KC TARBOTON
RE SCHULZE

DISTRIBUTED HYDROLOGICAL MODELLING SYSTEM FOR THE MGENI CATCHMENT

Report to the
WATER RESEARCH COMMISSION
by the
DEPARTMENT OF AGRICULTURAL ENGINEERING
UNIVERSITY OF NATAL

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DISTRIBUTED HYDROLOGICAL MODELLING SYSTEM FOR THE MGENI CATCHMENT

by

K C TARBOTON and R E SCHULZE

with contributions by

S D LYNCH, J C SMITHERS, E J SCHMIDT, R M GUY and M MAHARAJ

FINAL REPORT TO THE WATER RESEARCH COMMISSION

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EXECUTIVE SUMMARY

1 INTRODUCTION

The Mgeni catchment is the primary source of water supplying the Pietermaritzburg Metropolitan Region and the Durban Functional Region. In 1985 water from the Mgeni catchment was supplied to 3.6 million people and supported industry and agriculture producing 20% of South Africa's Gross National Product (Breen, Akhurst and Walmsley, 1985). In Water Plan 2025 (Horne Glasson Partners, 1989) it is predicted that depending on future growth, the population in the area presently supplied with water could increase to between 9 and 12 million by the year 2025. Concomitant with the population increase the anticipated rural, urban and industrial development will increase water demand to exceed presently available water resources, making effective water resource management within the Mgeni catchment vital. A distributed hydrological modelling system for the Mgeni catchment has therefore been developed to aid in the integrated planning and development of the catchment and to provide hydrological information to those responsible for management of the catchment's water resources.

The development of this distributed hydrological modelling system for the 4353km^2 Mgeni catchment constitutes the first phase of the Water Research Commission funded project entitled "Development of a Systems Hydrological Model to Assist with Water Quantity and Quality Management in the Mgeni Catchment". This project was undertaken by the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg at the request of the Mgeni Modelling Group. Phase I of the project, reported on in this document, spanned the period from April 1988 to September 1991 and focused on the development and testing of a physical-conceptual modelling system to simulate the water quantity components within the highly complex Mgeni catchment. Development of the distributed hydrological modelling system to provide initial information on water quality will be undertaken as a second phase of this project from October 1991 to December 1994.

2 OBJECTIVES

The ***specific objectives*** that have been met by the Department of Agricultural Engineering in the development of the distributed hydrological modelling system for the Mgeni catchment are the following:

* collection and processing of input data and information for the modelling system including, *inter alia*, daily rainfall, daily streamflow, monthly A-pan equivalent evaporation, land cover, soils, water transfer and reservoir information,
* establishment of a Geographical Information System (GIS) containing the relevant spatial information for the Mgeni catchment and the development of interfacing techniques to integrate the GIS with the hydrological modelling system,
* systems model development, including rainfall estimation techniques, reservoir yield routines, channel routing procedures, evaporation estimation, and a soils decision support system,
* verification of the modelling system at each stage of development against observed data for selected subcatchments of Mgeni catchment, including verification of the model's accounting for observed changing land uses over the past 30 years,
* transfer of modelling techniques to ungauged subcatchments within the Mgeni catchment, illustrating the transferability of the modelling system,
* realistic, objective simulation of streamflow in the Mgeni catchment, downstream to the inlet of the Inanda dam for the past 30 years, and
* simulation of impacts of likely development scenarios such as increased farm dam construction, afforestation and the spread of informal settlements, on the Mgeni catchment water resources.

3 APPROACH

Conceptually the hydrological modelling system for the Mgeni catchment consists of a "system" which includes the catchment data and information, the processes and routines used to "derive" model inputs, and the hydrological model which "drives" the system and simulates the catchment hydrology. The wide ranging spatial variability within the Mgeni catchment in regard to its climate, soils, underlying geology, vegetation, land use and physiography made it essential to use "distributed" modelling techniques to simulate the catchment hydrology. The *ACRU* agrohydrological modelling system (Schulze, 1989) was selected to be "at the heart of " and to "drive" the Mgeni catchment system. Development of the following aspects of the hydrological modelling system for the Mgeni were undertaken during the course of the project:

* data collection,

* development of processes and techniques for the translation of data into hydrological information and model inputs,

* creation of a GIS for the Mgeni catchment to facilitate the processing of geographically spatial data and information and to act as an interface between the data base and the *ACRU* modelling system,

* development of modelling routines within the *ACRU* modelling system to enhance the hydrological simulations.

The Mgeni catchment was subdivided into 123 subcatchments, each with relatively homogeneous rainfall, land cover and soils distribution. Data and information collected for each subcatchment were translated into hydrological model inputs by interfacing the GIS with the *ACRU* hydrological modelling system in order to simulate streamflow from the catchment over a 30 year period.

4 ACCESS TO HYDROLOGICAL MODELLING SYSTEM FOR THE MGENI CATCHMENT

The input menus used to "run" the *ACRU* modelling system for the Mgeni catchment, together with the climatic and physiographic data and information files required by the modelling system, are housed on the Computing Centre for Water Research's (CCWR) mainframe computer. The modelling system for the Mgeni catchment uses *ACRU* -Version 3 which is due for public release later in 1992. It is envisaged that the most effective way of simulating the water resources in the Mgeni catchment using the modelling system developed will be by way of requests to the Department of Agricultural Engineering from planners and managers who wish to simulate the impacts of various scenarios of potential future development on water resources of the catchment.

5 ACHIEVEMENTS OF THE PROJECT

Rainfall

Accurate estimation of rainfall was regarded as essential for successful hydrological modelling. The relatively sparse rainfall gauging network over the Mgeni catchment necessitated an in-depth investigation into techniques for estimating daily rainfall for distributed hydrological modelling. Rainfall estimation using interpolated rainfall surfaces was evaluated and rejected due to an attenuation of rainfall quantities and an exaggerated number of raindays which distorted the rainfall frequency distribution. An alternative technique using rainfall driver stations was selected to estimate daily rainfall for each subcatchment. Frequency distributions of rainfall generated for each subcatchment using driver stations were similar to those of rainfall observed at measuring sites, and the streamflow generated when using driver station rainfall matched observed streamflow more closely than that streamflow generated when using rainfall estimated by interpolated surfaces.

Evaporation

Monthly A-pan equivalent evaporation was estimated for each subcatchment using temperature based equations developed for the region in which the Mgeni catchment is situated. Temperature based equations were chosen to estimate equivalent A-pan evaporation because there were three times more temperature stations than pan evaporation stations and they were distributed more evenly throughout the catchment. Temperature information is also more easily interpolated to unmeasured locations than evaporation pan information.

Land cover

Land cover over the Mgeni catchment was classified into 23 hydrologically distinct land cover response classes using satellite images, available aerial photography and topographical maps. New land cover classes were incorporated into the land cover Decision Support System (DSS) within *ACRU* to enable the translation of percentage areas of each land cover obtained from the GIS into hydrological land cover variables for each subcatchment. New routines were introduced into the *ACRU* modelling system to accommodate urban land covers, including informal settlements, with varying amounts of impervious area.

Reservoirs

All reservoirs, including small farm dams, were located within the catchment using orthophotos, topographical maps and satellite images. The accuracy of reservoir location using satellite imagery was assessed and routines were developed to synthesize hydrological processes involving many small reservoirs located within subcatchments. Techniques to estimate reservoir capacities were evaluated for seven different reservoir shapes.

Water transfers

Water transfers were divided into small and large scale transfers, where large scale transfers included water abstractions for municipal and industrial use, effluent discharges and inter-catchment transfers, while small scale transfers included irrigation abstractions and return flows. Daily and monthly abstraction and return flow data were collected for points of abstraction and discharge and updated in *ACRU* month by month basis, by means of a "dynamic" file.

Soils

Unpublished Land Type field maps from the Soil and Irrigation Research Institute (SIRI) were digitized and the proportion of each Land Type in each catchment obtained. Land Type information for each subcatchment was translated into hydrological variables using a soils DSS developed for the *ACRU* modelling system.

Streamflow

Available streamflow data were collected and used to verify simulated streamflow for selected subcatchments. Streamflow routing techniques were developed to route streamflow along river reaches and through reservoirs. Streamflow routing was applied to the subcatchments upstream of Henley dam for verification.

Mgeni GIS

The Mgeni GIS was developed to integrate geographically spatial information into a unified system enabling interfacing between the GIS and the *ACRU* hydrological modelling system. Data and information collected within the scope of this project was stored in layers or coverages in the GIS and these coverages were either extracted individually for each subcatchment or combined to obtain further information for the subcatchments.

Results

Results of simulated versus observed streamflow for catchments with good quality streamflow data confirms the ability of the *ACRU* modelling system to simulate the hydrology of the Mgeni catchment realistically. Simulated streamflows for dry years, wet years and years of median flow are presented for critical points of interest in the catchment such as the inlets to the major reservoirs located within the system.

Development scenarios

Three scenarios of possible future development within the Mgeni catchment were evaluated in terms of their impacts on the quantity of streamflow simulated for selected subcatchments. The construction of farm dams was shown to have reduced streamflow into Midmar dam by 6% while a scenario which doubled the area under forestry upstream of Midmar indicated that streamflow into the dam would be reduced further by 10%. An urbanization scenario simulated runoff from selected subcatchments in the Msunduzi catchment for so called "Status Quo" and "Emergent Trends" conditions. Runoff was increased significantly (up to 92% under certain conditions) from areas converted to informal settlements and to a lesser extent (up to 11%) from subcatchments with anticipated increased formal urbanization.

6 CONCLUSIONS

The wide climatic and physiographic variability within the Mgeni catchment necessitated the use of distributed modelling with the catchment subdivided into 123 relatively homogeneous subcatchments. Data collection from various sources formed a major part of the project and included making use of satellite and aerial photography for determination of land cover data and digitizing SIRI Land Type field maps to obtain soils information. Management of the extensive data base containing data and information collected for each subcatchment was facilitated by the creation of a GIS for the Mgeni catchment.

The *ACRU* modelling system was selected to be at the "core" of the distributed hydrological modelling system for the Mgeni catchment and was developed further to accommodate simulations of multiple reservoirs within subcatchments and urban land covers. Streamflow routing techniques capable of routing streamflow down river reaches and through reservoirs were developed to enhance streamflow simulation.

Since an accurate estimate of rainfall is fundamental to successful hydrological modelling, rainfall estimation methods were evaluated and a technique was developed using a selected "driver" station with daily rainfall data for each subcatchment in conjunction with long term rainfall trends. A-pan equivalent evaporation was estimated using temperature surrogates and evaporation equations developed in the Department were applied to the Mgeni catchment.

Techniques were developed to "translate" data and information into the hydrological variables used in the *ACRU* modelling system. Translation was carried out in the soil and vegetation DSSs which form part of *ACRU*. Interfacing of the Mgeni GIS and the hydrological modelling system formed an important component of this project.

Scenarios of likely development scenarios were valuable in showing the impacts on streamflow of possible future agricultural and urban development.

7 RECOMMENDATIONS AND FUTURE RESEARCH

Rainfall is the single most critical factor in hydrological simulation. It is recommended that the daily spatial rainfall distribution be estimated from radar measurements in the future because of the relatively sparse rainfall gauging network and variability of rainfall over the catchment. It is envisaged that the subcatchment be disaggregated into smaller, more homogeneous subcatchments for future water quality modelling but this exercise *per se* will only bear fruit if daily rainfall can be estimated accurately for each subcatchment. "Real time" modelling is a future recommendation in the Mgeni catchment and automatic transmission of radar recorded rainfall data together with other climatic data from automatic weather stations is perceived a direction to follow..

Simulation of water quality is recommended for future research as water quality within the catchment is deteriorating rapidly. Towards this end Phase II of the project has received support and funding from the Water Research Commission and commenced on October 1, 1991.

It is recommended that interfacing between the GIS and *ACRU* modelling system be automated in the future to minimize the human element and stand alone processes.

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Other Department of Agricultural Engineering Staff

S.D. Lynch - instrumental in creation of the Mgeni GIS and for contributing significantly to the development of programs to manipulate data and geographical information

J.C. Smithers - for developing streamflow routing routines for *ACRU* modelling system

M. Maharaj - for developing A-pan equivalent evaporation estimation equations

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Mr J.M. Bosch	:	FORESTEK
Dr M.C. Dent	:	Computing Centre for Water Research
Mr H.M. du Plessis	:	Water Research Commission
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Mr P.W. Wiedeman	:	Water Research Commission (Secretary)

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CHAPTER 1

INTRODUCTION

In 1985 water from the Mgeni catchment was supplied to 3.6 million people and supported industry and agriculture producing 20% of South Africa's Gross National Product (Breen, Akhurst and Walmsley, 1985). In Water Plan 2025 (Horne Glasson Partners, 1989) it is predicted that depending on future growth, the population in the area presently supplied by Umgeni Water could increase to between 9 and 12 million by the year 2025. Concomitant with the population increase, the anticipated rural, urban and industrial development will increase water demand in excess of available water resources, making effective water resource management within the Mgeni catchment vital.

The primary objective of this research programme was to develop a distributed modelling system which could provide hydrological information essential to those responsible for planning, development and management of the Mgeni river catchment. The model was developed to aid planners and managers who are faced with a number of questions which need to be answered objectively in order to achieve the optimum development of water resources within the Mgeni catchment. While these questions relate both to water quality and quantity, the focus of this project was on the development and testing of a physical-conceptual modelling system to represent the water quantity components of the hydrological system. Development of the distributed hydrological modelling system to provide initial information on water quality will be undertaken as a second phase of this project from October 1991 to December 1994.

In this introductory chapter the characteristics of the Mgeni catchment are described briefly followed by the background to and motivation for the development of a systems model to simulate the hydrology of the catchment. The objectives of the project are reviewed and the approach adopted to achieve these objectives is presented.

1.1 MGENI CATCHMENT DESCRIPTION

The Mgeni catchment covers an area of 4353 km^2 and is located between the latitudes of 29 and 30 degrees south, and the longitudes of 30 and 31 degrees east, in the province of Natal on the east coast of South Africa (Figure 1.1). Rising in a wetland area called the Mgeni Vlei at an altitude of 2000 m.a.s.l. in the western extremity of the catchment near Nottingham, the perennial Mgeni flows 257 km to its mouth into the Indian Ocean at the Mgeni estuary in Durban (Figure 1.2). Rainfall over the catchment is highly variable with mean annual precipitation ranging from in excess of 1400 mm p.a. at Swartkop near Hilton to 600 mm p.a. in parts of the Valley of a Thousand Hills (Figure 3.2).

In terms of geology, unconsolidated recent sediments and coastal sands have been deposited at the Mgeni mouth, while upstream and inland, Ecca Shale, Dyamictite and Natal Group Sandstone are found (King, 1982). Intrusions of dolerite dykes and sills near Pietermaritzburg give rise to the Howick, Karkloof and other water falls on the Mgeni. West of Pietermaritzburg the shales of the Ecca and Beaufort groups predominate. Soils at the coast consist of grey and red coastal sands with some black and red structured clays and duplex soils located directly inland of the coastal soils (Fitzpatrick, 1978; Schulze, 1982a). Further inland soils are weakly developed, with lithocutanic subsoil horizons, and consist of either red and black clays or duplex and plinthic soils. At the higher altitudes to the west of Albert Falls and Pietermaritzburg well drained yellow and red dystrophic or mesotrophic soils predominate. Soils are described more fully in Chapter 8.

Natural vegetation in the catchment consists of Coastal Forest and Thornveld in the coastal lowlands and Ngongoni Veld in the coastal hinterland (Acocks, 1975). The bioclimate in both these regions was described by Phillips (1973) as humid to subhumid. Further inland temperate and transitional forest and scrub of the Highland Sourveld and Ngongoni Veld types are found in a region with a subhumid to mild subarid bioclimate. Natural vegetation has been replaced in many areas by agricultural crops and through commercial afforestation. Present day vegetation in the catchment is described more fully in Chapter 6.

