along the main channel and major tributaries, while high values occur in external subcatchments. This observation once again highlights the fact that water users who are located near the major tributaries are generally assured of more consistent supply than those who live in external subcatchments. This is of particular relevance in water poverty studies when considering those rural communities with no formal water supply schemes laid on as yet.

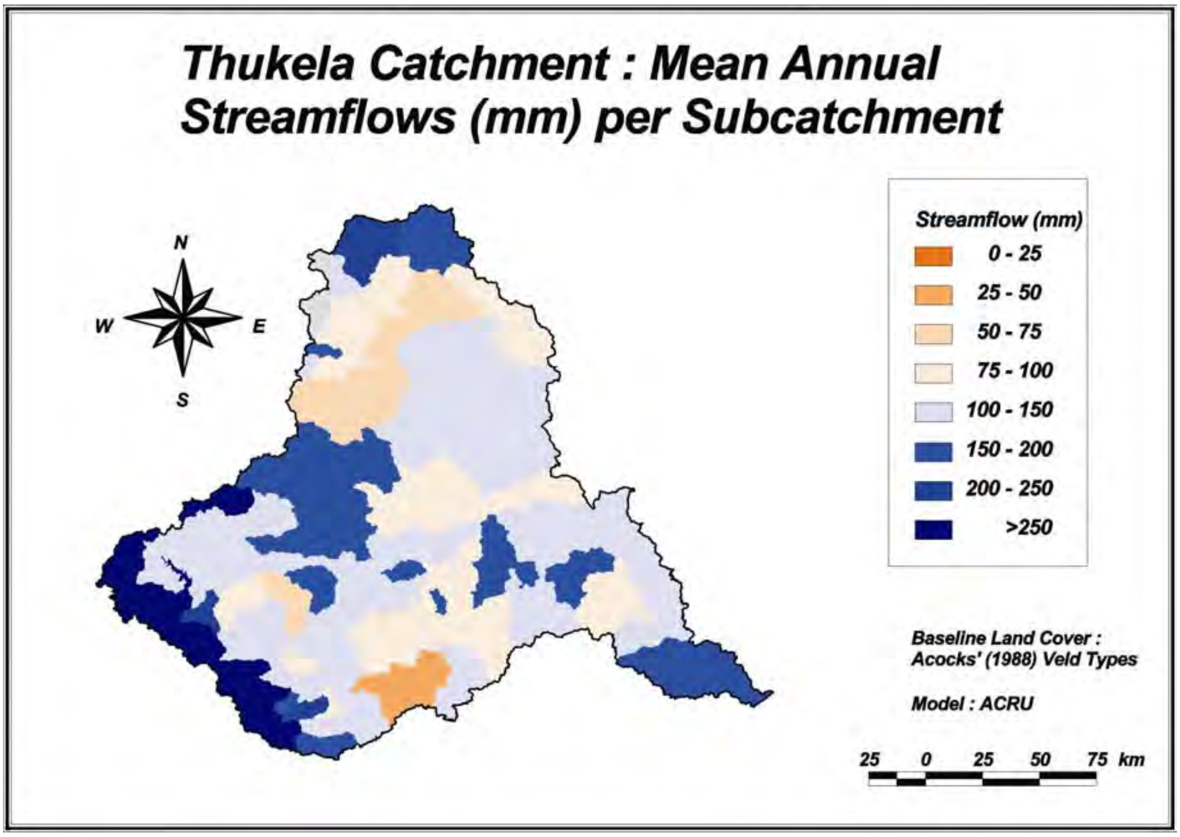

Figure 9.19 Simulated subcatchment MAR (mm) in the Thukela under baseline land cover conditions

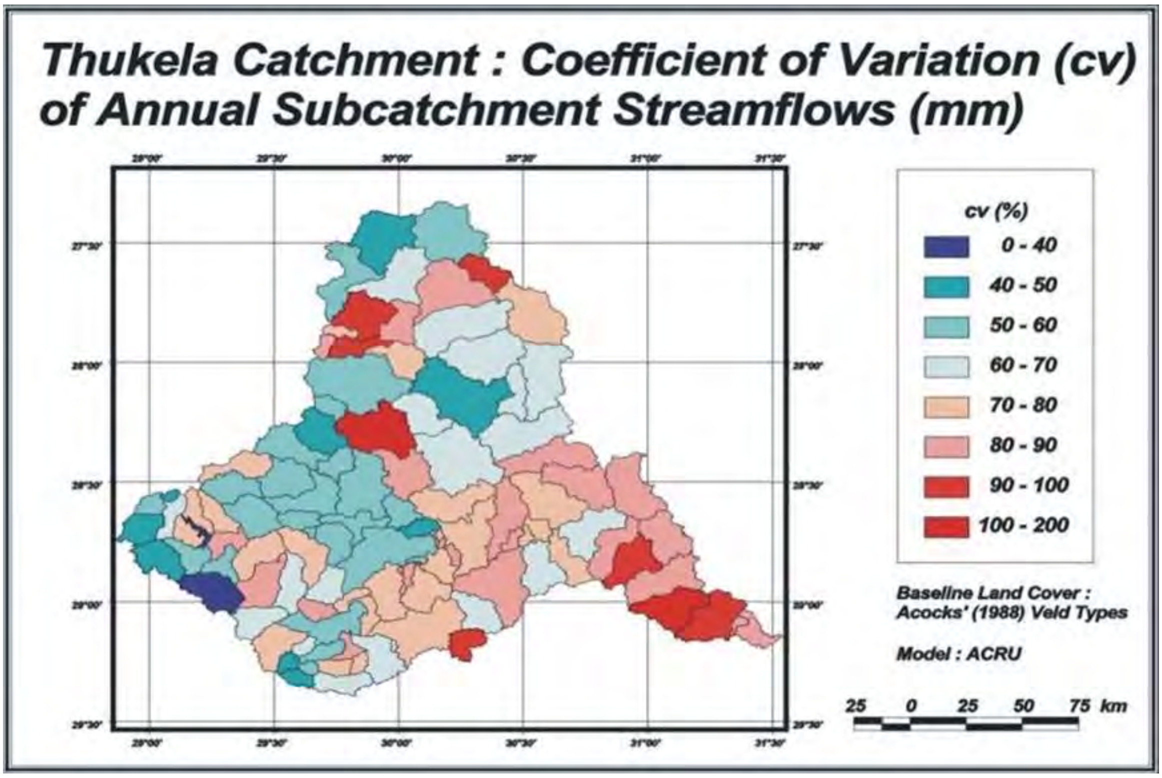

Figure 9.20 Inter-annual coefficients of variation (CVs) of individual subcatchment streamflows within the Thukela