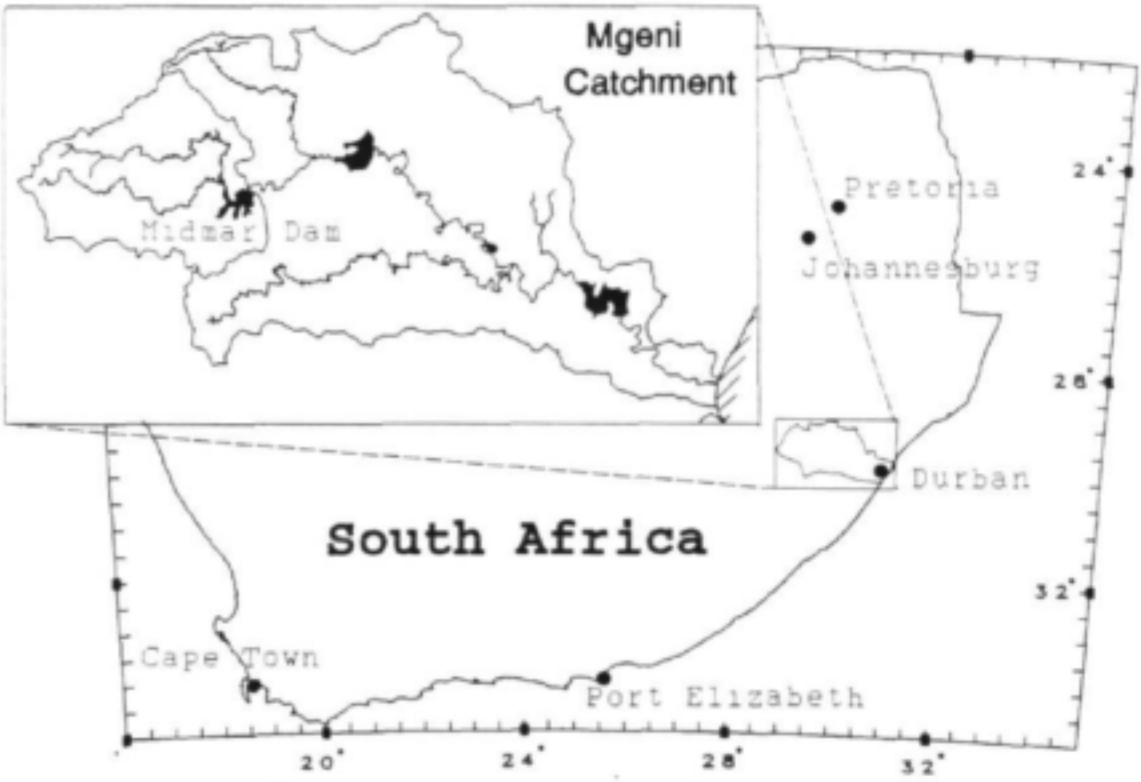


Figure 1.1 Location of the Mgeni catchment (after Tarboton and Schulze, 1991)

Along the Mgeni river, which forms the central axis of the catchment, four major water supply reservoirs are located, *viz.* the Midmar, Albert Falls, Nagle and Inanda dams. Dominating the southern portion of the catchment is the Msunduzi river which is the main tributary to the Mgeni, and on which the fifth major reservoir, namely Henley dam is located. Urban areas within the catchment include Howick, on the Mgeni below Midmar dam, Pietermaritzburg which straddles the Msunduzi river, and Cato Ridge, Hammarsdale, Pinetown and Durban along the southern watershed with the Mlazi catchment. Areas of rapidly growing informal settlements within the Mgeni catchment include Vulindlela, to the west of Pietermaritzburg, Inanda and Ndwedwe both northwest of Durban (Horne Glasson Partners, 1989).

1.2 BACKGROUND

Some 20% of South Africa's gross national product is generated within the water supply area of Umgeni Water (UW), the Statutory Water Board responsible for the management and supply of water to an area covering 7092 km^2. At present, the Mgeni river provides 90% of UW's water requirements. However, the rapidly accelerating water demands (a compound annual growth rate in excess of 5.8% between 1951 and 1980) will soon outstrip local raw water resources (Breen, Akhurst and Walmsley, 1985). Increased use will have to be made of return flows as well as supplementary schemes involving the transfer of water from adjacent catchments.

The increase in water demand, which is due to an increase in population and in the associated rural, urban and industrial development, is likely to be accompanied by a decrease in water quality. A major concern is that unco-ordinated development of the catchment could lead to this deterioration of the quality of the vital water resources with resultant higher purification costs to water supply authorities and consumers and possibly irreparable degradation of the environment. In response to these perceived potential problems, concerned parties met at a workshop entitled "Water Quality Management in the Mgeni Catchment" which was convened by the Natal Town and Regional Planning Commission and the Foundation for Research Development in February 1985 (Breen, Akhurst and Walmsley, 1985). Arising from this workshop the Mgeni Modelling Group was established to answer some of the questions raised at the workshop. The Modelling

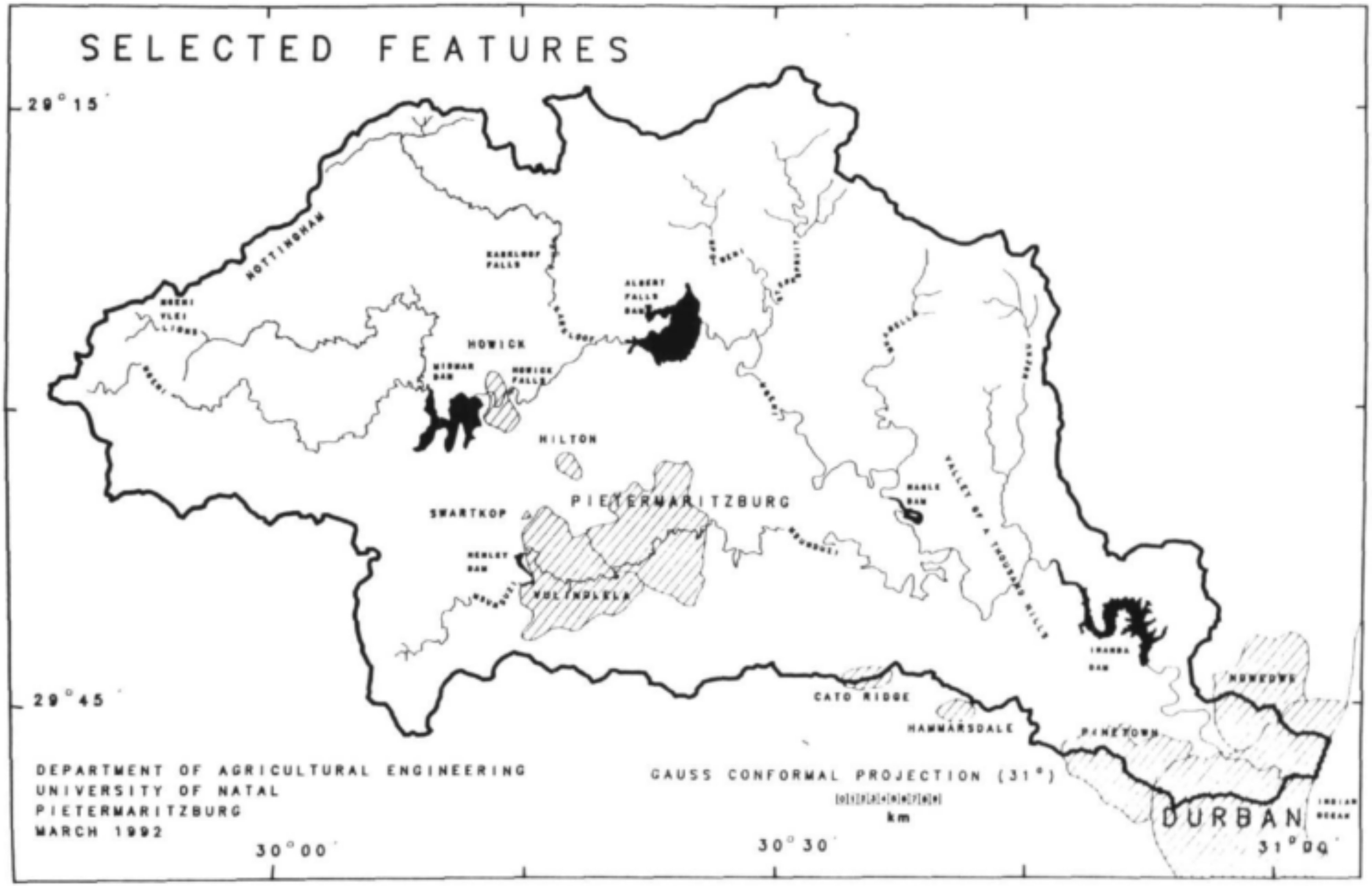


Figure 1.2 Selected features of the Mgeni catchment

Group came to the conclusion that a modelling approach could provide information essential to those responsible for planning the development of, and managing, the Mgeni catchment (Walmsley and Furness, 1987). The Department of Agricultural Engineering at the University of Natal in Pietermaritzburg was requested to undertake a research programme which would develop the framework of such a model with funding provided by the Water Research Commission (WRC).

The modelling approach was perceived as being able to satisfy the urgent need for a scientific management aid which could draw a large amount of information and techniques together for presentation to decision makers. This transfer of technology to the manager would enable more effective use to be made of the available water resources while at the same time indicating areas of immediate and long term research priority.

1.3 OBJECTIVES

Developed as an aid to managers and planners who need to answer questions regarding the Mgeni catchment's hydrology, the primary objective, focus and specific objectives to be achieved in the development of a distributed hydrological modelling system for the Mgeni catchment are as follows:

1.3.1 Primary objective

The *primary objective* of this project was to *develop a distributed modelling system which could provide hydrological information essential to those responsible for planning, development and management of the Mgeni river catchment.*

1.3.2 Focus

While the hydrological information required for management of the catchment relates to both water quantity and quality *the focus of this project was on the development and testing of a physical-conceptual modelling system to represent the water quantity components of the hydrological system*. The model has, however, been structured to accommodate, in future, the water quality modelling work being conducted by WATERTEK and allows for the integration of water quality data from UW and what is now the State Department of Water Affairs and Forestry (DWAF).

1.3.3 Specific objectives

With regard to water quantity, the specific objectives that have been met by the Department of Agricultural Engineering at the University of Natal, in the development of the modelling system, are the following:

a) development of model input data and information files including those of daily rainfall, daily streamflow, monthly temperature, monthly A-pan equivalent evaporation, monthly abstractions, altitude, land cover, soils and reservoir information

b) establishment of a Geographical Information System (GIS) containing the relevant spatial information for the Mgeni catchment and the development of interfacing techniques to integrate the GIS with the Hydrological Modelling System (HMS)

c) systems model development, including rainfall estimation techniques, reservoir yield routines, channel routing procedures, evaporation estimation, and a soils decision support system

d) verification of the modelling system at each stage of development against observed data for selected subcatchments of Mgeni catchment

e) transfer of modelling techniques to ungauged subcatchments within the Mgeni catchment, illustrating the transferability of the modelling system

f) realistic and objective simulation of streamflow in the Mgeni catchment, downstream to the inlet of Inanda dam, over the past thirty years

g) simulation of impacts of likely development scenarios on the Mgeni catchment water resources, such as increased afforestation and the spread of informal settlements.

Development of the hydrological modelling system to meet the above objectives was achieved using the approach described in the following section.

1.4 APPROACH

The wide ranging spatial variability within the Mgeni catchment in regard to its climate, soils, underlying geology, land cover and physiography makes it essential to use "distributed" modelling techniques to simulate the catchment hydrology. Distributed modelling involves subdividing the catchment into interconnected subcatchments where each subcatchment is delimited so that it is quasi-homogeneous in terms of climate, soils, vegetation and geology. In order to meet the objectives of the project, development of the modelling system for the Mgeni catchment was required at different levels which included, *inter alia*, the following:

a) selection of a model or modelling system capable of simulating the catchment hydrology in a distributed mode

b) assessing the data requirements of the selected model and collecting the data

c) transforming the data into hydrological information and model inputs

d) interfacing the hydrological information with the model and

e) developing modelling routines to enhance the hydrological simulations.

In order to develop a distributed hydrological modelling system for the Mgeni catchment, which included development at the above levels and achieved the project objectives, the integrated approach conceptualised in Figure 1.3 was adopted.

Conceptually the hydrological modelling system for the Mgeni catchment consists of a "system" which includes firstly the input data base with data for each distributed subcatchment within the catchment, secondly processes and techniques used to translate data into hydrological information, thirdly a geographical information system which acts as an interface, and fourthly the hydrological model which in turn "drives" the system and simulates the catchment hydrology. The *ACRU* hydrological modelling system (Schulze, 1989) was selected to be the heart of the distributed hydrological modelling system for the Mgeni catchment. The background, concepts and structure of the *ACRU* distributed modelling system are presented together with its application to the Mgeni catchment and data and information requirements in Chapter 2.

Data and information collected, translated into hydrological information and used in the distributed hydrological modelling of the Mgeni catchment is discussed in greater detail for each section of the modelling system, represented by the radial segments making up Figure 1.3. Each heading around the periphery of the outer concentric ellipse is the title of a separate chapter covering a component of the system development, including data collection, processes to transform data to hydrological information and the development of subroutines to enhance hydrological simulation within the *ACRU* modelling system.

Chapter 3 presents details on available rainfall data in the Mgeni catchment and discusses techniques for daily rainfall estimation for each distributed subcatchment. The rainfall estimation techniques are evaluated statistically and runoff generated using each technique is compared with observed runoff. The technique selected is then used to estimate daily rainfall for each distributed subcatchment in the Mgeni catchment.

The need for evaporation information and the selection of a reference evaporation is discussed in Chapter 4. Methods used to estimate A-pan equivalent potential evaporation using temperature-based equations are discussed and details of the generation of temperature-based equations to estimate A-pan equivalent evaporation for the Mgeni catchment are given.

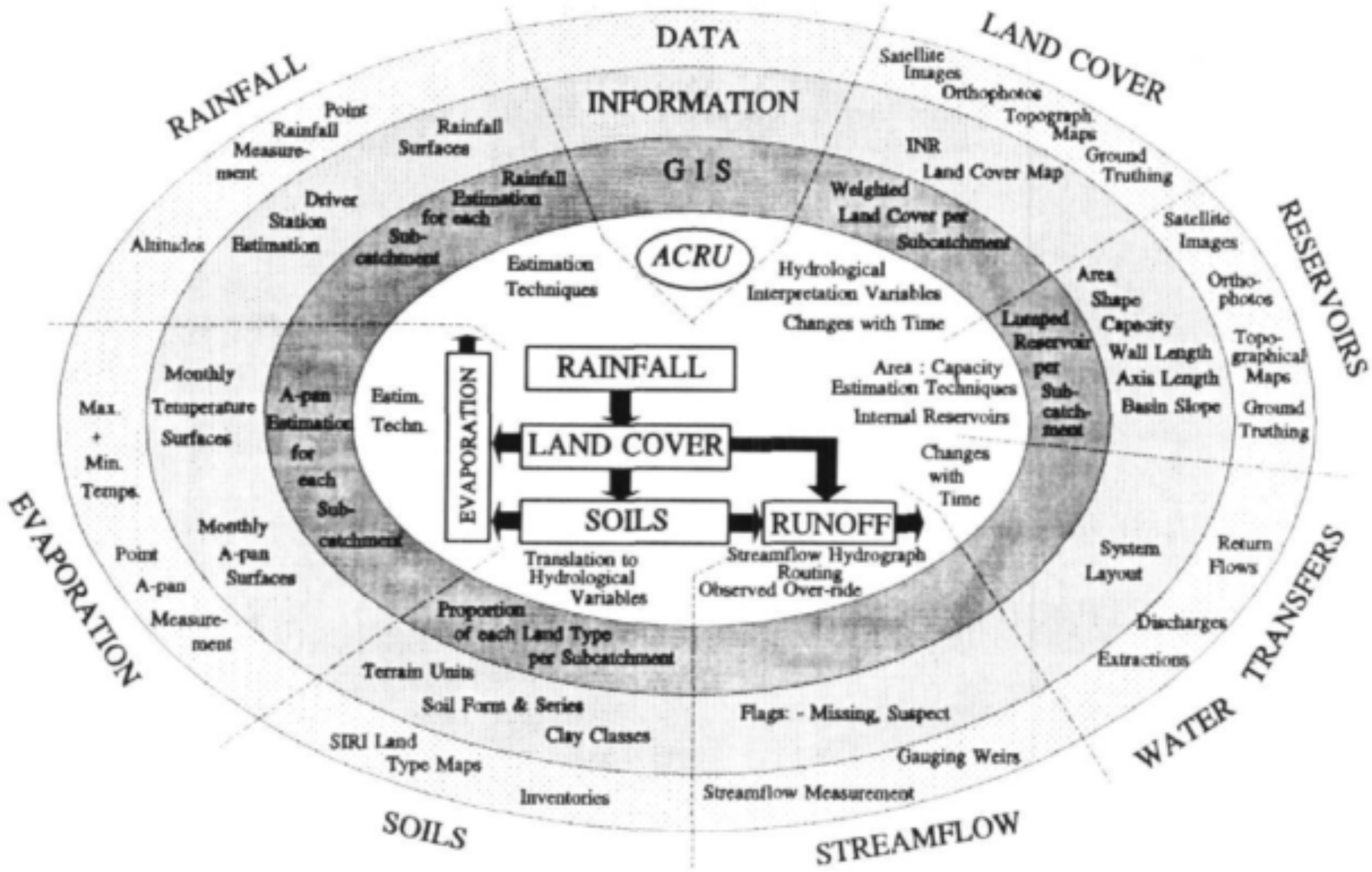


Figure 1.3 Concept of integrated distributed hydrological modelling system for the Mgeni catchment

Collection of land cover data and information, the problems associated therewith and the translation of land cover into hydrological information is covered in Chapter 5. This chapter also includes model development to incorporate impervious land covers and discusses the importance of considering land cover changes over time for modelling long term hydrological responses.

In Chapter 6 the location of reservoirs and collection of reservoir information relevant for hydrological modelling is discussed. The accuracy of locating reservoirs using satellite images is assessed and the development of reservoir modelling routines are presented.

Small and large scale water transfers are discussed in Chapter 7. Small transfers include water abstractions for irrigation and return flows from irrigation to streams and reservoirs. Abstractions from the large storage reservoirs for municipal water supply, inter-basin transfers and effluent disposal to rivers are reviewed in the section on large scale transfers.

Land Type maps and inventories from the Soil and Irrigation Research Institute (SIRI) are presented as the main source of soils information in Chapter 8. Interpreting hydrological soils information from Land Type information and automated translation of Land Type information for hydrological application are also discussed in this chapter.

Chapter 9 discusses streamflow, including available streamflow data from point measurements, the development of routines to route streamflow hydrographs down river reaches and through reservoirs, and the application of streamflow hydrograph routing to the Mgeni catchment.

The development of the Mgeni GIS is discussed in Chapter 10. The GIS is perceived as being the interface between the data and information and the *ACRU* hydrological modelling system and a section on interfacing the GIS with the modelling system is included. The GIS is also the link that ties the collected data and processed information of the preceding chapters into a unified system of segments (Figure 1.3).

Results of simulations in the Mgeni catchment are presented in Chapter 11. Model simulations are verified for subcatchments where gauged streamflow data were available and modelling techniques developed on the gauged subcatchments are transferred to the subcatchments without streamflow data. Chapter 12 presents some possible development scenarios within the Mgeni catchment and shows the value of the modelling system in assessing the impact of a forestry and an urbanisation scenario on streamflow in the catchment. Conclusions and recommendations for future research are presented in Chapter 13.

1.5 TERMINOLOGY

For clarity the definitions of certain hydrological terms as used in this report are given below:

Stormflow	is the water that flows over or near the surface of a subcatchment during and after a rainfall event to contribute to flows in the rivers within a subcatchment.
Baseflow	consists of water from previous rainfall events that has percolated through the soil horizons into the intermediate and groundwater zones and then contributes as a delayed flow to the streams within a subcatchment.
Seepage	is the water that seeps through the base and wall of a reservoir.
Normal flow	is the water that should be released legally from a reservoir to supply downstream users.
Runoff	is the water yield from a certain subcatchment and consists of stormflow and baseflow as well as any seepage, normal flow and overflow from any reservoirs within the subcatchment.
Streamflow	consists of runoff from the subcatchment under consideration plus the runoff contribution from all upstream subcatchments.

CHAPTER 2

ACRU DISTRIBUTED MODELLING SYSTEM

The description which follows is one of *ACRU*, which forms the core of the distributed hydrological modelling system for the Mgeni catchment. For a complete description of *ACRU* the reader is referred to Schulze (1989) and Schulze, George, Lynch and Angus (1989). A brief background to the *ACRU* modelling system is, however, presented giving the *ACRU* modelling philosophy and showing how development of *ACRU* to model the hydrology of the Mgeni catchment is consistent with this philosophy. Concepts of the *ACRU* model, a description of its structure and the application of *ACRU* to the Mgeni catchment follow thereafter.

2.1 BACKGROUND TO THE *ACRU* MODELLING SYSTEM

The acronym *ACRU* is derived from the *A*gricultural *C*atchments *R*esearch *U*nit within the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg. As a team effort and through the generous funding of the Water Research Commission, the *ACRU* model has developed from its origins as an in-depth evapotranspiration-based study at one location (Schulze, 1975) to its present status of an internationally recognised modelling system.

The philosophy in developing *ACRU*, as with other sophisticated interactive modelling systems, has been to adopt a team approach with different members of the team specialising in different aspects/components of the model construction processes. To facilitate team development and easy access to the latest developments by multiple users, *ACRU* is housed on the Computing Centre for Water Research's (CCWR) mainframe computer and is available to all accredited users who have attended an *ACRU* course. *ACRU* - Version 2 is currently available to users and is supported by documentation which includes: "*ACRU*: Background, Concepts and Theory" (Schulze, 1989) and the "*ACRU*-2: User Manual" (Schulze, George, Lynch and Angus, 1989). The *ACRU* modelling effort is an ongoing process with research developments continually being included in the latest version. Development of the *ACRU* modelling system to model the hydrology of the Mgeni catchment, reported in this document, has been included in *ACRU* - Version 3 due for release late in 1992.

2.2 CONCEPTS OF THE *ACRU* MODEL

The *ACRU* hydrological modelling system depicted in Figures 2.1 and 2.2 is based on the following concepts:

a) It is a *physical-conceptual* model, i.e. it is conceptual in that it conceives of a one, two or three dimensional system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly.

b) *ACRU* is not a parameter fitting/optimising model and variables (rather than optimising parameters) are *estimated* from physical features of the catchment.

c) It is a *multi-purpose* model, outputting (with risk analysis) either
   - runoff elements (e.g. stormflow, baseflow, peak discharge at daily, monthly or annual level)
   - reservoir yield analysis (overflow, reservoir status, abstractions, transfers)
   - sediment yield analysis (daily, monthly, annual; reservoir sedimentation)
   - soil water status and total evaporation (i.e. "actual evapotranspiration")
   - irrigation water demand (for different crops, application efficiencies, modes of scheduling)
   - irrigation water supply (from streams, reservoirs and combinations)
   - effects of land cover and use changes (gradual or abrupt) or
   - seasonal crop yields (maize, sugarcane, winter wheat - dryland or irrigated).

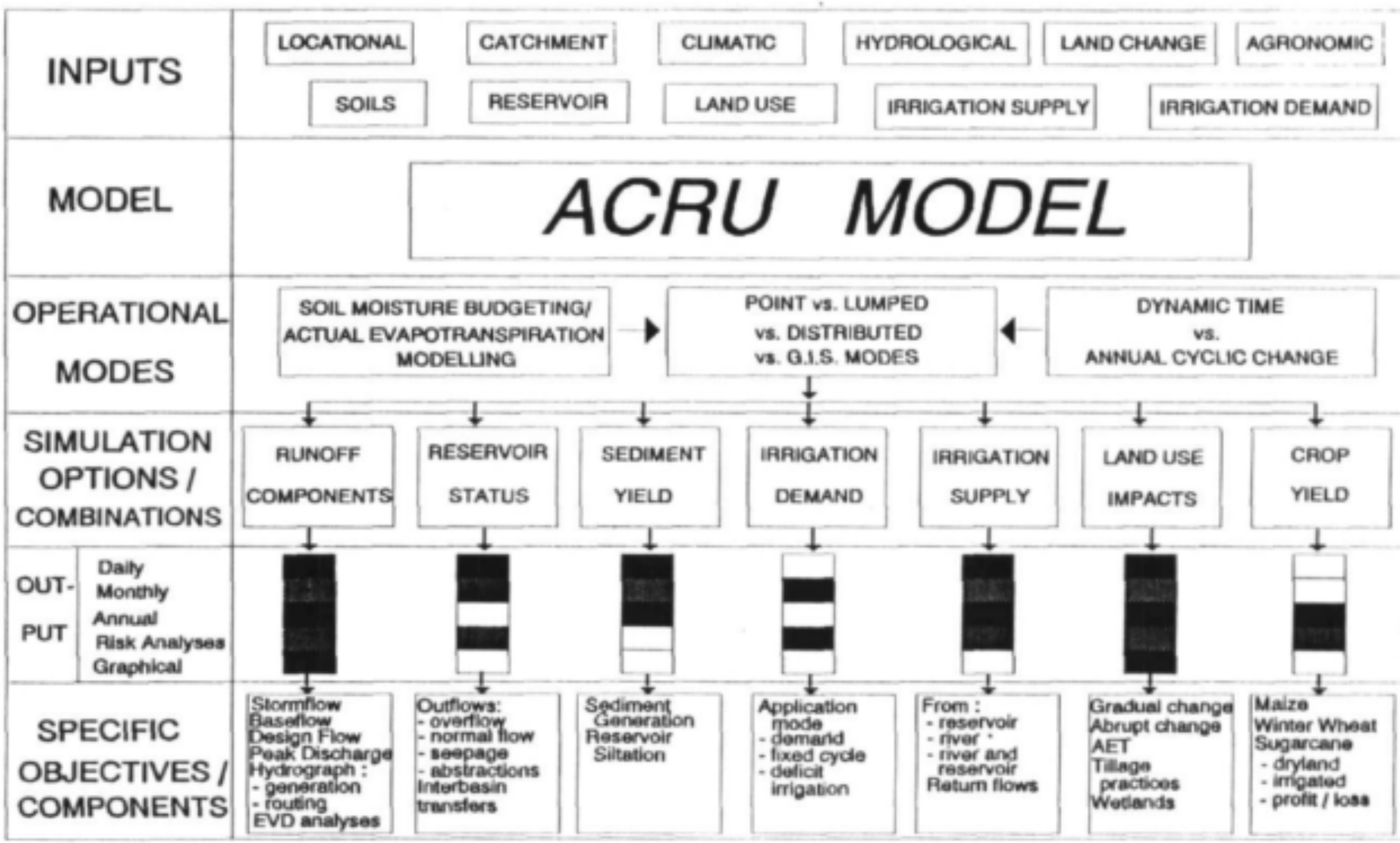


Figure 2.1 Concepts of the *ACRU* hydrological modelling system (after Schulze, 1989)

d) The model uses *daily time intervals as the basic time step*, and thus daily climatic input, thereby making optimal use of available data. Certain more cyclic, conservative and less sensitive variables (e.g. temperature, crop coefficients) which may have to be input at monthly level are transformed internally in *ACRU* to daily values by Fourier Analysis. More sensitive variables input at daily level may be disaggregated synthetically to give intra-daily distributions.

e) 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 been structured to be highly sensitive to land use and cover changes on the soil water and runoff regimes.

f) *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 sophistication of available input information and the type of output required. Thus, for example, reference evaporation, interception losses, soil water retention constants, maximum as well as total evaporation, leaf area index, peak discharge equations, reservoir storage:area relationships or the length of phenological periods in crop growth, all may be estimated by various methods according to the level of input data at hand.

g) Although *ACRU* can operate at a *point* or as a *lumped* catchment model, in the Mgeni catchment it is operated as a *semi-distributed* cell-type model. In distributed mode subcatchments are discretised, flows can take place from "exterior" through "interior" subcatchments according to a predetermined scheme and each subcatchment can generate individually requested and different output.

h) The model includes a *dynamic input option* to facilitate modelling the hydrological responses to land use or management changes within a time series, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of irrigation project) or abrupt changes (e.g. clearfelling, fire, construction of a dam, development of an irrigation project, or introduction of new land management strategies, such as tillage practices), changes of an inter-annual nature (e.g. crops with non-annual cycles) or changes in the nature of climatic input data. A dynamic input file is then accessed in the relevant month of each year in which the new input variables are acquired.

i) *ACRU* operates in conjunction with the interactive *ACRU Menubuilder*, which prompts with unambiguous questions, leading the user into inputting, for example, complex distributed catchment information easily and which contains alternative decision paths with preprogrammed *Decision Support Systems*. The *Menubuilder* includes built-in *default values* and error traps and is structured along the lines of an *expert system*.

2.3 STRUCTURE OF THE *ACRU* MODEL

The *ACRU* modelling system is structured on daily multi-layer soil water budgeting by partitioning and redistribution of soil water as depicted in Figure 2.2. That rainfall and/or irrigation application which is not abstracted as interception or as stormflow (quickflow or delayed), "resides" in the topsoil horizon. When that is "filled" to beyond field capacity the remaining water percolates into the subsoil horizon(s) as saturated drainage at a rate depending on respective horizon soil textures, wetnesses and other properties. Should the soil water content of the bottom subsoil horizon of the plant root one exceed field capacity, saturated vertical drainage/irrigation recharge into the intermediate and eventually the groundwater stores occurs, from which baseflow is generated. Unsaturated soil water redistribution, both upward and downward, also occurs but at a rate considerably slower than water movement under saturated conditions and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root one. Evaporation takes place from previously intercepted water as well as from various soil horizons simultaneously, either separately as a soil evaporation (from the topsoil only) and as plant transpiration (from all soil horizons in the root one) or combined, as total evaporation. Evaporative demand on the plant is estimated, *inter alia*, according to its stage of growth and the roots are assumed to absorb the water from the soil water in proportion to the distribution of root mass density within the respective soil horizons, except when conditions of low soil water content prevail. Under such conditions the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

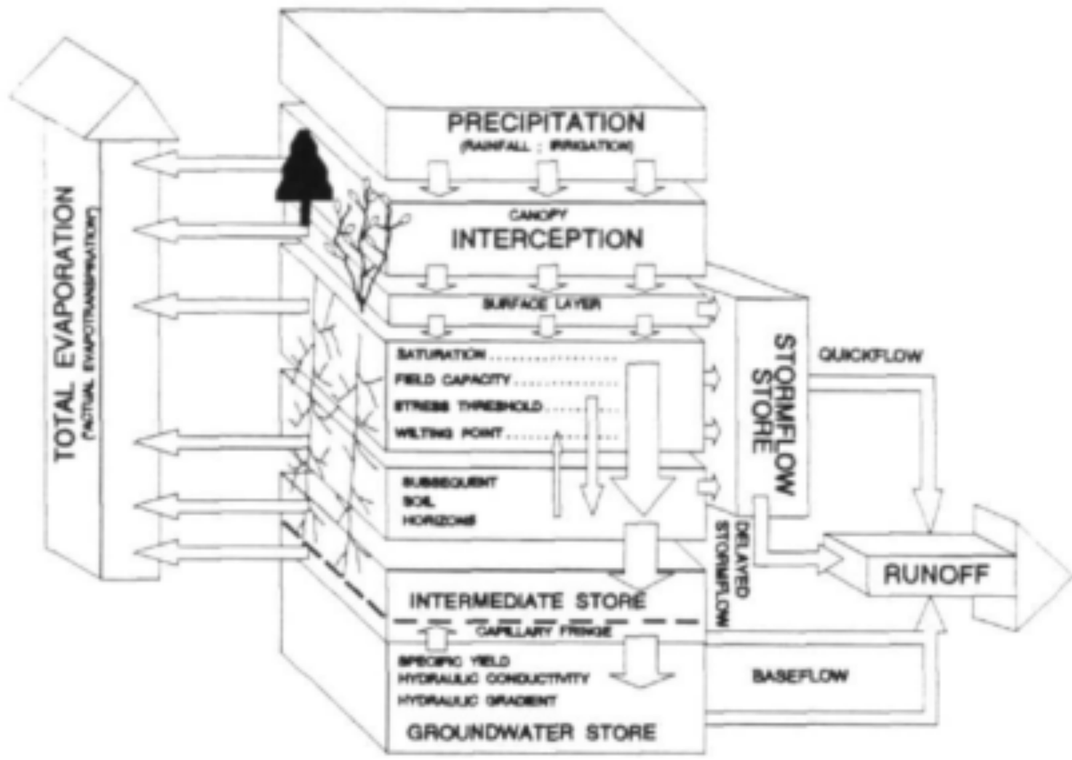


Figure 2.2 General struture of the *ACRU* hydrological modelling system (modified after Schulze, 1989)

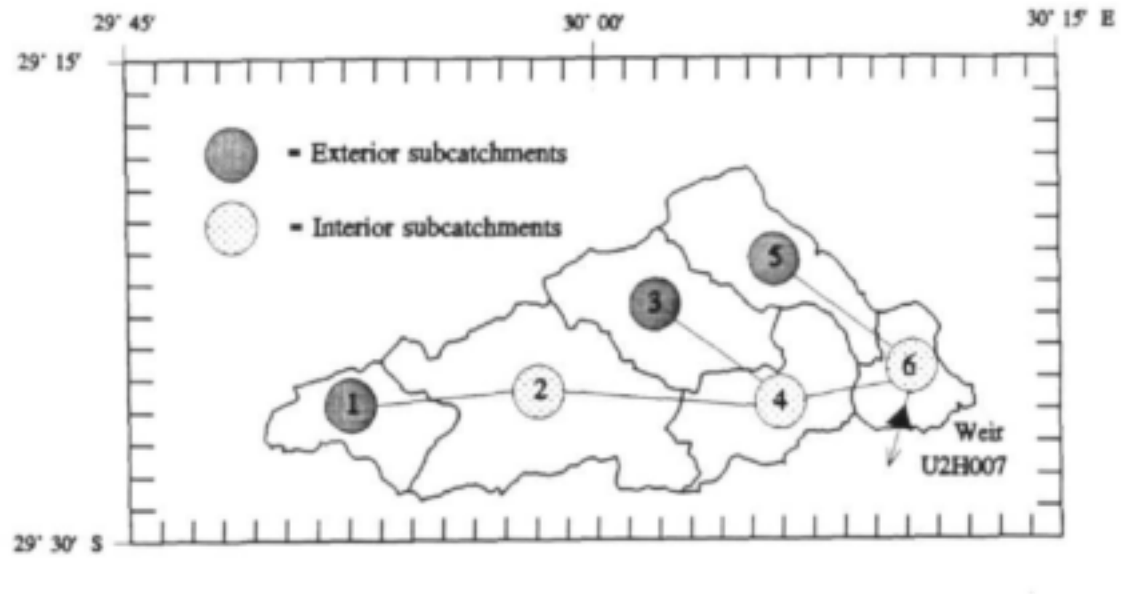


Figure 2.3 System layout for Lions river subcatchments of Mgeni showing the concept of exterior and interior subcatchments (after Tarboton and Cluer, 1991)

The generation of stormflow in *ACRU* is based on the premise that, after initial abstractions, the runoff produced from rainfall is a function of the soil water deficit from a critical response depth of the soil. This is an adaptation of the United States Department of Agriculture's 1972 Soil Conservation Service (SCS) concept in which runoff potential is, *inter alia*, an inverse function of the soil's relative wetness. The soil water deficit antecedent to a rainfall event is simulated by multi-layer soil water budgeting on a daily basis rather than from seasonal catchment runoff curve numbers used in the SCS method. 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, and deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff mechanisms predominate. Not all the stormflow that is generated is same day response; stormflow is therefore split into quickflow (i.e. same day response) and delayed stormflow (Figure 2.2) with this "lag" being dependent, *inter alia*, on soil properties, catchment size and the drainage density.