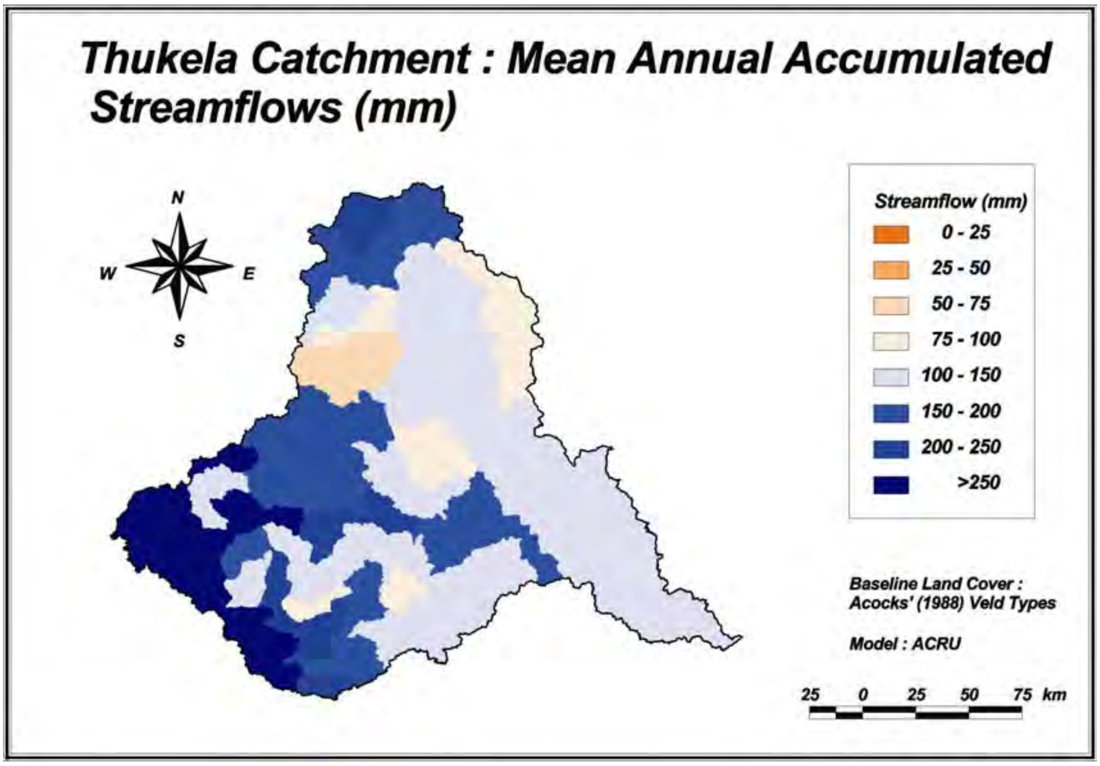

Figure 9.21 Accumulated MAR (mm) in the Thukela catchment

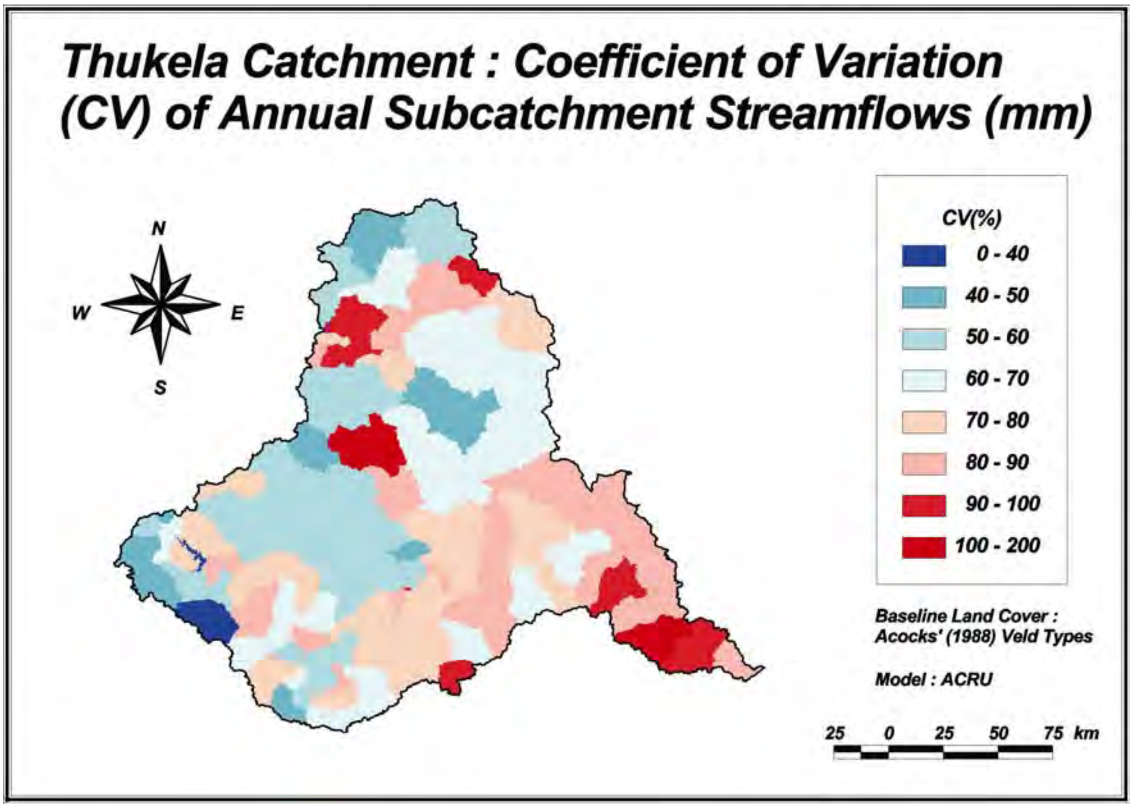

Figure 9.22 Inter-annual coefficients of variation (CV%) of accumulated streamflows within the Thukela

9.5 STREAMFLOW CHARACTERISTICS AT SPECIFIC W.P.I. CASE STUDY LOCATIONS IN THE THUKELA CATCHMENT

9.5.1 Background

As a central focus of the WPI project, in-depth case study surveys of household water use and accessibility were conducted at two locations within the Thukela catchment, *viz*. at Keate's Drift and Wembezi (Figure 9.23). In South Africa, these surveys were carried out by Zulu speaking students from the SBEEH on behalf of the GeoData Institute from the University of Southampton in the UK. The sections which follow outline the objectives of the analyses, describe field survey locations and present results of the analyses of streamflows simulated for the subcatchments in which these sites are located.

9.5.1.1 The objectives of the hydrological analyses

- to present and interpret output statistics of simulated baseline flows, including flow variability, on a month-by-month basis rather than only as annual totals,
- to interpret time series of streamflows to establish patterns of flows, particularly during low flow months, and
- evaluate flow duration curves for total, high flow month and low flow month conditions in order to establish patterns of flow at critical threshold occurrences, and
- to distinguish between respective contributions of stormflows and baseflows to total streamflows.