2.4 APPLICATION OF *ACRU* TO THE MGENI CATCHMENT

Being a daily time step model, *ACRU* does not account for the temporal rainfall 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 catchments, the hydrological responses are occurring and with what magnitude. The distributed version of *ACRU* was applied to the Mgeni catchment to account for the spatial variability of the catchment climate and physiography.

2.4.1 Subcatchment discretisation

ACRU makes use of a cell-type discretisation to subdivide the catchment into an assembly of interconnected units of area, or cells, where each cell is a subcatchment. Ideally subcatchments should be delimited so that each is quasi-homogeneous in terms of climate (rainfall and evaporation), land cover and soils. However, because rainfall is the predominant force driving the *ACRU* hydrological model and the rainfall gauging network in the Mgeni catchment is relatively sparse (Chapter 3, Rainfall), it would have been futile to disaggregate the catchment into subcatchments at a finer scale than that at which daily rainfall could be estimated accurately. Consequently subcatchments were delimited according to physiographic boundaries with due consideration being given to the raingauge network plus altitude, land cover, reservoirs and soils to make subcatchments as homogeneous as possible. In total 123 subcatchments were delimited and are shown in Figure 2.4. Subcatchments were delimited for the entire catchment although simulation in this report was only downstream to the Inanda dam inlet, i.e. subcatchment 104. The system layout of subcatchments is presented in Figure 2.5. The system layout for the Lions river section of the Mgeni catchment (Figure 2.3) is used to describe the operation of *ACRU* in distributed mode.

2.4.2 Operation in distributed mode

When operating in distributed mode *ACRU* makes a distinction between exterior and interior subcatchments (Figure 2.3). An exterior subcatchment has a portion of its boundary as a common boundary with the main catchment and the outflow from an exterior subcatchment is assumed to be independent of all the other subcatchments. An interior subcatchment has one or more upstream subcatchments and the outflow from an interior subcatchment may include contributions from upstream subcatchments.

In Figure 2.3 subcatchments 1, 3 and 5 are exterior while 2, 4 an 6 are interior. When analysing interior subcatchments it is important that runoff contributions from upstream subcatchments have been determined previously and are available for consideration in runoff determination of internal subcatchments. It is therefore important that the sequence in which subcatchments are analysed be defined accurately. By applying a simple numbering system to the subcatchment layout (Figures 2.3 and 2.5), each subcatchment is allocated a number greater than that allocated to any of the subcatchments upstream of its position. The model analyses each subcatchment in ascending numerical order, thereby ensuring that outflow information from upstream subcatchments is always available when analysing any internal subcatchment downstream.

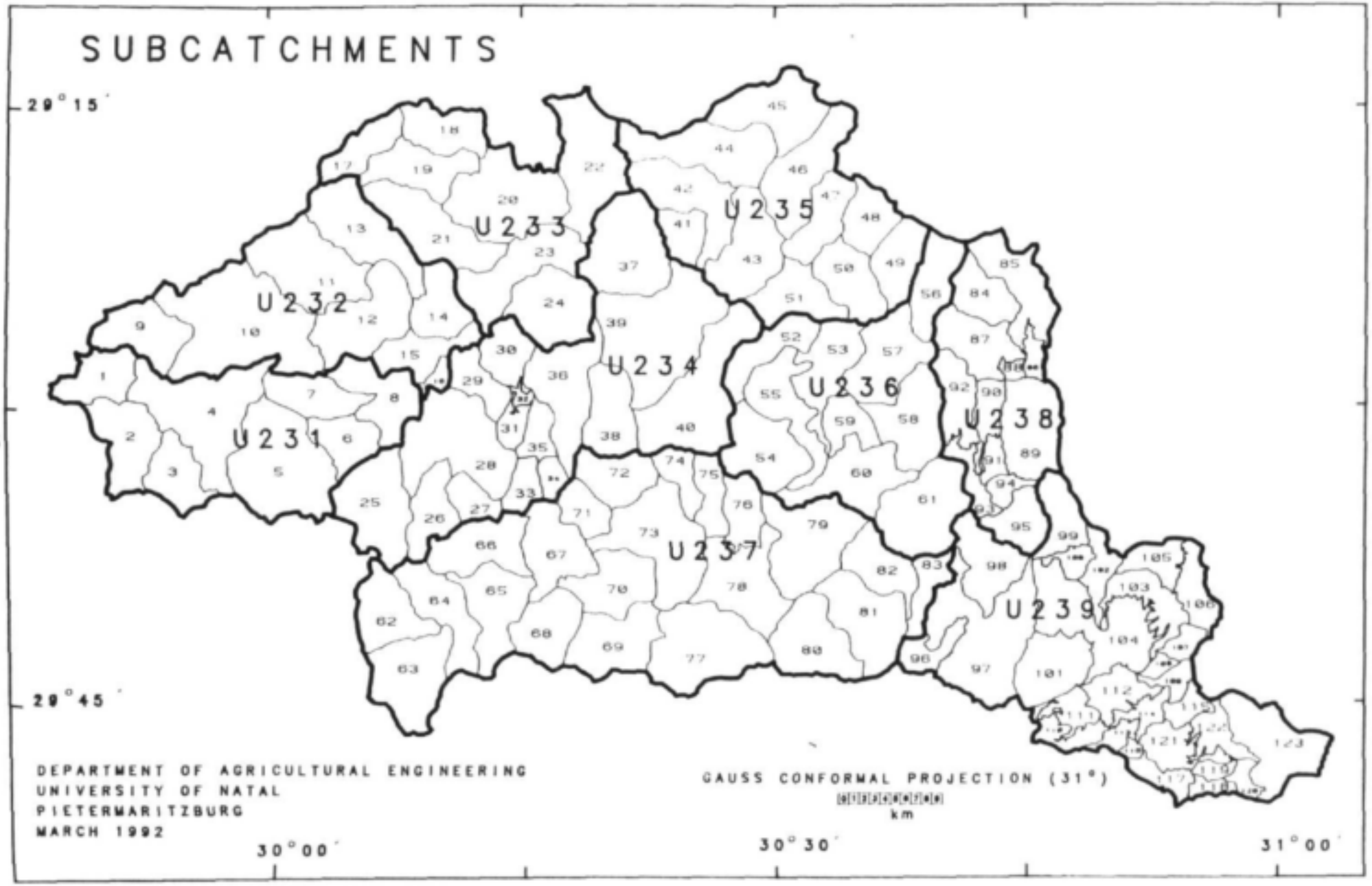


Figure 2.4 Subcatchment delimitation within the Mgeni catchment

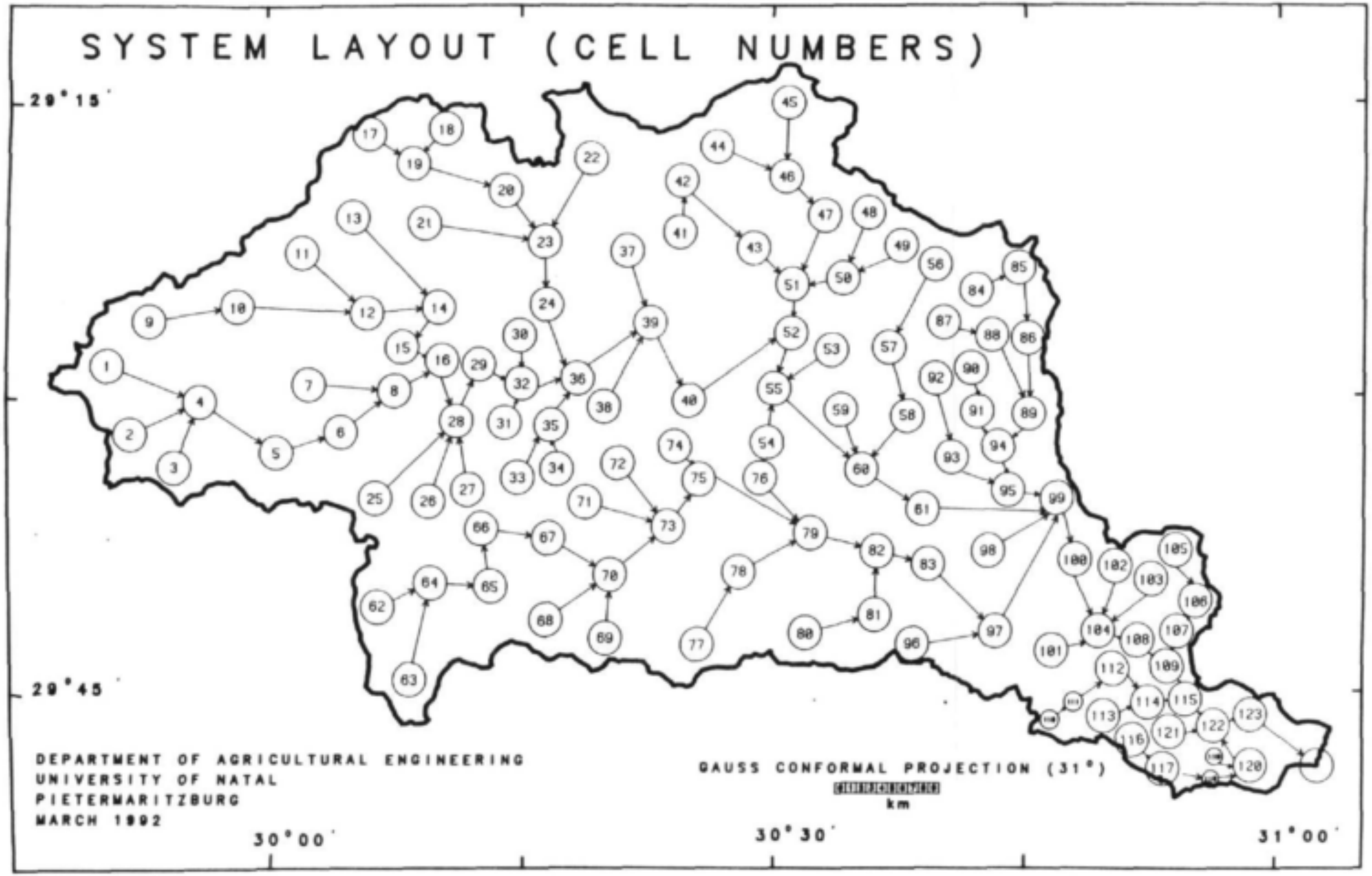


Figure 2.5 System layout for the Mgeni catchment

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 from Subcatchment 1 with only a risk analysis of monthly streamflow, whilst requesting an irrigation requirement analysis, reservoir yield risk analysis and daily water budget printout from the next subcatchment.

Distributed modelling makes high demands on input because each subcatchment is modelled individually and requires a unique and separate set of input variables. In the case of the Mgeni catchment input data and information requirements were large, as a result of the highly variable nature of the catchment physiography and the number of subcatchments used, *viz*. 123.

2.5 DATA AND INFORMATION REQUIREMENTS

In order to model the hydrology of the Mgeni catchment large amounts of different types of data were collected, transformed into hydrological information and used to generate the modelling inputs. Inputs required by the *ACRU* model are presented in Figure 2.1. Some of these inputs are elaborated on below to illustrate the model data and information requirements.

a) Locational and catchment: These include system layout, catchment names, areas, geographical location and mean elevation.

b) Climatic: Rainfall, A-pan equivalent potential evaporation or variables to estimate evaporation including, *inter alia*, maximum and minimum temperatures, temperature lapse rates, wind speed and day length are climatic input.

c) Hydrological: This category comprises streamflow data from gauging weirs, hydrological response rates, catchment hydraulic length and catchment response time.

d) Soils: Hydrological properties of soils are considered, including horizon depths, soil water properties of each horizon and soil water redistribution rates between horizons.

e) Land cover and change: Crop coefficients, leaf area indices, interception loss rates, root distribution, impervious areas and changes of these variables both seasonally and historically are included.

f) Reservoir: These inputs comprise capacities, surface area, wall length, normal flow, seepage, area:capacity relationships, drafts and inflows.

g) Irrigation: Information on irrigated soils and crops includes area irrigated, mode of scheduling, months in which irrigation water is applied, conveyance losses and water source.

Owing to the spatial nature of the data and information collected for the Mgeni catchment, a GIS was developed for the Mgeni to facilitate processing of the data to information and generation of modelling inputs. The creation of a GIS for the Mgeni catchment and interfacing of the GIS with the *ACRU* modelling system are discussed in Chapter 10. Data and information requirements for each aspect of the distributed modelling system for the Mgeni catchment, represented by the segments of Figure 1.3, are discussed in more detail in the chapters that follow.

CHAPTER 3

RAINFALL

A fundamental requirement for successful hydrological modelling is an accurate estimation of rainfall at the time and space scales required by the particular modelling system. Distributed catchment modelling using a daily time step requires an accurate estimation of daily rainfall for each subcatchment. Areal rainfall at the subcatchment scale can be estimated using satellite or radar systems (Seed, 1989) but raingauge networks still provide the bulk of the rainfall data to hydrologists throughout the world (Seed and Austin, 1990). The accuracy of areal rainfall estimated from point measurements depends on the representativeness of the point measurements, the spatial variability of the rainfall (Nicks and Hartman 1966) and the method used to estimate the areal distribution from the point measurements.

In this chapter the available rainfall data from point measurements in the Mgeni catchment is presented and two different methods used to estimate the representative rainfall for a selected subcatchment are discussed. The rainfall estimation methods are assessed by comparing the rainfall frequency distribution of the estimated rainfall, using each method, with that of rainfall measured at a raingauge, measurements from which are assumed to represent the rainfall frequency distribution of the subcatchment. Streamflow simulated by the *ACRU* model using daily rainfall estimated by the two methods is compared to observed streamflow in a gauged catchment to further assess the rainfall estimation methods. The selected method is used to estimate daily rainfall for each subcatchment of the Mgeni catchment.

3.1 AVAILABLE DATA

Daily rainfall data, available from 127 stations within the Mgeni catchment and surrounding area, was extracted from Weather Bureau files accessed through the CCWR. Over the entire catchment this represents a raingauge density of one gauge per 34 km^2, but an evaluation of the locational distribution (Figure 3.1) indicates that certain areas, such as the Valley of a Thousand Hills, are less than adequately represented. The highly variable rainfall over the Mgeni catchment (Figure 3.2) necessitated the discretisation of the catchment into numerous subcatchments with a more homogeneous rainfall distribution over each subcatchment. Even though discretised subcatchments were limited to an area of approximately 50 km^2 where possible, the poor raingauge distribution implies that many subcatchments have no rainfall gauging stations within their bounds. Furthermore rainfall records are often discontinuous, with days and in many cases months, without recorded data. The lengths of records for the stations extracted are summarized in Table 3.1 while a full summary of the statistics for each station is given in Appendix A.1. Only three recording rainfall stations with records in excess of 20 years occur within the Mgeni catchment, *viz.* Louis Botha, Cedara, Pietermaritzburg.

Table 3.1 Number of daily rainfall stations with varying record length occurring in or close to the Mgeni catchment

Length of record (years)	>5	>10	>20	>30	>50	>75
Number of daily rainfall stations	102	90	63	45	14	1

With regard to the minimum length of rainfall record to use in the Mgeni catchment for the purposes of hydrological risk modelling, it was decided to satisfy the international convention of using a minimum base period of 30 years as discussed by Dunne and Leopold (1978). This is consistent with the recommendations of Dent, Schulze, Wills, and Lynch (1987) who analysed the spatial and temporal distributions of recent drought in southern Africa and suggested a period of at least 30 years of data be used in simulations. Because of the sparsity of daily rainfall stations and the desire to use rainfall estimates from at least 30 years it was necessary to estimate rainfall using either a generated daily rainfall surface or by using rainfall "driver" stations.

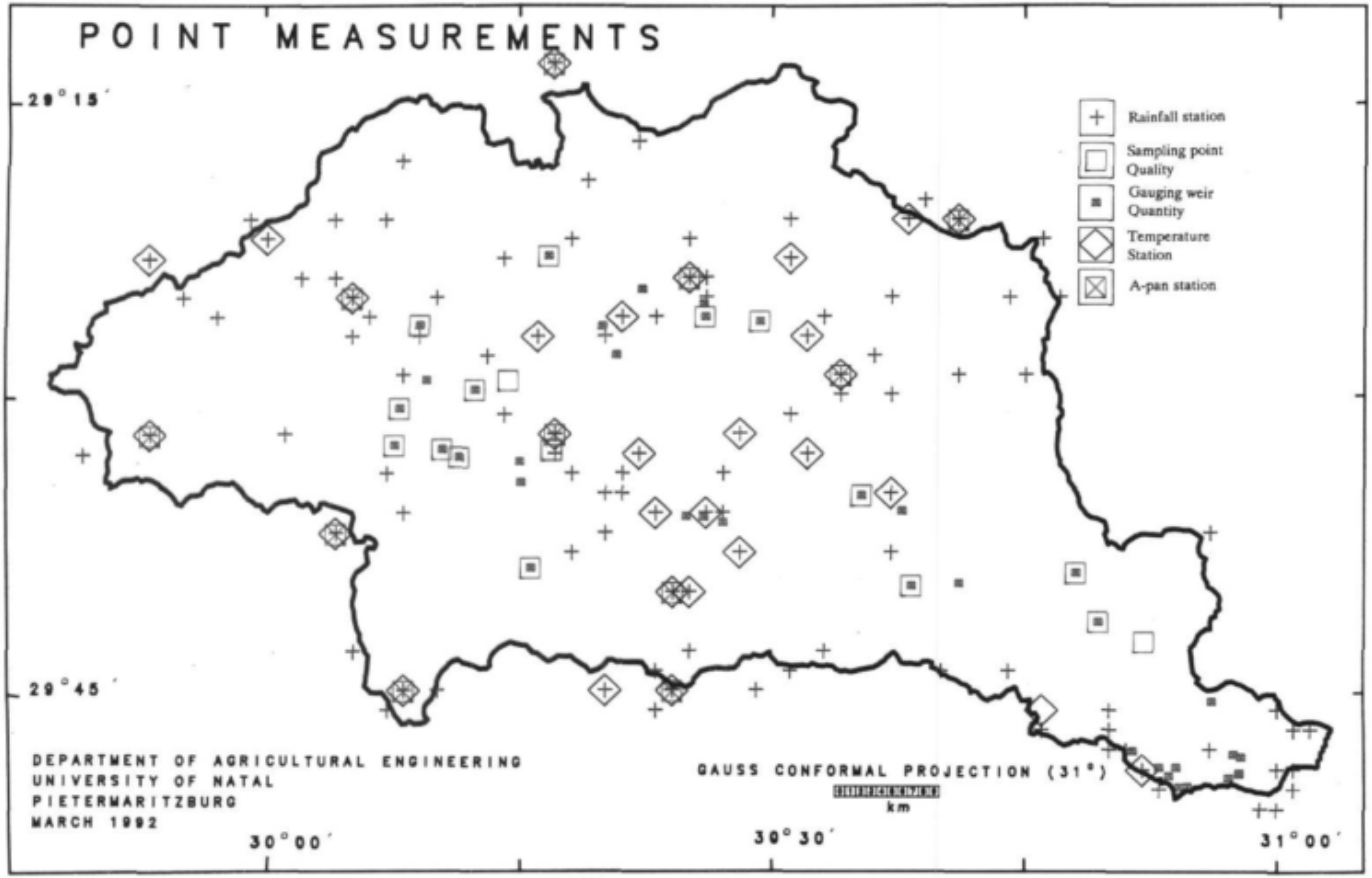


Figure 3.1 Locational distribution of point measurements of rainfall, temperature, A-pan evaporation, water quantity and water quality in the Mgeni catchment

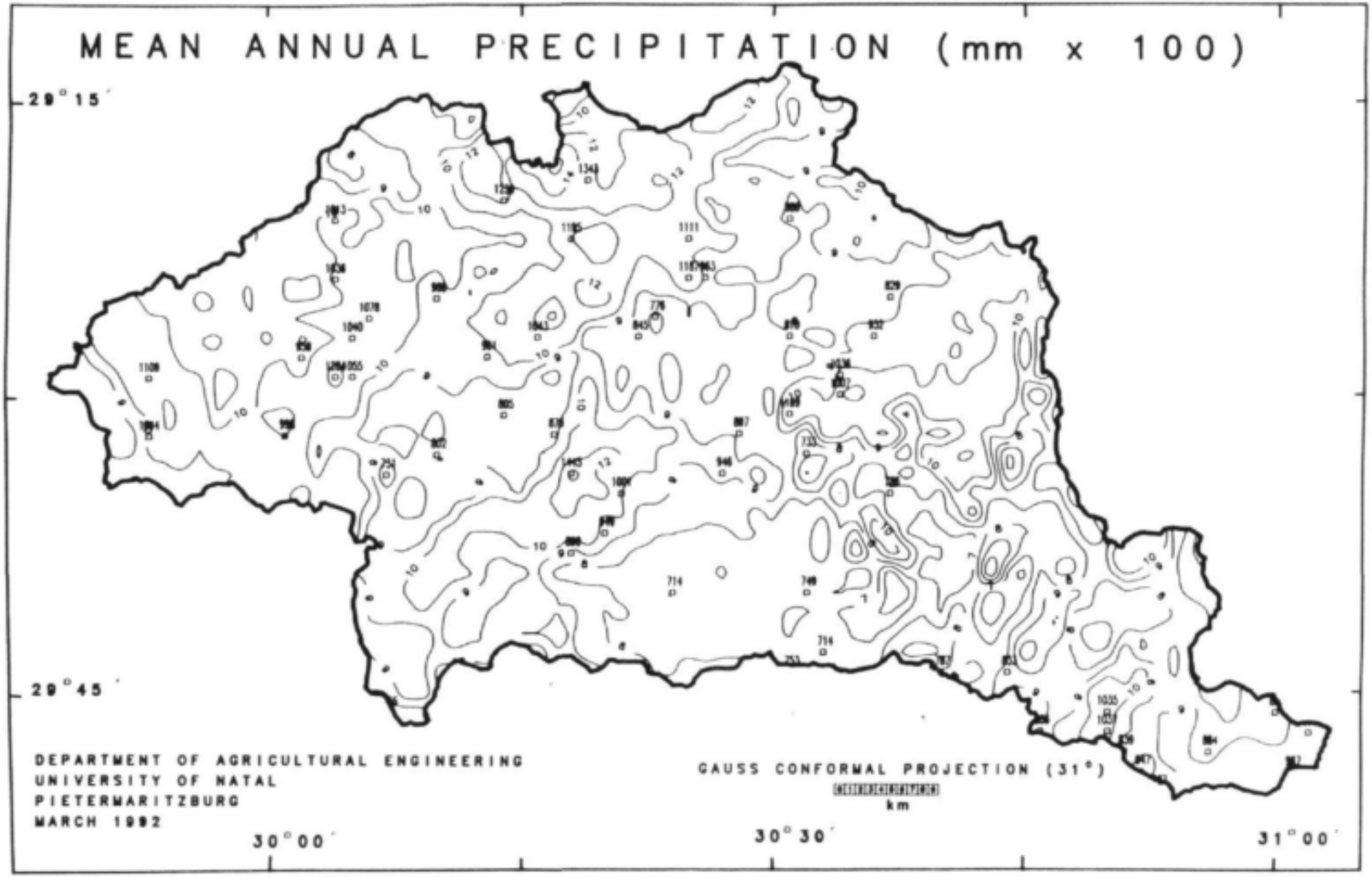


Figure 3.2 Mean annual rainfall for the Mgeni catchment

The 30 year period from 1960 to 1989 was selected, because there were rainfall records from more stations for this period than other periods. From the 122 stations in and around the Mgeni catchment 89 with more than 5 years of rainfall record and a minimum of missing data during this period were selected for further evaluation in the estimation of daily rainfall representative of each subcatchment.

3.2 RAINFALL ESTIMATION METHODS

The 347 km^2 Lions river catchment with its six component distributed subcatchments (Figure 3.3) was used to test two methods of estimating rainfall for distributed modelling in the Mgeni catchment. The Lions river catchment was selected for this purpose because:

a) it had a gauging weir (U2H007) at the outlet of Subcatchment 6, data from which could be used for comparison of observed streamflow with that generated using the estimated rainfall

b) it had a subcatchment without a raingauge (Subcatchment 1), for which rainfall would need to be estimated and

c) it had a small subcatchment with a raingauge located at its centre (Subcatchment 6) which, it was assumed, would measure rainfall representative of that of the subcatchment, and this rainfall could be used for comparison with rainfall estimated for the subcatchment using the different estimation methods.

The two methods used to estimate rainfall for each of the six distributed subcatchments making up the Lions river catchment were the method of generating a daily rainfall surface using interpolation techniques described by Schäfer (1991) and an alternative method which coupled a selected "driver" station's daily rainfall with long term median monthly rainfall ratios (Tarboton, 1991a). A description of the methods follows.

3.2.1 Estimation of interpolated rainfall surfaces

Generation of daily rainfall surfaces using gridded long-term median monthly rainfall and interpolation between point rainfall measurements is described in detail by Schulze, Schäfer and Lynch (1989) and Schäfer (1991). The main steps used to estimate daily rainfall for the Lions river subcatchments using this method were as follows:

a) Daily rainfall data from the South African Weather Bureau files with a minimum record length of 5 complete years within the period from January 1960 to December 1990 were extracted for stations in and around the catchment. The 15 stations that met these requirements are shown in Figure 3.3.

b) A file was set up containing the median monthly rainfalls, calculated over the entire rainfall record length, for each of the stations for which data had been extracted.

c) For each day, the daily rainfall file was scanned and rainfalls at stations with observed data for that day were expressed as a ratio of the median monthly rainfalls for those particular stations.

d) These ratios were then interpolated onto a rectangular (1 x 1 minute of a degree) grid and combined with the (1' x 1') median monthly rainfall image produced by Dent, Lynch and Schulze (1987) for the month in which the rain fell in order to produce a (1' x 1') daily rainfall surface of point values.

e) The (1' x 1') daily rainfall point values within each subcatchment were then averaged to produce an estimate of areal daily rainfall for each distributed subcatchment.

Three rainfall surfaces were produced using different interpolation distances to incorporate a greater or lesser number of rainfall stations in the interpolation process. Initially an interpolation distance of 22 minutes of a degree was used to allow interpolation over the whole area of the Lions river catchment (Surface 1, Table 3.3). Later, rainfall estimation in Subcatchment 6 was investigated in greater detail by using an interpolation distance of 3 and then 4 minutes of a degree (Figure 3.4 and Surfaces 2 and 3, Table 3.3).

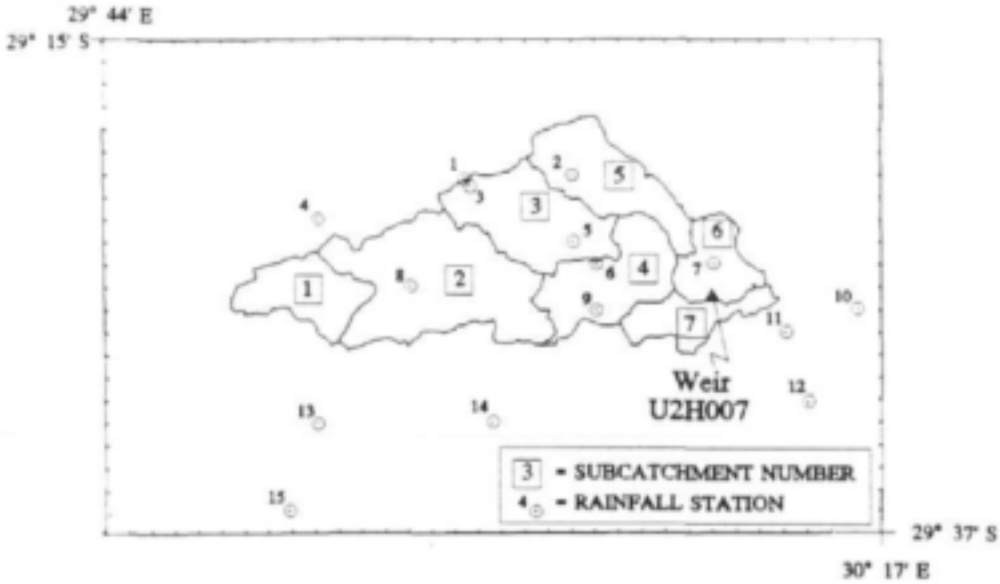
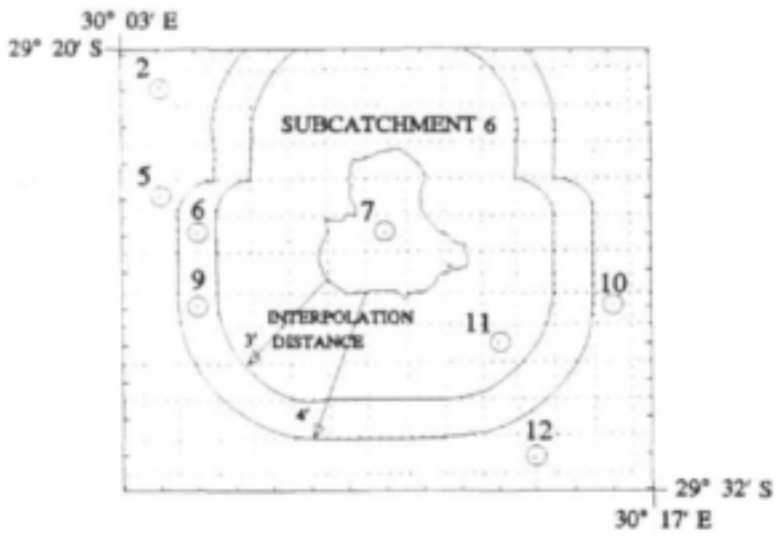


Figure 3.3 Lions river subcatchment layout and location of rainfall stations (Tarboton, 1991a)



Index to Rainfall Stations

No.	Rainfall Station
1	0268891 W
2	0269111 A
3	0268862 W
4	0268863 A
5	0269114 A
6	0269145 A
7	0269295 A
8	0268806 A
9	0269147 A
10	0269477 A
11	0269388 A
12	0239421 W
13	0238662 A
14	0239002 W
15	0238636 W

Figure 3.4 Subcatchment 6 with interpolation distances of 3 and 4 minutes of a degree (Tarboton, 1991a)

3.2.2 Driver station rainfall estimation

Estimation of daily rainfall for each subcatchment using the driver station method was carried out according to the following steps:

a) A driver station was selected for each subcatchment according to the following criteria:
   (i) it had to be as close as possible to, or within, the subcatchment,
   (ii) the difference between driver station mean annual rainfall and subcatchment mean annual rainfall had to be acceptably small,

(iii) its altitude was representative of the subcatchment's mean altitude,
(iv) it had a long continuous record with a minimum of missing or suspect data, and
(v) when data were missing the next best driver station, according to the above criteria, was used to estimate the missing rainfall.

b) Median monthly rainfalls for each selected driver station were extracted from the CCWR data base.

c) Median monthly rainfalls for (1' x 1') grid points (Dent, Lynch and Schulze, 1987) within each subcatchment were extracted from the CCWR data base and averaged to obtain spatially representative subcatchment median monthly rainfalls.

d) Daily rainfall was estimated for each subcatchment by calculating weighted ratios between the subcatchment median rainfall and driver station median rainfall for a respective month for each driver station used in order to estimate rainfall for a particular subcatchment. The weighted ratio was calculated according to the following equation:

$$R_w = P.R_m + R_a.(1 - P)$$

where R_w = weighted ratio for a respective month,
P = subcatchment median monthly rainfall as a proportion of subcatchment median annual rainfall,
R_m = ratio of the subcatchment's median monthly rainfall to the driver station's median monthly rainfall,
R_a = ratio of the subcatchment's median annual rainfall to the driver station's median annual rainfall.