9.5.1.2 Keate's Drift

Keate's Drift (KD) was selected to represent a poor rural indigenous community consisting of scattered non-nucleated households, where one section of the community, *viz*. Ethembeni, already has access to potable water from a pre-paid token (akin to debit card) system at scattered water points, while the other section of the community at KwaLatha has no water service provision as yet and water has to be collected from rivers and springs.

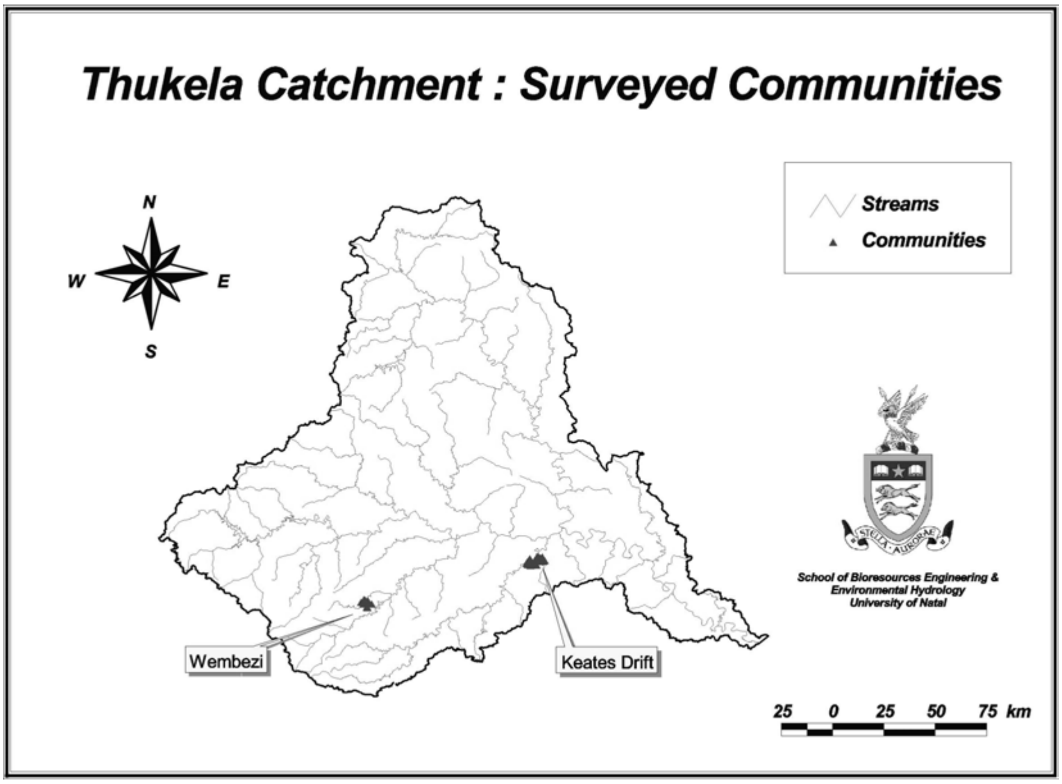

Figure 9.23 Location of the case study sites within the Thukela catchment

The Keate's Drift communities are located close to the Mooi River along the Greytown-Dundee road at latitude 28°51'S, longitude 30°30'E and altitude about 700 m. The subcatchment in which these communities are located is SC99 (Figure 9.12) which has an area of 309.77 km^2, while the accumulated upstream area of the Mooi at Keate's Drift is 2880.22 km^2. 9.5.1.3 Wembezi

Wembezi (WB) was selected to represent peri-urban township conditions. One section of the population, *viz*. at Depot, lives in formal housing with running water while the other, poorer community, Section C, lives more under shack conditions with no individual household water supply, but with communal standpipes approximately 150 m apart. Wembezi is a satellite township near Estcourt. Located at 29°03'S, 29°47'E and at an altitude of 1400 m, Wembezi flanks the Bushman's River. The subcatchment in which it is located is SC23 (Figure 9.12) with an area of 77.86 km^2 and the total catchment area upstream of WB is 195.55 km^2.

9.5.2 An Overview of Streamflow Statistics

The tables with streamflow statistics which follow all have mm equivalent flows as the unit rather than m^3, in order to represent flow equivalents per unit of area. The 10th percentile of flow exceedence represents flows in the driest month/year in 10, the 20th percentile the driest in 5, the 90th percentile the wettest in 10, and so forth. Also note that monthly percentile flows are computed for that particular month only and that the 12 monthly totals of percentile flows therefore do not add up to the annual total, which computed separately. Furthermore, note that because the *ACRU* model simulates a subcatchment's stormflows and baseflows explicitly (i.e. without recourse to baseflow separation curves), the statistics on stormflow and baseflow are available only for flows of an individual subcatchment and not for accumulated flows from upstream, in which case mixing of these two streamflow components has already taken place.

Table 9.2 Statistics on monthly and annual simulated total streamflows generated under baseline land cover conditions from the individual subcatchment SC23 at Wembezi

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	17.5	19.2	12.0	3.8	1.8	0.7	0.7	2.7	9.3	7.5	9.5	16.0	100.7
Std. Deviation	18.8	22.4	14.1	4.6	2.7	0.9	1.3	5.7	28.0	12.2	9.6	15.7	75.5
CV (%)	107.8	116.8	117.5	121.4	149.9	131.2	176.4	210.6	302.2	161.0	101.4	98.1	75.0
Skewness Coef.	1.6	1.9	2.5	2.0	2.3	1.8	4.5	2.7	5.0	2.7	1.9	1.7	1.9
Kurtosis Coef.	2.3	3.8	7.0	3.9	5.1	2.9	24.8	6.7	27.2	7.6	4.4	2.9	5.4
10th Percentile	1.7	1.5	1.5	0.3	0.0	0.0	0.0	0.0	0.1	0.5	1.0	3.1	22.3
20th Percentile	3.1	2.5	2.1	0.6	0.1	0.0	0.0	0.1	0.2	0.9	2.7	3.3	46.3
50th Percentile	10.1	10.3	8.7	2.3	0.9	0.3	0.3	0.4	0.6	2.5	6.4	12.7	83.3
80th Percentile	29.8	37.1	18.1	6.2	2.3	1.1	1.2	2.6	7.9	10.3	15.2	24.7	147.0
90th Percentile	41.6	47.1	22.8	12.1	5.0	2.1	1.7	10.2	22.7	22.8	22.0	33.9	178.0

Table 9.3 Statistics on monthly and annual simulated total streamflows generated under baseline and cover conditions from the accumulated area upstream of Wembezi

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	18.1	18.6	11.0	4.5	1.9	1.1	1.2	1.8	7.1	6.5	7.9	14.9	94.6
Std. Deviation	19.9	19.5	11.7	4.5	2.6	1.9	2.5	3.2	21.0	11.3	7.3	13.3	72.9
CV (%)	110.0	104.9	106.3	99.9	137.0	172.6	216.3	173.3	296.7	172.5	92.2	89.5	77.1
Skewness Coef.	2.1	1.7	1.8	1.2	1.9	3.5	4.5	2.7	4.9	3.2	1.5	1.4	1.7
Kurtosis Coef.	5.5	3.1	2.9	0.3	3.3	16.0	23.3	7.4	25.6	11.0	1.6	1.8	3.3
10th Percentile	2.7	1.7	1.8	0.7	0.0	0.0	0.0	0.1	0.2	0.7	1.0	2.5	23.1
20th Percentile	4.0	3.3	2.3	1.0	0.1	0.0	0.0	0.1	0.2	0.9	2.1	4.0	39.8
50th Percentile	9.4	15.1	6.3	2.3	0.9	0.4	0.4	0.5	0.6	2.0	6.4	10.9	80.6
80th Percentile	28.4	28.0	18.9	9.2	3.8	2.1	1.6	2.0	6.6	8.3	10.6	24.3	132.1
90th Percentile	43.2	42.6	24.4	11.6	5.6	3.0	2.7	6.6	15.0	13.3	18.9	35.8	194.5

Table 9.4 Statistics on monthly and annual simulated stormflows generated under baseline land cover conditions from the individual subcatchment SC23 at Wembezi

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	16.0	17.4	9.8	2.1	0.8	0.1	0.4	2.4	8.2	4.9	7.6	14.5	84.3
Std. Deviation	18.4	20.8	12.2	3.8	1.8	0.2	1.2	5.4	26.3	7.0	7.4	15.1	58.0
CV (%)	115.2	119.6	124.6	178.5	221.7	158.1	316.5	229.6	319.0	143.2	97.4	103.7	68.8
Skewness Coef.	1.7	1.8	2.2	3.1	2.9	2.2	5.6	2.8	5.2	2.2	1.9	1.8	1.9
Kurtosis Coef.	2.8	3.6	5.3	10.4	8.7	5.0	34.1	7.5	29.3	4.1	4.0	3.2	5.9
10th Percentile	1.5	1.4	0.7	0.1	0.0	0.0	0.0	0.0	0.1	0.4	1.0	1.9	21.8
20th Percentile	2.5	2.0	1.2	0.3	0.0	0.0	0.0	0.0	0.1	0.7	2.6	3.2	40.6
50th Percentile	9.4	8.3	5.2	0.6	0.1	0.0	0.0	0.2	0.4	1.8	4.7	8.1	75.1
80th Percentile	28.2	30.8	15.9	3.0	0.5	0.2	0.3	1.9	4.5	7.6	11.3	24.6	129.2
90th Percentile	37.9	42.4	22.8	4.5	3.0	0.3	0.8	9.9	22.7	14.8	19.3	29.4	140.2

Table 9.5 Statistics on monthly and annual simulated baseflows generated under baseline land cover conditions from the individual subcatchment SC23 at Wembezi

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	1.4	1.7	2.2	1.7	1.0	0.6	0.4	0.4	1.0	2.7	1.8	1.5	16.4
Std. Deviation	2.6	3.0	4.1	3.0	1.6	0.9	0.6	0.7	2.9	8.3	4.7	2.7	24.1
CV (%)	183.3	173.8	184.8	177.2	158.3	154.6	154.6	191.6	275.1	313.4	252.7	185.4	146.5
Skewness Coef.	2.4	2.6	2.7	2.7	2.1	2.0	1.9	4.0	3.5	4.1	3.6	2.9	2.4
Kurtosis Coef.	5.9	8.3	6.9	7.4	4.6	3.4	3.3	19.8	11.7	17.3	13.2	9.1	5.8
10th Percentile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20th Percentile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
50th Percentile	0.1	0.2	0.5	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.1	7.8
80th Percentile	1.7	3.2	3.3	2.5	1.6	1.0	0.6	0.6	0.5	0.4	2.2	2.4	22.5
90th Percentile	5.2	6.0	4.8	4.2	3.5	2.1	1.3	1.0	3.6	7.1	4.3	4.0	43.5

Table 9.6 Statistics on monthly and annual simulated total streamflows generated under baseline land cover conditions from the individual subcatchment SC99 at Keate's Drift

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	28.7	24.4	15.9	4.2	3.3	0.9	1.8	4.2	9.4	9.1	10.1	19.6	131.5
Std. Deviation	34.0	33.6	21.6	7.0	11.3	1.8	5.0	9.4	36.2	14.8	12.0	28.4	82.4
CV (%)	118.7	137.8	136.1	166.5	343.0	197.7	281.2	224.1	386.6	162.3	118.6	145.3	62.7
Skewness Coef.	2.2	2.8	2.2	2.8	5.7	2.7	4.1	2.6	5.8	3.7	1.5	5.0	1.2
Kurtosis Coef.	4.3	9.5	4.9	8.8	34.8	6.9	17.7	5.5	36.0	16.6	1.4	28.8	2.0
10th Percentile	3.0	1.0	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.3	0.6	2.4	47.1
20th Percentile	6.5	4.3	1.2	0.3	0.1	0.0	0.0	0.1	0.1	0.6	1.2	5.8	66.6
50th Percentile	18.0	10.9	5.4	1.1	0.5	0.1	0.2	0.3	0.6	5.7	4.8	13.3	108.9
80th Percentile	38.5	41.4	25.2	5.9	2.1	1.1	1.2	2.8	7.8	13.2	18.0	25.4	201.0
90th Percentile	85.0	58.4	49.3	12.4	4.5	3.2	4.3	22.9	12.2	23.6	29.4	29.8	228.6

Table 9.7 Statistics on monthly and annual simulated total streamflows generated under baseline land cover conditions from the accumulated area upstream of Keate's Drift

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	20.8	18.1	14.5	5.5	3.4	1.7	1.2	2.7	7.2	7.6	10.2	18.5	111.4
Std. Deviation	14.3	13.2	12.6	4.7	4.5	2.5	1.5	4.3	24.2	12.1	7.6	9.7	62.0
CV (%)	68.7	72.9	87.1	85.3	134.7	145.3	128.4	158.5	335.2	158.7	74.8	52.5	55.6
Skewness Coef.	1.2	1.1	2.3	2.1	3.2	3.9	2.9	2.9	5.9	3.3	1.3	1.2	2.1
Kurtosis Coef.	1.0	1.2	7.3	5.1	12.8	18.7	10.6	10.0	36.8	11.6	1.5	1.3	5.1
10th Percentile	7.5	4.4	3.8	1.6	0.4	0.2	0.1	0.3	0.3	1.3	2.5	7.4	59.1
20th Percentile	8.8	5.7	5.0	2.2	0.7	0.5	0.2	0.3	0.4	1.7	3.3	11.5	67.3
50th Percentile	16.5	15.3	11.0	4.2	1.9	1.1	0.6	1.2	1.0	3.3	8.7	15.6	95.3
80th Percentile	32.0	29.7	22.3	8.2	4.8	1.9	1.9	3.5	4.8	8.6	13.8	24.6	128.7
90th Percentile	44.4	37.9	27.5	10.4	8.8	4.9	3.1	8.2	12.6	13.5	20.0	31.3	175.4