The advantages of using a weighted ratio (R_w) rather than a simple annual ratio (R_a) or a simple monthly ratio (R_m) are that it places more weight on the annual ratio when the month has low rainfall and at the same time still allows the monthly variation in subcatchment to driver station median rainfall to exert an influence. This influence is greater in the months with high rainfall and lower in months with low rainfall, dispensing with abnormally high ratios that could occur in low rainfall months (winter) if a simple monthly ratio were used. The original assumption that daily rainfall trends reflect the monthly trends is thus extended to the assumption that daily rainfall trends reflect the monthly and annual trends in the same proportion as the ratio between the monthly and annual median rainfall for the subcatchment. The weighted ratio is limited to a minimum of 0.8 and a maximum of 1.2 and when weighted ratios for a driver station fall outside these limits for two or three months of a year the driver station is rejected and the next best driver station selected.

As was the case for the estimation of rainfall using interpolated surfaces the rainfall estimated for Subcatchment 6 was investigated in greater detail, in this case by using the second choice driver station to generate daily rainfall.

3.3 ASSESSMENT OF RAINFALL ESTIMATION METHODS

The two rainfall estimation methods were assessed by comparing the frequency distribution of the estimated rainfall using each method with the frequency distribution of the rainfall from the station at the centre of Subcatchment 6. Streamflow simulated by the *ACRU* model using daily rainfall estimated by each method was then compared with observed streamflow at the outlet of Subcatchment 6, which includes the runoff from Subcatchment 6 and the runoff contributions from upstream Subcatchments 1 to 5.

3.3.1 Comparisons of rainfall frequency distributions

It was assumed that the rainfall frequency distribution of Station 7 (Figure 3.4), located at the centre of

Subcatchment 6, represented the rainfall frequency distribution of Subcatchment 6. The Kolmogorov-Smirnov two-sample test (Groebner and Shannon, 1985) was used to determine whether the rainfall frequency distributions of:

a) the surrounding rainfall stations

b) the generated rainfall surfaces and

c) the driver station estimates

were significantly different from the rainfall frequency distribution of Station 7. The maximum absolute difference in cumulative relative frequency D was compared to a critical value D_{crit} for a significance level of 0.1% ($\alpha = 0.001$). Where the calculated D was greater than the critical value, it was concluded that there was a significant difference between the two samples being compared. In each case samples from two distinct populations were compared. These were the population of rainfall values on all days, including days with zero rain, and the population of rainfall values only from days with rainfall.

It was found that the subcatchment rainfall input file derived by the interpolated rainfall surface method contained many more rain days with lower rainfall, and fewer days with high rainfall than the rainfall station's daily files from which the rainfall surface was generated. Figure 3.5 illustrates this point for Subcatchment 6. Over the 10 year period from 1970 to 1979 the rainfall surface technique estimated 287 fewer days with zero mm rainfall than were found at rainfall station 0269295 (i.e. Station 7 in Figure 3.4). The rainfall surface also displayed higher rainday frequencies for the intervals between zero mm and 15 mm and lower rainfall frequencies for raindays with an excess of 15 mm. There were 232 days with rainfall greater than 15 mm measured at the rainfall station compared with 156 days estimated using the rainfall surface. This general attenuation of rainfall using the interpolation method was the likely cause of the undersimulation of streamflow compared against observed values (shown in Table 3.4 and discussed in the section 3.3.2), especially as the runoff producing rainfall is likely to be associated with those events of 15 mm or more rainfall. By contrast, it can be observed (Figure 3.5) that the driver station rainday frequency distribution is very similar to that of the representative rainfall station.

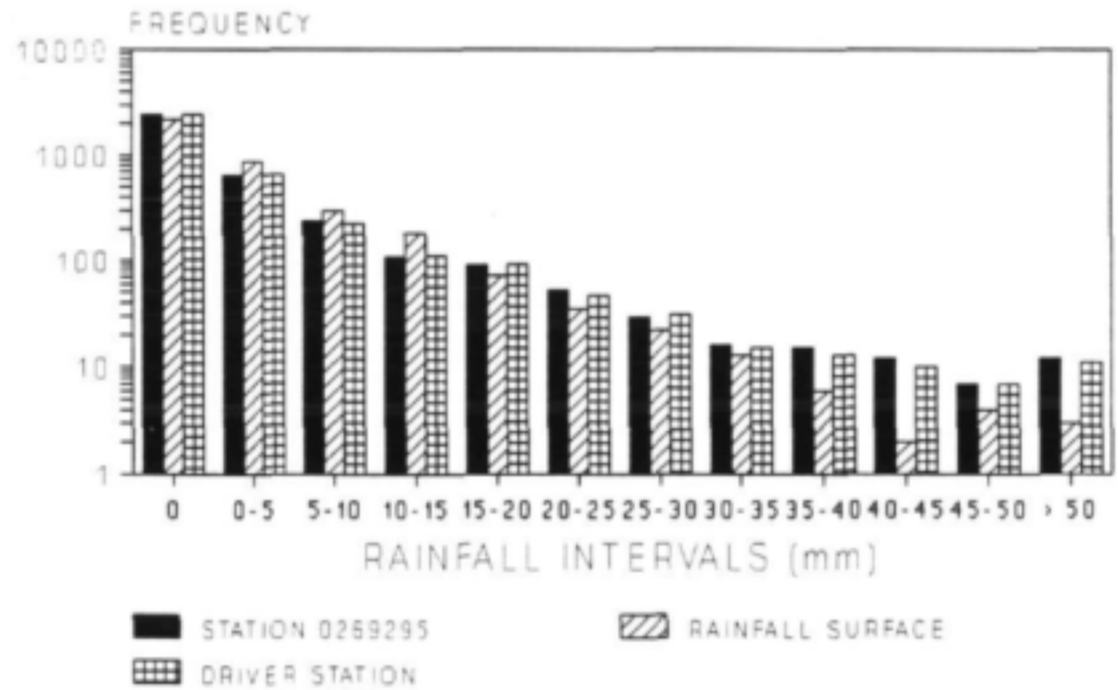


Figure 3.5 Comparison of rainfall frequency distributions for station 0269295, the interpolated surface and driver station rainfall estimation for the period 1970-1979 (Tarboton, 1991a)

Table 3.2 Interpolated rainfall surface and driver station estimations for Subcatchment 6 in January 1978, with the eight closest stations used for interpolation (after Tarboton, 1991a)

Day	Rainfall in mm for each of the following stations								Rainfall surface method	Driver station method
	2	5	6	**7**	9	10	11	12		
1	0	0	10	**14**	3	6	7	5	10.3	13.5
2	0	0	6	**6**	6	6	5	0	5.1	6.4
3	6	51	2	**6**	3	4	5	0	6.4	6.1
4	0	38	0	**4**	5	0	0	9	4.2	3.6
5	8	0	7	**0**	13	8	2	5	2.4	0.0
6	13	0	0	**4**	10	16	12	7	5.9	3.6
7	5	20	13	**25**	1	13	8	0	18.0	24.6
8	0	8	0	**10**	0	6	3	0	6.8	10.4
9	0	0	0	**2**	0	0	0	0	0.0	2.3
10	0	0	6	**0**	9	18	7	31	3.8	0.0
11	28	0	32	**8**	19	43	32	0	14.5	7.9
12	0	28	8	**24**	10	7	9	0	17.5	23.6
13	0	0	0	**16**	0	0	0	0	9.5	16.3
14	14	0	0	**0**	0	0	0	0	0.6	0.0
15	0	0	0	**0**	0	0	0	0	0.0	0.0
16	0	0	4	**0**	3	8	4	0	1.2	0.0
17	0	4	0	**2**	1	0	1	0	1.3	1.8
18	0	5	0	**0**	0	0	0	0	0.0	0.0
19	18	0	32	**0**	28	6	5	0	5.2	0.0
20	20	0	3	**3**	7	7	7	0	4.4	3.3
21	0	13	1	**8**	2	0	2	26	6.6	7.9
22	19	0	0	**2**	0	3	1	0	2.2	1.8
23	6	0	10	**1**	9	33	27	32	7.2	1.3
24	17	0	10	**22**	9	28	22	11	19.1	21.8
25	0	0	10	**28**	4	6	15	8	19.7	28.4
26	17	0	2	**7**	5	0	2	1	5.5	7.4
27	0	33	4	**1**	5	9	5	1	2.5	1.3
28	0	14	1	**8**	2	0	1	1	5.3	8.4
29	6	0	0	**1**	0	0	0	0	0.0	0.8
30	25	0	3	**0**	1	0	0	0	1.3	0.0
31	0	10	0	**0**	0	0	0	0	0.3	0.0
Rain days	14	11	19	**22**	22	18	12	12	27	22

The reason for the attenuation of high rainfall amounts and increase in the number of raindays when the interpolation technique is used is clear when one examines Table 3.2, which shows daily rainfall for the eight rainfall stations closest to Subcatchment 6 for January 1978. The total number of raindays in the month varies between 11 and 22 while the rainfall surface has 27 days with rainfall. The variability of the rainfall is apparent and although it was initially thought that this may have been caused by stations' recorded rainfall being out of phase by a day in either direction due to inconsistency in the date of recording, no regular pattern of error is recognizable. It is this large variability of rainfall over relatively short distances that appears to severely limit the applicability of the interpolation method for estimating daily rainfall in distributed subcatchments with sparse gauging networks.

Schäfer (1991) recognized that the selection of the interpolation distance was critical in the calculation of rainfall surfaces using the interpolation technique. Too large an interpolation distance exaggerates the number of raindays and too small an interpolation distance could results in areas between rainfall stations with continuous zero rainfall. Schäfer (1991) recommended that the interpolation distance be large enough for at least three rainfall stations to contribute to estimated rainfall at any point.

When an interpolation distance of three minutes of a degree was used to estimate rainfall for Subcatchment 6, the two contributing rainfall stations (7 and 11) each had 22 raindays for January 1978 while the rainfall surface generated using these two stations had 26 raindays. Using an interpolation distance of four minutes, four rainfall stations (6, 7, 9 and 11) contributed to the interpolated surface which then had 27 raindays compared to the average 21 raindays for the contributing stations. It appears that when rainfall stations are sparsely spaced, the large variability between even the closest two to four stations is sufficient to distort the rainfall frequency distribution. The driver station estimation method has of necessity the same number of raindays (22) as the driver station (Station 7, shaded in Table 3.2).

Results of the Kolmogorov-Smirnov two-sample test to determine significant differences between the rainfall frequency distribution at Station 7 and other rainfall frequency distributions are given in Table 3.3 The rainfall frequency distribution of the interpolated rainfall surfaces is significantly different from that of the representative rainfall station for all of the rainfall surfaces generated, indicating that the interpolation technique distorted the rainfall frequency distribution even when the interpolation distance was reduced. Again there was no significant difference between the driver station rainfall frequency distributions and that of the representative rainfall station, indicating the preferability of this method even when the second choice driver station is used to estimate rainfall.

Table 3.3 Kolmogorov-Smirnov two-sample statistics to determine whether different rainfall frequency distributions are significantly different or not (after Tarboton, 1991a)

	All days		Raindays only	
Rainfall Estimation c.f. Station 7	D D crit, (α=0.001) = 0.046	Significantly Different	D D crit, (α=0.001) = 0.075-0.092	Significantly Different
Station 2	0.140	YES	0.302	YES
Station 5	0.051	YES	0.099	YES
Station 9	0.012	NO	0.022	NO
Station 10	0.034	NO	0.083	YES
Station 11	0.046	NO	0.094	YES
Surface 1	0.079	YES	0.087	YES
Surface 2	0.079	YES	0.082	YES
Surface 3	0.079	YES	0.084	YES
Driver 1	0.014	NO	0.011	NO
Driver 2	0.012	NO	0.036	NO

Comparison of the rainfall frequency distribution at Station 7 with other nearby stations showed that it had a significantly different distribution to Stations 2 and 5 located farthest from it, while it had a similar distribution to the closer Stations 9, 10 and 11 when all days were considered. When only raindays were considered Station 7 had a similar distribution to Station 9 only. The significant differences in rainfall frequency distributions between Station 7 and its surrounding stations indicates the high variability of the rainfall and points to the danger of using an interpolation technique when interpolation is between stations with significantly different rainfall distributions. Care in the selection of the driver station is also critical to obtain a driver station with a frequency distribution representative of the subcatchment for which rainfall is being estimated. The driver station selection criteria outlined in the "Method" section appears adequate as Station 9 was selected as the second best driver station even though Station 11 was closer to the subcatchment, and it was only found later that Station 9 had a similar frequency distribution to Station 7 while Station 11 did not.

3.3.2 Effect of rainfall estimation methods on simulated streamflow

The *ACRU* agrohydrological modelling system (Schulze, 1989) was used for simulating daily streamflows and for statistical comparison of simulated with observed streamflows at weir U2H007 at the catchment outlet. Simulations of daily streamflow were performed from 1970 through 1979 to span a 10 year period with good rainfall records. Input variables for *ACRU*, described by Tarboton and Schulze (1991), were estimated from the physical features of the catchment; there was thus no calibration of model parameters.

Streamflows simulated using the interpolated rainfall surface underestimated observed streamflow by 14% for the daily simulation and 12% for monthly totals of daily simulation (Table 3.4). Because of the physical, non-calibrating nature of *ACRU*, this underestimation led to the checking of inputs, and particularly rainfall, for validity as it is well documented that simulated streamflow can only be as "good" as the estimated rainfall used to generate the streamflow (Schultz, 1985). The distortion of the rainfall frequency distribution and attenuation of high rainfall events already discussed (3.3.2) led to the development of the driver station method as a pragmatic solution to estimate daily rainfall for the situation in the Mgeni catchment where many subcatchments have few or no rainfall gauging stations. Streamflow simulated using driver station rainfall matched very closely the observed streamflow for both daily and monthly totals of daily simulations (Table 3.4). More importantly the regression coefficient was improved considerably (0.63 to 0.79 for daily simulation statistics), as was the variance of the simulated values (0.77mm simulated by the driver station method vs 0.52mm by the rainfall surface method when compared with an observed value of 0.88mm).

Table 3.4 Statistics of performance of simulated versus observed streamflow for simulations using the rainfall surface and rainfall driver station methods of determining daily subcatchment rainfall (Tarboton, 1991a)

Statistic	Daily simulation		Monthly total of daily simulation	
	Driver station method	Rainfall surface method	Driver station method	Rainfall surface method
Total observed streamflow (mm)	2028.27	2028.27	1816.20	1816.20
Total simulated streamflow (mm)	2034.57	1749.12	1871.24	1591.62
Mean observed streamflow (mm)	0.59	0.59	16.82	16.82
Mean simulated streamflow (mm)	0.59	0.51	17.33	14.74
Correlation coefficient	0.84	0.83	0.91	0.86
Students' 't' value	91.63	86.01	22.10	16.97
Regression coefficient	0.79	0.63	0.77	0.65
Base constant for regression (mm)	0.13	0.14	4.33	3.73
Variance of observed values (mm)	0.88	0.88	577.73	577.73
Variance of simulated values (mm)	0.77	0.52	419.81	338.35
% difference in standard deviation	6.53	23.65	14.76	23.47
Coefficient of determination	0.71	0.68	0.82	0.73
Coefficient of efficiency	0.70	0.67	0.83	0.73

3.4 RAINFALL ESTIMATION FOR THE MGENI CATCHMENT

In the preceding evaluation of rainfall estimation techniques in the Lions river catchment, the interpolation technique was found to be less suitable for estimating daily rainfall for distributed catchment modelling with a sparse gauging network because it attenuated peak rainfall events and exaggerated the number of raindays, thereby significantly distorting the rainfall frequency distribution. Both the attenuation and the increased number of raindays were the result of interpolation between adjacent rainfall stations with significantly different rainfall distributions associated with high variability of the rainfall, a rapid decay in rainfall intensity and the low density of raingauge network.

A pragmatic solution for the estimation of daily catchment rainfall for distributed modelling was the use of a driver station with its daily rainfall weighted by an adjustment ratio obtained from monthly and annual long-term expected catchment rainfalls. Judicious driver station selection was necessary, but it was found that even the second best driver station estimated rainfall with a rainfall frequency distribution similar to that of the subcatchment under examination.