Table 9.8 Statistics on monthly and annual simulated stormflows generated under baseline land cover conditions from the individual subcatchment SC99 at Keates Drift

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	27.4	23.1	14.8	3.2	2.4	0.3	1.2	3.6	8.1	6.5	8.0	18.0	116.6
Std. Deviation	33.5	33.5	20.8	6.3	10.5	1.4	3.8	8.7	35.1	8.3	10.6	26.8	68.7
CV (%)	122.1	145.0	141.3	198.3	430.4	394.8	326.0	245.1	435.5	127.2	133.0	148.8	59.0
Skewness Coef.	2.1	2.8	2.3	3.0	5.7	4.8	3.6	2.7	6.0	2.6	2.0	4.8	1.0
Kurtosis Coef.	4.0	10.1	5.6	10.0	34.7	22.9	12.1	6.8	38.0	9.0	4.0	26.9	1.6
10th Percentile	2.8	0.9	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.5	2.2	41.1
20th Percentile	5.3	2.6	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.6	0.7	5.6	65.1
50th Percentile	16.2	9.9	5.2	0.6	0.1	0.0	0.0	0.2	0.3	4.0	3.1	10.8	97.1
80th Percentile	38.5	40.4	24.8	3.8	0.4	0.2	0.2	1.4	3.3	10.3	14.0	24.1	164.9
90th Percentile	84.8	54.5	44.9	10.7	4.0	0.4	1.2	17.8	8.1	14.7	22.1	28.8	204.9

Table 9.9 Statistics on monthly and annual simulated baseflows generated under baseline land cover conditions from the individual subcatchment SC99 at Keate's Drift

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	1.2	1.3	1.1	1.0	0.9	0.6	0.6	0.6	1.3	2.6	2.1	1.6	14.9
Std. Deviation	2.9	2.6	2.1	2.0	1.6	1.3	1.6	1.6	3.0	7.3	5.4	3.6	23.0
CV (%)	229.8	206.6	182.5	194.2	190.4	220.6	266.6	252.6	233.2	283.4	253.1	230.2	154.0
Skewness Coef.	3.6	2.9	3.1	3.4	2.4	3.6	4.7	3.4	2.5	4.1	3.5	2.9	2.1
Kurtosis Coef.	14.8	9.7	12.7	14.4	5.1	15.0	25.8	10.6	5.1	19.0	13.6	8.0	4.7
10th Percentile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20th Percentile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
50th Percentile	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5
80th Percentile	1.7	2.0	1.9	1.9	1.4	0.8	0.7	0.6	0.8	2.5	3.1	2.0	24.5
90th Percentile	4.4	4.2	3.9	3.4	2.7	1.6	1.6	1.3	5.0	7.1	5.7	4.8	48.8

The following may be gleaned from Tables 9.2 to 9.9:

- A strong seasonality of flows is evident at both sites, with very low winter month flows (June – August) compared with high summer month flows (November – February).
- Total streamflow is dominated by stormflows (83.7% of the total flows at Wembezi, 88.7% at Keate’s Drift), indicative of the episodic and pulsar nature of rainfall events in the Thukela, which often occur as thunderstorms.
- Streamflow variability from year to year for any given month is very high. For the individual subcatchments, at Wembezi 11 of the 12 months have CVs > 100%, at Keate’s Drift it is 12 out of 12.
- It is notable that median monthly flows (i.e. 50th percentile) are markedly lower than mean monthly flows, particularly in the low flow months (e.g. at Wembezi in August: 0.4 mm vs 2.7 mm). This non-normality of the flow distribution manifests in very high coefficients of skewness.
- While baseflows only make up 16.3% of the annual flows in the Wembezi subcatchment, and 11.3 % at Keate’s Drift, they do play an important role in the low flow season. For the period June to August, for example, baseflows make up 34 % and 26 % respectively of total flows at Wembezi and Keate’s Drift.
- According to the *ACRU* model simulations, baseflows are not generated at all in any month of the year, in the driest year in 5 or condition drier than that at Wembezi and in the driest year in 2 or drier at Keate’s Drift.
- Where a total upstream catchment is large, as is the case at Keate’s Drift, CVs of monthly (and annual) flows are considerably lower than those from an individual subcatchment. For example, CVs are < 100 % in 6 of 12 months for accumulated flows vs 0 out of 12 months for individual subcatchment flows at Keate’s Drift. This is not the case with the small total area upstream of Wembezi, however, where accumulated flows are more variable than those of the local subcatchment.

9.5.3 Interpretation of the Time Series of Streamflows

Visual interpretation of the time series of annual streamflows in the subcatchments in which Keate’s Drift and Wembezi are located (Figure 9.24) highlights the following:

- There is a high inter-annual variability of flows.
- More importantly from a WPI perspective is that, in addition to isolated years with very high flows (e.g. 1957, 1976, 1987 at Keate’s Drift), sequences or clusters of persistent annual high flows occur, as do sequences of years of persistent low flows. The persistent low annual flows of the early 1960s, 1980s and especially 1990s have well documented associations with strong El Niño events.
- Neither the isolated high annual flows nor the consecutive years of lows necessarily occur at the same time or at the same strength at the two locations, which are only 75 km apart. For example, the sequence of low annual flows at Wembezi in the early 1990s is much stronger at Keate’s Drift.
- The implications of persistent low annual flow sequences for a WPI are quite profound, in that any storage of water will have to be large enough to withstand hydrological droughts of several years’ duration.

More significant for communities dependent on local surface water supplies are the patterns of the flow sequences in the low flow months, *viz*. June to August (Figure 9.25). The following may be observed:

- Inter-annual comparisons for the specified low flow months display a much more jagged pattern than for annual flows, particularly in the late low flow season (July – August).
- Prolonged hydrological droughts, i.e. when all three months have below average flows for several successive years, can be pronounced, as in the early 1960s, late 1960s and the decade 1975 – 85 at Wembezi.
- Again, differences occur in the low flow season persistencies at the two locations.
- The time series analyses highlight the necessity for monthly to seasonal streamflow forecasting to be tested and applied as a planning and operational tool for water poor areas.