Streamflows simulated by the *ACRU* agrohydrological modelling system using catchment daily rainfall estimated from the driver stations as inputs, matched observed streamflow more closely than did the simulation when interpolated surfaces were used to estimate rainfall. Although there could be other contributing factors within the *ACRU* modelling system for this improvement in streamflow simulation, the analysis of the statistics of model performance suggest that the improvement was due to a more realistic estimation of daily rainfall when using the driver station method (e.g. improved regression coefficient and variances for daily flows). It was therefore decided to use the driver station technique to estimate rainfall for each of the 123 subcatchments in the Mgeni catchment. At the same time it is suggested that a possible

Following the methods described in Section 3.2.1 above, representative median monthly and median annual rainfall values were obtained from the 1' x 1' gridded image of median rainfall for each subcatchment (Appendix A.2). Driver stations were selected following the previously described criteria (Section 3.2.1) and where the driver station had missing data a "next best" driver station was selected. In some cases, as a result of the paucity of data, a number of driver stations had to be used in order to obtain a complete rainfall estimate covering the 30 year period from 1960 to 1989 for each subcatchment. The driver stations used to estimate rainfall for each subcatchment are listed in Appendix A.3.

CHAPTER 4

EVAPORATION

All evaporative losses, whether they be from storage dams, soil evaporation and transpiration or from an irrigated crop, are a function of potential evaporation, E_p. Since by definition evaporation is the conversion of liquid water to vapour at an evaporating surface and the vertical transport of vapour into the atmospheric boundary layer (Ward, 1975), E_p may be considered an "atmospheric demand", determined by climatic variables such as net radiation, wind and vapour pressure deficits, or their surrogates. The accurate estimation of daily or monthly E_p is vital for hydrological modelling, particularly when simulations are performed in a region such as southern Africa, where overall an estimated 91% of mean annual rainfall is returned to the atmosphere by evaporative losses (Whitmore, 1971), as against a global average of 65-70%.

4.1 A-PAN REFERENCE POTENTIAL EVAPORATION

There are many methods of estimating E_p, ranging from lysimeters and complex physically-based equations (e.g. Penman, 1948) to evaporation pans to simple surrogates based often on single variables such as temperature. These methods all yield different answers under different climatic conditions. However, A-pan evaporation (with its inherent advantages and defects) has been selected as the reference potential evaporation for southern Africa (Schulze and Maharaj, 1991).

To clarify the terminology as used in this report with respect to evaporation, reference evaporation and reference potential evaporation are used synonymously, with the A-pan evaporation as the reference. Reference evaporation corresponds with what has up to recently in the literature been referred to as potential evaporation. Maximum evaporation is the term now used for what has previously been referred to as potential evapotranspiration and total evaporation is the term now used for what previously was expressed as actual evapotranspiration (Schulze, 1989).

Reasons for the selection of A-pan evaporation as a reference and problems with the use of A-pan evaporation data are discussed in Schulze and Maharaj (1991). One of the problems with using A-pan evaporation is that there is generally a relatively sparse network of A-pan measuring stations and the spatial distribution of these point measurements is poor, with the A-pans often located near dams or irrigation projects or in areas of low relief. This certainly holds true for the Mgeni region, where the total of 23 A-pans in or near the catchment (listed in Appendix B) are poorly distributed (Figure 3.1), with large areas without any A-pans. It was therefore necessary to use surrogates of A-pan evaporation which, when calibrated against pan data of acceptable quality, yielded equivalent evaporation information that could be extrapolated with greater confidence than A-pan point data from a sparse network could have been, to locations in the Mgeni catchment where no evaporation measurements were available.

4.2 ESTIMATING A-PAN EQUIVALENT POTENTIAL EVAPORATION USING TEMPERATURE INFORMATION

A number of reasons may be advanced for using temperature information as a surrogate for estimating A-pan equivalent evaporation in the Mgeni catchment:

a) Temperature, while closely associated with the generally dominant solar energy forcing function in the evaporation process, is less susceptible than evaporation pans to measurement errors or to effects of local anomalies in micro-climate.

b) There are, within the catchment, three times more temperature stations than pan evaporation stations (69 vs 23; example of temperature data in Appendix C). Furthermore, their distribution is more even spatially (Figure 3.1) and the network covers a wider range of altitudes than that of A-pans.

c) Temperature information may be interpolated to unmeasured locations more readily than evaporation pan information by use of multivariate techniques, including trend surface analysis (Schulze, 1982b), and also may be extrapolated to altitudes beyond the range of observations by application of regional lapse rate equations (Schulze, 1989), because of the close association of temperature with altitude and other physiographic factors.

Several methods are available within the *ACRU* modelling system for the estimation of A-pan equivalent potential evaporation from temperature information (Schulze, 1989). These include the Linacre (1977;1984) equations, the Thornthwaite (1948) equation and the Blaney and Criddle (1950) equation. Regression equations, rather than one of the above named methods, were used to estimate A-pan equivalent evaporation, because the regression equations take account of physiographic and climatic variability within subcatchments and can be used to estimate A-pan equivalent evaporation on a 1' x 1' grid. The development of appropriate temperature-based equations for A-pan equivalent evaporation for each month, enabling A-pan evaporation to be estimated from detailed temperature and other climatic and physiographic information, is now discussed.

4.3 GENERATION OF TEMPERATURE BASED EQUATIONS TO ESTIMATE MONTHLY A-PAN EQUIVALENT EVAPORATION

4.3.1 Factors affecting A-pan equivalent evaporation

The major factors affecting A-pan evaporation at a location (Schulze and Maharaj, 1991) are those related to the

a) energy budget component of evaporation, expressed by the net radiation term, i.e. solar radiation (with its attendant attenuation by atmospheric pressure and cloudiness) minus net longwave radiation (dependent on temperature, with its attenuation by atmospheric water vapour content and cloudiness); also those factors affected by the

b) mass transfer/aerodynamic component of evaporation, i.e. the temperature and humidity driven vapour pressure deficit and the wind function; and those determined by

c) dimensions, exposure and micro-site conditions of the evaporation pan.

In terms of those climatic and physiographic variables for which values are readily available for southern Africa the above factors affecting evaporation may be simplified and reduced to

d) maximum temperature, which like evaporation is predominantly a daytime phenomenon and is used as a surrogate for net radiation, and the variation of which relates to the influence of cloudiness on evaporation rates;

e) a correction factor to the maximum temperature to account for the relative influence of daylength, this factor being expressed through the extra-terrestrial radiation term for different latitudes and seasons (which may be derived mathematically or simply from published tables);

f) altitude, to account for the atmospheric pressure influence on the vaporisation process,

g) median monthly rainfall (applied especially in those regions where large spatial variability of monthly rainfall is displayed), as a simple determinant of intra-regional differences of cloudiness and hence also vapour pressure deficits, and

h) defined "evaporation regions" in which, *inter alia*, regional wind and vapour pressure deficit characteristics could be assumed to be relatively uniform.

The Mgeni catchment falls predominantly within the Natal Interior Region 3 of 12 regions of relatively uniform evaporation response identified in southern Africa and delineated in Figure 4.1. Details for Region 3 of the regression equations based on the above factors, and some goodness-of-fit measures, follow.

Because of the relatively few pan evaporation stations within the Mgeni catchment *per se*, the equations for the entire Region 3 were used in this study.

4.3.2 Evaporation equations and statistics : Region 3, Natal Interior

The data from 71 pan stations within Region 3 at which a minimum of three years' concurrent monthly temperature, rainfall and A-pan evaporation data were available, were used to develop a suite of temperature-based equations of A-pan equivalent evaporation for each month (on the premise that the relative importance of the forcing functions of the E_p process change with season). Data sets were obtained from the S.A. Weather Bureau, Soil and Irrigation Research Institute, Department of Water Affairs and Forestry and S.A. Sugar Association. Data were subjected to quality control before being used in conjunction with the other regional/altitude/climate factors to derive month-for-month equations of E_p by multiple regression. The monthly A-pan equivalent evaporation equations derived for Region 3 are given in Table 4.1.

By way of illustration, scatter plots of January simulated A-pan equivalent vs observed data for the 71 stations used in the analysis of Region 3 are given in Figure 4.2. Goodness-of-fit statistics for the 71 stations in Region 3 are shown in Table 4.1, with values reduced to those for daily A-pan equivalent evaporation. The scatter plots and statistics indicate generally good estimations, especially in the summer months of high evaporation. However, the simulated values at the upper and lower bounds in this region do not display the same range that observed values do, with the result that the statistics of simulated variability are slightly more suppressed than those of A-pan observations. Figure 4.3, which depicts the per cent residuals between simulated and observed values, illustrates that in January 62% of simulated values are within 7% of the observed value, and 81% within 12%, while in winter (July), when both lower evaporation rates as well as considerably poorer simulation statistics prevail, 68% of the simulated values are still within 12% of those observed.

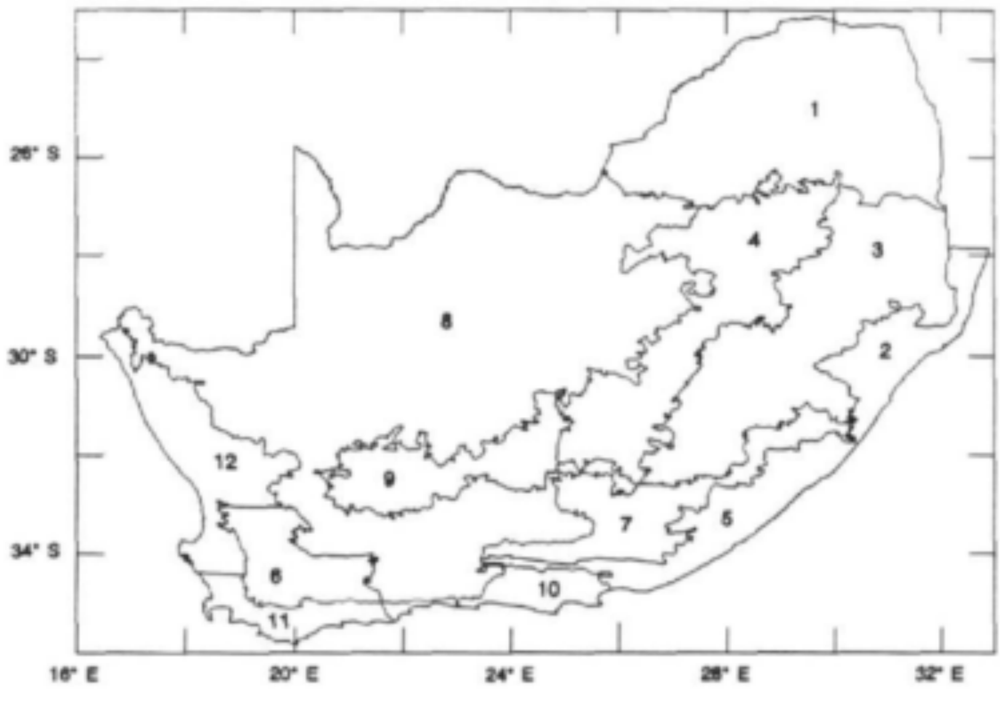


Figure 4.1 Evaporation regions over southern Africa (after Schulze and Maharaj, 1991)

Table 4.1 Equations for monthly A-pan equivalent evaporation totals and goodness of fit statistics of simulated vs observed evaporation derived for Region 3, Natal Interior

MONTHLY A-PAN EQUIVALENT EVAPORATION EQUATIONS DERIVED FOR REGION 6	ADJUSTED r^2	STD DEV ($mm.day^{-1}$)		STATION VALUE WITH MINIMUM A-PAN EVAP ($mm.day^{-1}$)		STATION VALUE WITH MAXIMUM A-PAN EVAP ($mm.day^{-1}$)	
		OBS	EST	OBS	EST	OBS	EST
$E(1) = 0.21*T_{max}(1)*R_a(1) + 0.000*A - 0.158*P_{md}(1) + 4.09*D_{sea} + 0.00*L_t + 0.00*L_g + 0.69$	0.68	0.96	0.80	4.98	4.31	9.12	8.26
$E(2) = 0.19*T_{max}(2)*R_a(2) - 0.039*A - 0.089*P_{md}(2) + 2.53*D_{sea} + 0.00*L_t - 2.75*L_g + 6.52$	0.60	0.83	0.66	4.40	4.25	8.14	7.40
$E(3) = 0.03*T_{max}(3)*R_a(3) - 0.070*A - 0.162*P_{md}(3) + 3.75*D_{sea} + 0.00*L_t + 0.00*L_g + 5.22$	0.55	0.62	0.47	4.14	3.86	6.44	5.96
$E(4) = 0.05*T_{max}(4)*R_a(4) - 0.011*A + 0.000*P_{md}(4) + 0.00*D_{sea} - 1.71*L_t + 0.00*L_g + 6.49$	0.32	0.46	0.27	3.19	3.68	5.85	4.85
$E(5) = 0.15*T_{max}(5)*R_a(5) - 0.062*A - 0.360*P_{md}(5) + 0.00*D_{sea} - 3.63*L_t + 0.00*L_g + 12.33$	0.37	0.49	0.31	2.15	2.74	4.87	4.22
$E(6) = 0.00*T_{max}(6)*R_a(6) + 0.000*A - 0.790*P_{md}(6) + 0.00*D_{sea} + 0.00*L_t + 2.20*L_g - 0.61$	0.30	0.47	0.27	1.66	2.27	4.60	3.63
$E(7) = 0.08*T_{max}(7)*R_a(7) + 0.000*A - 0.369*P_{md}(7) + 0.00*D_{sea} - 1.68*L_t + 2.75*L_g + 2.22$	0.20	0.44	0.22	2.30	2.66	4.91	3.81
$E(8) = 0.13*T_{max}(8)*R_a(8) + 0.034*A = 0.000*P_{md}(8) + 0.00*D_{sea} - 2.49*L_t - 0.72*L_g + 7.94$	0.20	0.59	0.29	3.00	3.88	6.06	5.08
$E(9) = 0.17*T_{max}(9)*R_a(9) + 0.000*A + 0.000*P_{md}(9) + 4.65*D_{sea} + 0.00*L_t + 0.00*L_g + 1.67$	0.46	0.70	0.48	4.00	4.59	6.81	6.34
$E(10) = 0.15*T_{max}(10)*R_a(10) - 0.047*A + 0.000*P_{md}(10) + 6.82*D_{sea} + 0.00*L_t + 0.00*L_g + 2.00$	0.68	0.79	0.66	4.38	4.61	7.73	7.03
$E(11) = 0.12*T_{max}(11)*R_a(11) - 0.060*A - 0.127*P_{md}(11) + 7.71*D_{sea} + 0.00*L_t + 0.00*L_g + 2.89$	0.71	0.90	0.76	4.43	4.48	8.21	7.60
$E(12) = 0.11*T_{max}(12)*R_a(12) - 0.061*A - 0.079*P_{md}(12) + 2.98*D_{sea} - 2.53*L_t - 5.80*L_g + 18.75$	0.60	0.86	0.69	5.02	5.17	9.23	8.21

E = A-pan equivalent evaporation estimate ($mm.month^{-1}$)
T_{max} = Monthly mean of daily maximum temperature (°C)
R_a = Mean extra-terrestrial radiation ($cal.cm^{-2}.day^{-1}$) for the month
A = Altitude (m)
P_{md} = Median monthly precipitation (mm)
D_{sea} = Distance from the sea (m)
L_t = Latitude (minutes of a degree)
L_g = Longitude (minutes of a degree)

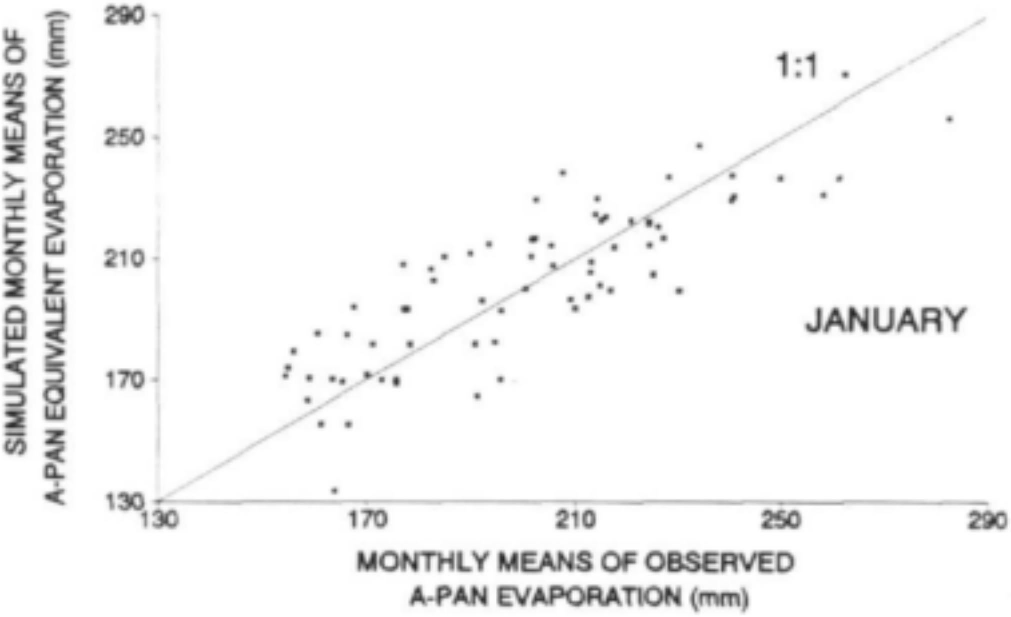


Figure 4.2 Scatter plot of January totals of simulated vs observed A-pan equivalent evaporation from 71 stations used for Region 3

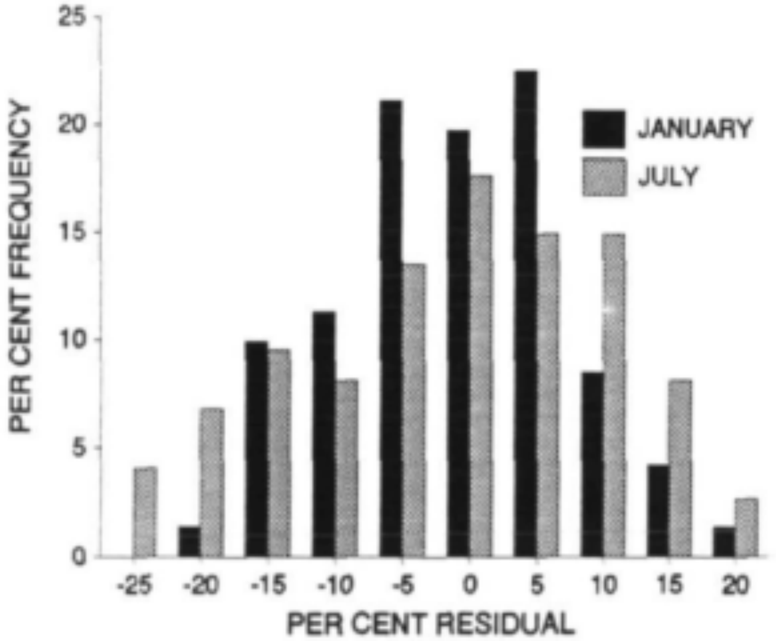


Figure 4.3 Frequency analysis of residuals (per cent) between simulated and observed A-pan equivalent evaporation from 71 stations used for Region 3

4.3.3 Development of relevant gridded images for the Mgeni catchment

Having established equations for the A-pan equivalent evaporation for each month in Region 3, gridded point values of those climatic, physiographic and location dependent variables used in the equations were then developed for the region. Monthly means of daily maximum temperatures, for example, had to be estimated at unmeasured points in the Mgeni catchment, prior to estimating monthly means of evaporation amounts for each subcatchment.