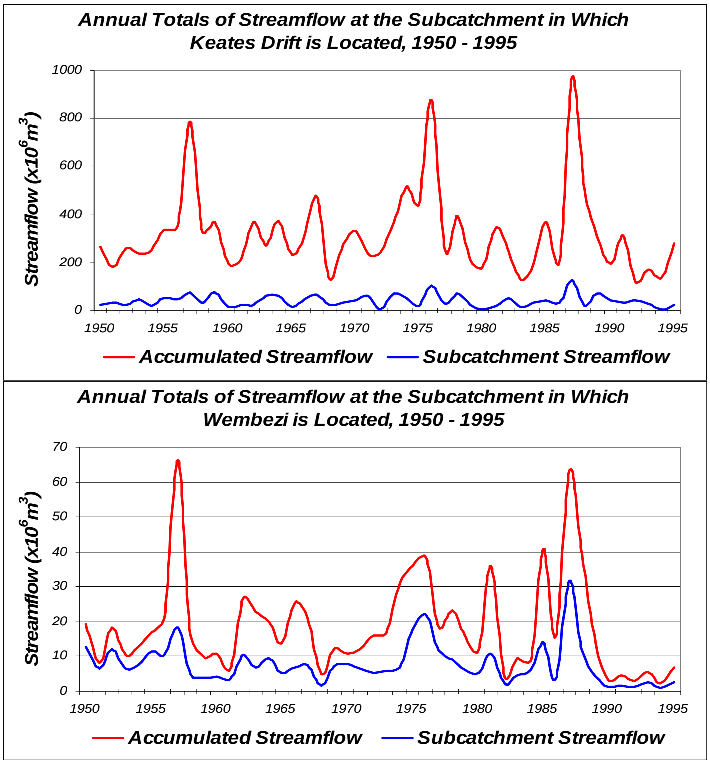

Figure 9.24 Time series of annual streamflows in the subcatchments in which Keate's Drift and Wembezi are located

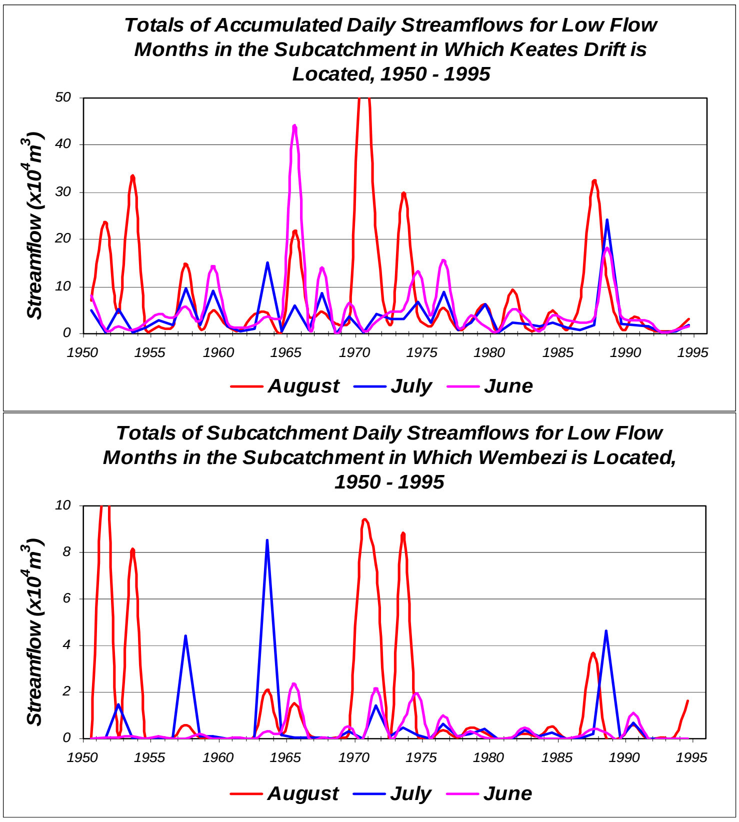

Figure 9.25 Time series of monthly flows for the low flow months June to August in the subcatchments in which Keate's Drift and Wembezi are located

9.5.4 Evaluation of Flow Duration Curves for Year Round Flows and for High and Low Flow Months

Flow duration curves (FDCs) show the percentage of time that a specified flow is exceeded or not. When evaluated together with a population or development-driven water demand, a FDC can be used as an indicator of the proportion of time that water stress occurs, either in regard to too much water (low percentage exceedence) or too little water (high percentage exceedence).

Figures 9.26 and 9.27 illustrate the following:

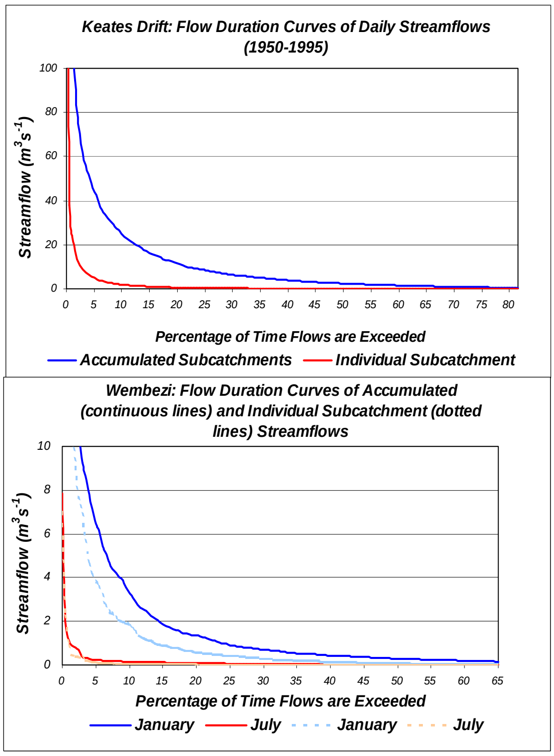

Figure 9.26 Flow duration curves for total flows as well as for high flows (January) and low flows (July) months at Keate's Drift

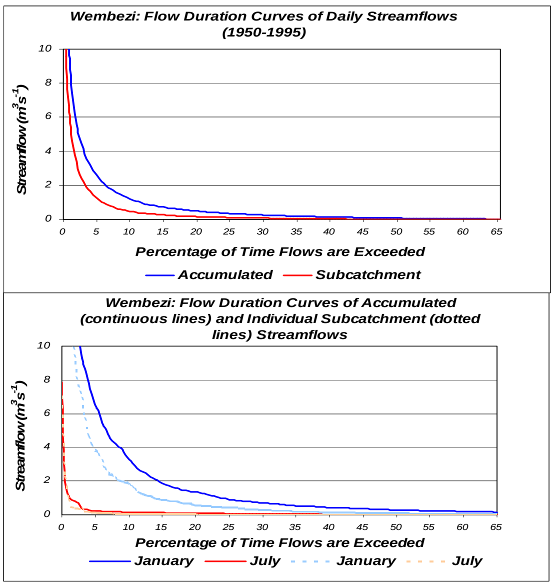

Figure 9.27 Flow duration curves for total flows as well as for high flows (January) and low flows (July) months at Wembezi

- In absolute terms (i.e. $m^3.s^{-1}$ of water available), the proximity of a mainstem river commanding a large upstream catchment area (as at Keate's Drift) provides a much more sustained water availability than a smaller catchment would (Figure 9.26 top vs Figure 9.27 top). Unfortunately, the rural poor do not always have access to water from rivers with large upstream catchments.
- Secondly, sustained water yield above a critical threshold of flow in months with high streamflows (e.g. January) is just so much more readily available than in months with low flows, e.g. July (Figure 9.26 bottom vs Figure 9.27 bottom).
- While being informative on percentage exceedences of flows of a given magnitude, the FDC does not, however, address the issue of persistent sequences of high or low flows.

For the purposes of comparing streamflow generation from large vs small catchments, FDCs may be expressed in terms of a unit area, i.e. $m^3.s^{-1}.km^{-2}$. Such a comparison is made in Figure 9.28.

While results look deceptively similar, close scrutiny shows that from a WPI perspective, i.e. at the low end of streamflow generation for which flows are exceeded frequently,

- a unit of area upstream of Keate's Drift generates considerably more streamflow than upstream of Wembezi and that
- an individual subcatchment may reverse a trend when its flows are compared with those of the accumulated flows of the total upstream catchment, as is the case at Wembezi for high flows occurring less frequently than 7% of the times.

9.5.5 Contributions of Stormflows and Baseflows to Total Streamflows

The respective contributions to total flows of stormflows (Q_s) and baseflows (Q_b) are a reflection not only of the type of rainfall generating mechanism in a region, but have an influence also on water quality. For example, high stormflows are associated with high sediment and phosphorus yields; high baseflows have bearing on nitrate concentrations of streamflows.

The dominance of stormflows at both Keate's Drift and Wembezi has already been emphasised. This is borne out graphically for the two case study locations in Figures 9.29 (top) and 9.30 (top). In relative (percentage) terms, the middle diagrams of Figures 9.29 and 9.30 show that only in June at Keate's Drift and only from May – July at Wembezi, do baseflows contribute more to total flows than stormflows. The bottom diagrams of Figures 9.29 and 9.30 illustrate that for median flows, the dominance of Q_s over Q_b is even greater than for means, because the means are influenced by extreme events which tend to produce more baseflows.

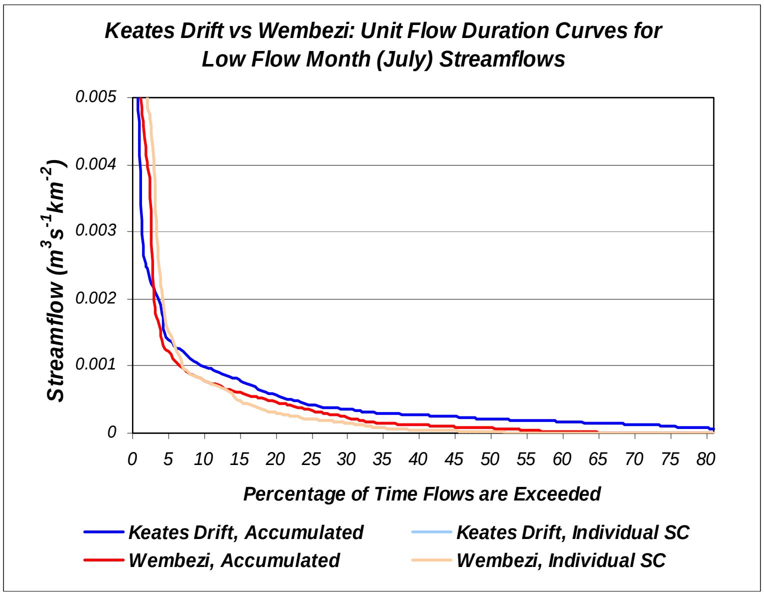

Figure 9.28 Flow duration curves per unit area ($m^3.s^{-1}.km^{-2}$) at Keate's Drift and Wembezi

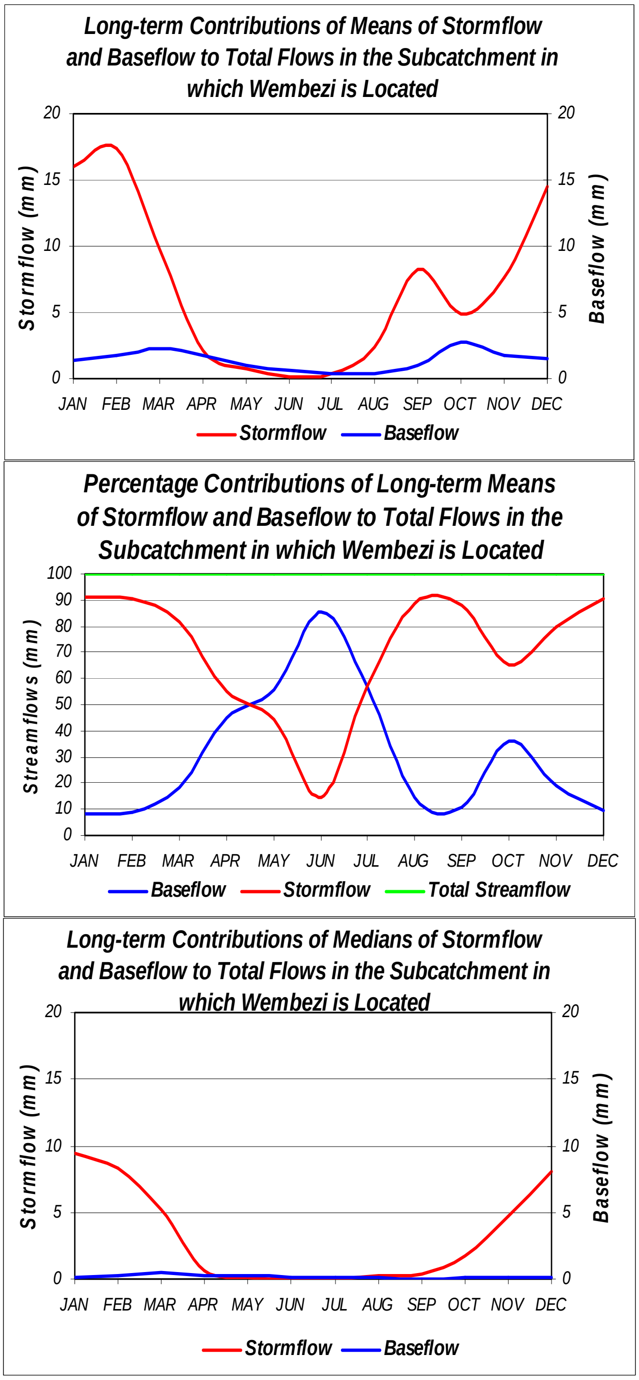

Figure 9.29 Contributions of stormflows and baseflows to total streamflows at Keate's Drift

9.6 LESSONS LEARNED AND THE ROAD AHEAD

9.6.1 Why Water Poverty Indicators at the Meso-Scale?

Water stress and water poverty indices tend to be developed for, and applied at, either macro-scales on a country or major catchment level, or on the other hand, at the micro-scale the individual rural communities. At the macro-scale little to no indication is given to where, when, how often, or for what duration water stress occurs at a given point of interest within the country, while at community scales in-depth studies tend to be undertaken in isolation of broader operational water resources issues.

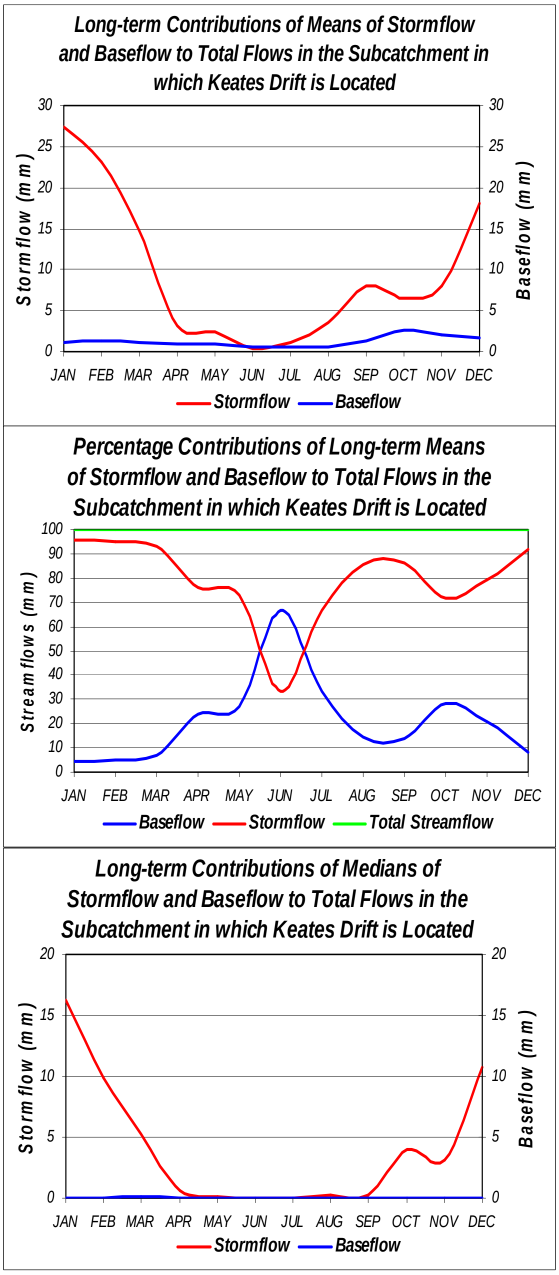

Figure 9.30 Contributions of stormflows and baseflows to total streamflows at Wembezi

This evaluation of indicators of water poverty under baseline conditions in the Thukela catchment has focused on the meso-scale, i.e. at catchments in the range of 10s to 100s km^2 in area. Two reasons are forwarded for developing a WPI at this scale:

- It is at the meso-scale that the intra-catchment streamflow response differences can be identified, i.e. the where, when, how frequently or how persistently water is available at a location of interest.
- It is, furthermore, at the meso-scale that water resources planners operate and many decisions on integrated water resources management are made.

9.6.2 What Lessons Have Been Learned from the Thukela Catchment in Regard to the Development of Water Poverty Indices?

- Primary indicators of potential water stress occurrence within the Thukela may already be gleaned from simple hydroclimatic analyses such as those on mean annual precipitation and its spatial variation (Figure 9.3), the seasonality of rainfall, its inter-annual variability (Figure 9.4) and potential evaporation rates (Figure 9.7).

- The amplification of any changes in rainfall patterns in hydrological responses cannot be over-emphasised. For example, a 3- to 4-fold range of MAP within the Thukela manifests itself as a 10-fold range in subcatchment streamflows, with MARs ranging from < 25 mm to > 250 mm (Figure 9.19).
- The hydrological amplification is even more pronounced in the inter-annual variabilities, with CVs of annual rainfalls around 20% (Figure 9.4) converting to CVs of annual streamflows of 40 to 100% (Figure 9.20).
- Variabilities of annual totals are the "mildest" form of assessing dispersion about the mean, with CVs of monthly streamflows being consistently and considerably higher than those of annual streamflows (Tables 9.2 to 9.9). To us it is imperative that this observation needs to be factored into a realistic WPI if it is to be applicable in rural areas with poor infrastructure.
- In the Thukela catchment, and probably in many other catchments in South Africa, the rural poor for historical reasons and more recently for more political reasons settled in those parts of the catchments characterised by higher climatic/hydrological variability. This renders rural poor communities even more vulnerable to water stress than had they settled more randomly throughout the catchment.
- Mainstem rivers and large tributaries generally produce higher and more sustained flows and have dampening effect on flow variability when compared with flows from individual subcatchments (Figures 9.21 and 9.22; Tables 9.2 to 9.9).
- However, the rural poor in the Thukela catchment tend not to live close to larger rivers. In fact, they often live close to watershed boundaries where streams are more prone to be ephemeral rather than permanently flowing. This observation needs quantification and verification, however.
- Median (i.e. statistically expected) monthly and annual flows within the Thukela catchment are considerably lower than their corresponding means (Tables 9.2 to 9.9). This indication of skewness in the distribution of streamflows further exacerbates water stress and ideally needs to be accounted for in a WPI.
- Time series of streamflows of the 46 year period of simulation display long sequences of years with persistent low flows, both for annual flows and the low flow months (Figure 9.24). These long sequences of low flows place a heavy burden on the water-poor communities.
- Long low flow sequences are closely associated with the well documented El Niño phenomenon in South Africa and if seasonal climate forecasting skills were to increase, rural communities concerned with water security would be important beneficiaries of such forecasts.
- The low flow persistencies furthermore imply that any impoundments designed to store water have to be large in order to cope with frequent occurrences of low inflows and high demands.
- Any water alleviation planning or WPIs should include flow duration curves as an input. In particular where local community planning is undertaken, the value of Unit FDCs (i.e. flows generated per km^2) should not be underestimated as a design tool (Figure 9.28).

9.6.3 The Road Ahead

The main objective of this study in the Thukela catchment has been to assess the primary natural endowment of streamflows under baseline land cover conditions at the meso-scale level, as an indicator of the potential availability of water and its constraints to development, with specific reference to contributing towards the quantification of a Water Poverty Index. A number of the streamflow attributes which were evaluated were found to have potential for inclusion in a WPI.

This first phase of the study has not, however, yet taken cognisance

- of present land use impacts on flow characteristics, through agricultural intensification or extensification, degradation, urbanisation, mining activities, or the major inter-basin transfers out of the Thukela system of over 600 x $10^6 m^3$ per annum out of a total water resource of 4 000 x $10^6 m^3$ per annum,
- of the above impacts on water quality and recharge to groundwater, or
- of population distributions and their water demands.

In particular the distribution of where the "water poor" populations reside has to be identified, not only in which subcatchments they reside, but also with respect to where, within a subcatchment, they are located with respect to more local streamflow variability.

The above are the challenges to be considered in further phases of WPI studies.

9.7 ACKNOWLEDGEMENTS

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