Procedures were as follows: Relevant portions of SAGRID, which consists of a set of over 440 000 one minute of a degree latitude/longitude grid points covering southern Africa, were used in the generation of grid point values of evaporation for the Mgeni catchment. SAGRID was developed by the Department of Agricultural Engineering at the University of Natal, and includes grid point information for southern Africa on, *inter alia*,

a) altitude (used directly in the evaporation equations)

b) latitude (from which month-by-month mean extra-terrestrial radiation is estimated)

c) longitude (used in temperature estimations)

d) median monthly rainfall (used as a co-determinant of E_p)

e) monthly means of daily maximum temperature (used in the evaporation equations) and

f) a distance from the sea index (used in temperature simulations).

In the simulation of monthly means of A-pan equivalent evaporation the major driving variable is maximum temperature. The estimation of maximum temperatures at locations without observations involved development of equations similar to those already described; techniques will therefore only be summarised here.

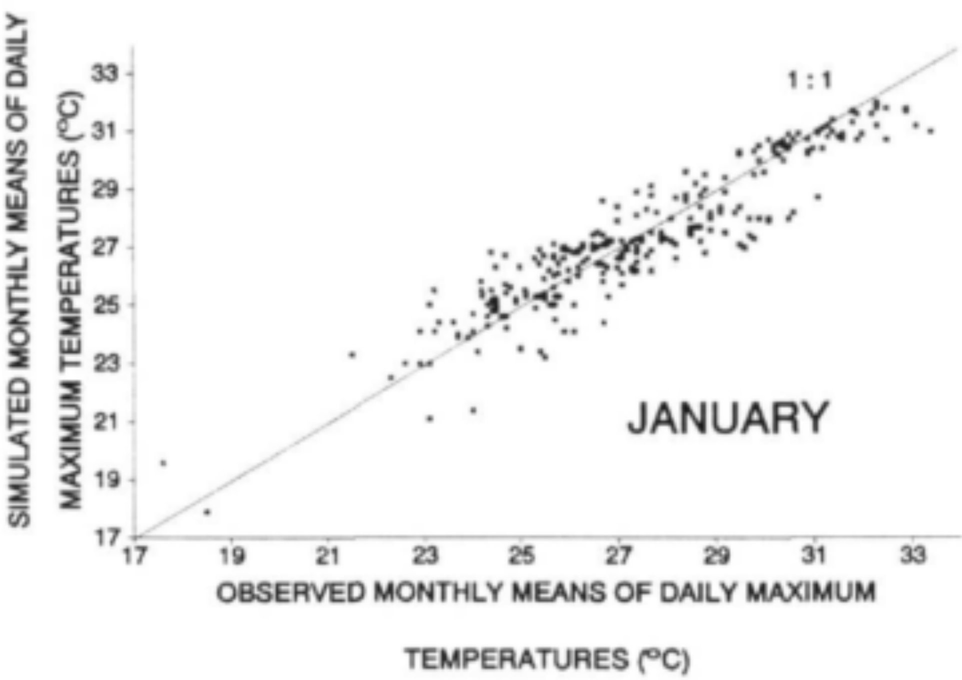


Figure 4.4 Scatter plot of January simulated vs observed monthly means of daily maximum temperatures from 71 temperature stations used for Region 3

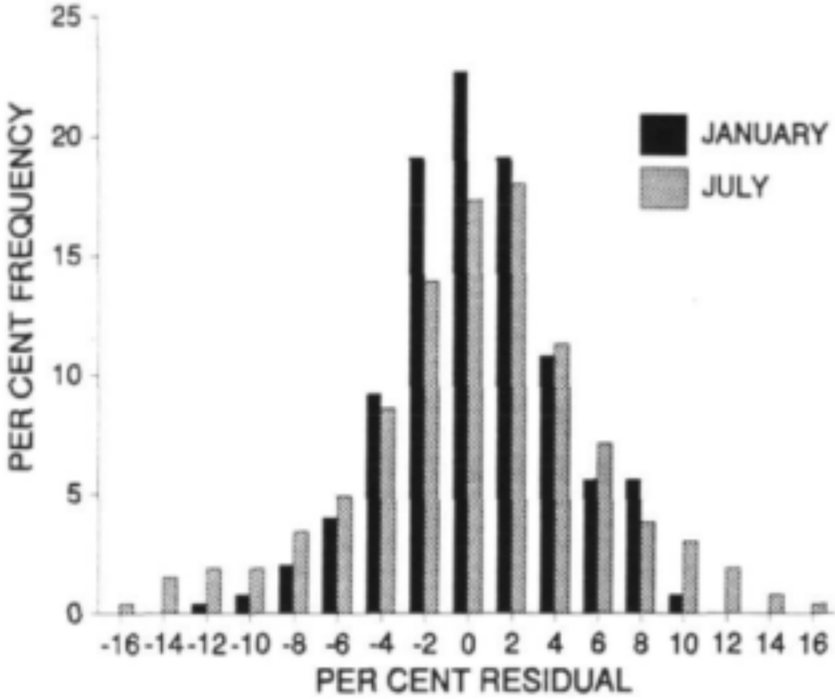


Figure 4.5 Frequency analysis of residuals (per cent) for January and July from 71 temperature stations used for Region 3

For Region 3 equations for means of daily maximum temperature were developed for each month of the year from temperature station data by step-wise multiple regression using observed temperature data against latitude, longitude and altitude as well as distance from sea. Simulations for Region 3 were highly successful (for example, Figure 4.4), with some 80% of simulated January temperatures being within 5% of observed values and 70% of simulated July temperatures being within 5% of observed values (Figure 4.5). Grid point information on monthly means of daily maximum temperature was then obtained month-by-month by applying the relevant physiographic/locational variables to the temperature equations at each grid point of the region, using information from SAGRID. Where means of the maximum temperatures had to be extrapolated to grid points with altitudes beyond the range of those used in the development of the equations, regional monthly temperature lapse rates (given in Schulze, 1989) were applied, and gridded point values then estimated.

Using the 1' x 1' information stored on SAGRID the respective monthly A-pan equivalent equations (Table 4.1) were applied to the relevant variables stored for each grid point in Region 3 in order to create monthly evaporation images over the Mgeni catchment which have been stored in the Mgeni GIS. Mean monthly A-pan equivalent evaporation was obtained for each of the 123 Mgeni subcatchments by calculating an average of the all 1' x 1' gridded point values within each subcatchment.

The mean monthly A-pan equivalent evaporation is converted by Fourier Analysis within the *ACRU* modelling system to yield mean daily A-pan equivalents, which are then further "perturbed" to give more realistic actual daily estimates of A-pan equivalent evaporation by adjusting values according to whether or not it was a rainday (suppression to 0.8 of value) or a "rainless" day (enhancement to 1.05 of the mean value) (Schulze, 1989).

CHAPTER 5

LAND COVER

The term "Land Cover" is used broadly (throughout this report) to include natural vegetative cover, land use (for agriculture and forestry) and urban land cover. With regard to hydrological modelling, land cover processes may be grouped functionally into above ground and below ground processes (Schulze, 1989), hence in terms of hydrological classification, important factors that should be considered are:

a) above ground factors, concerned with
   (i) interception losses,
   (ii) consumptive water use,
   (iii) shading of soil, thereby separating total evaporation into soil evaporation and plant transpiration,
   (iv) erosion protection (by plant or litter),
   (v) impervious areas, and

b) below ground factors, concerned with
   (i) plant root distribution,
   (ii) root water uptake,
   (iii) the onset of stress and reduction of rate of root water uptake and transpiration.

Considering these factors the Institute for Natural Research (INR) at the University of Natal was requested to undertake a land cover survey to classify and map land cover in the Mgeni catchment into different hydrological response classes. Subsequently the land cover classes were regrouped and land cover information translated into hydrological information for use in the *ACRU* modelling system. This chapter elaborates on the INR land cover survey and discusses transformation of the land cover information into the variables used in the hydrological modelling system. Development of the modelling system by incorporation of impervious land cover is discussed and the importance of considering land cover changes over time for modelling long term hydrological responses is assessed.

5.1 INR LAND COVER SURVEY

The INR was commissioned by the Department of Agricultural Engineering at the University of Natal (DAE), with funding from the Foundation for Research Development to provide data and information on the Mgeni catchment land cover. For details on the INR land cover classification, the reader is referred to Bromley (1989a, 1989b). The methods used to classify land cover, together with the problems experienced therewith, are however discussed in this chapter for completeness.

5.1.1 Classification procedure

False Colour Composite (FCC) SPOT satellite images, aerial photographs, orthophotos and field verification were used to classify the Mgeni catchment into 27 land cover classes. The "spectral signature" (colour and hue) of each land cover class was recognized and delimited on FCC SPOT satellite images taken between May 26 and May 30, 1986 at a scale of 1:100 000. To supplement the SPOT images 1:10 000 orthophotos and aerial photography at scales ranging from 1:10 000 to 1:150 000 covering various parts of the catchment were used. Ground truthing was carried out by field checks. From the above sources a map of the catchment delineating areas of homogeneous land cover was produced at a scale of 1:100 000 which was digitised and then rasterised onto a 250 m grid for storage in the Mgeni GIS.

5.1.2 Problems experienced with the land cover information

Problems experienced with the land cover information are discussed to enlighten possible future users of the Mgeni land cover information as used in this report. To establish a co-ordinate grid on the FCCs, ground points recognizable on both the FCCs and 1:50 000 topocadastral maps were identified. A photocopy of the

1:50 000 map reduced to 1:100 000 scale was then placed over the FCC and features on the map were aligned with features on the FCC. Although it was reported by Bromley (1989a) that the scaling from 1:50 000 to 1:100 000 in the reduction procedure was checked to ensure "exact correspondence" and that the overlaying of the 1:100 000 map produced in this way with the FCC could be performed with "considerable accuracy", there was still distortion on the ground in the final land cover map produced, in places up to 750m. Furthermore the procedures adopted did not provide sufficient information on the location of irrigated lands and storage dams. The INR together with the Department of Survey and Mapping at the University of Natal, undertook to rectify this problem of distortion, but to date have been unable to do so. In order to use the land cover information, the DAE re-digitised the Mgeni catchment boundary and extended land cover to meet the catchment boundary in areas of distortion. The total area for the Mgeni catchment (4387 km^2) given in Table 5.1 differs from that of the catchment digitised by the DAE (4353 km^2) because of the different catchment boundaries assumed for each digitisation and because of the distortion in the INR land cover map. In this report the area of 4353 km^2 is assumed to be correct. To supplement and complete the land cover information on reservoirs, the DAE carried out an extensive survey (Chapter 6) to establish a data base of all reservoirs within the catchment. In collaboration with the DWAF a firm of consulting engineers, Murray Biesenbach and Badenhorst Inc. (MBB), was commissioned to collect information on, *inter alia*, irrigated areas and irrigation practices in the catchment (Chapter 7).

5.2 LAND COVER INFORMATION FOR USE IN THE *ACRU* MODEL

5.2.1 <u>*ACRU* model equivalent land cover classes</u>

The INR land cover classes were grouped into 7 main groups under which subgroups formed the 22 land cover classes shown in Table 5.1 (subtotals for each land cover group are shaded) and illustrated in Figure 5.1. Land cover classes were either compatible with the existing *ACRU* Decision Support System (DSS) on land cover information, or where necessary, new hydrological input information was developed for the equivalent *ACRU* land cover classification. Hydrological land cover information was extracted from the Mgeni GIS for each of the 123 subcatchments in the Mgeni catchment using the *ACRU* DSS and according to the *ACRU* land cover codes.

5.2.2 <u>Description of *ACRU* land cover classes</u>

A short description of land cover in each of the classes used in the hydrological modelling system follows. The number preceding the land cover name is the *ACRU* code (Table 5.2) used to extract hydrological variables from the DSS for each land cover class.

URBAN

62 <u>CBD and commercial</u>

Characterized by high runoff potential with approximately 85% of the surface area impervious, any rainfall on these impervious areas is assumed to flow directly to stormwater drains or streamflow channels. Covers such as quarries and transport routes (roads and railways) were included in this classification. Pervious areas adjacent to impervious areas were assumed to have good cover equivalent to that of permanent pastures.

48 <u>Formal residential, high density</u>

This is housing with a high percentage of impervious surface (>65%) present and includes schools and shopping centres within the urban area. Areas such as Ashdown and Imbali are examples.

49 <u>Formal residential, medium density</u>

In this category are newer suburbs with planted trees not yet fully established. Impervious area is around 40%. Examples are Lincoln Meade and Hayfields in Pietermaritzburg.

Table 5.1 Land cover groups and classification for the Mgeni catchment

GROUP	LAND COVER CLASSIFICATION	% Coverage	Area (km^2)	*ACRU* code
URBAN	CBD/Commercial	1.81	79.48	62
	Formal residential - high density	1.10	48.17	48
	- medium density	3.46	151.48	49
	- low density	3.77	165.35	64
	Informal residential - urban character	1.90	83.21	58
	- rural character	1.25	54.90	43
	Open spaces/Parkland	0.49	21.24	59
		13.78	603.83	
WATER BODIES	Dams/Lakes	1.42	62.44	50
	Wetlands	0.37	16.32	53
		1.79	78.76	
FOREST	Eucalypts	3.67	161.03	36
	Pines	6.46	283.44	37
	Wattle	1.89	82.89	39
	Indigenous	3.71	162.64	35
	Woodland	3.65	160.25	60
	Other	1.04	45.71	34
		19.44	853.10	
NATURAL GRASSLAND	Veld in fair condition	29.09	1276.50	47
BUSHVELD	Bushveld - Acacia tree bush savannah	5.31	232.75	56
	Valley of a Thousand Hills	10.03	439.90	57
		15.34	672.65	
DRYLAND AGRICULTURE	Maize	4.05	177.68	1
	Sugarcane	9.03	395.92	16
	Other	4.43	194.37	61
		17.51	767.97	
IRRIGATED AGRICULTURE	Pastures	2.08	91.15	24
TOTAL		100.00	4386.82	

64 <u>Formal residential, low density</u>

This category includes well vegetated suburbs with trees and shrubs. Impervious area is low, around approximately 20%. This would include suburbs like Montrose and Wembley in Pietermaritzburg and Hilton.

58 <u>Informal residential, urban in character</u>

Dwellings in this category would be on the periphery of urban areas where no formal services are provided, and would include informal settlements. They have very little vegetation or area under cultivation.

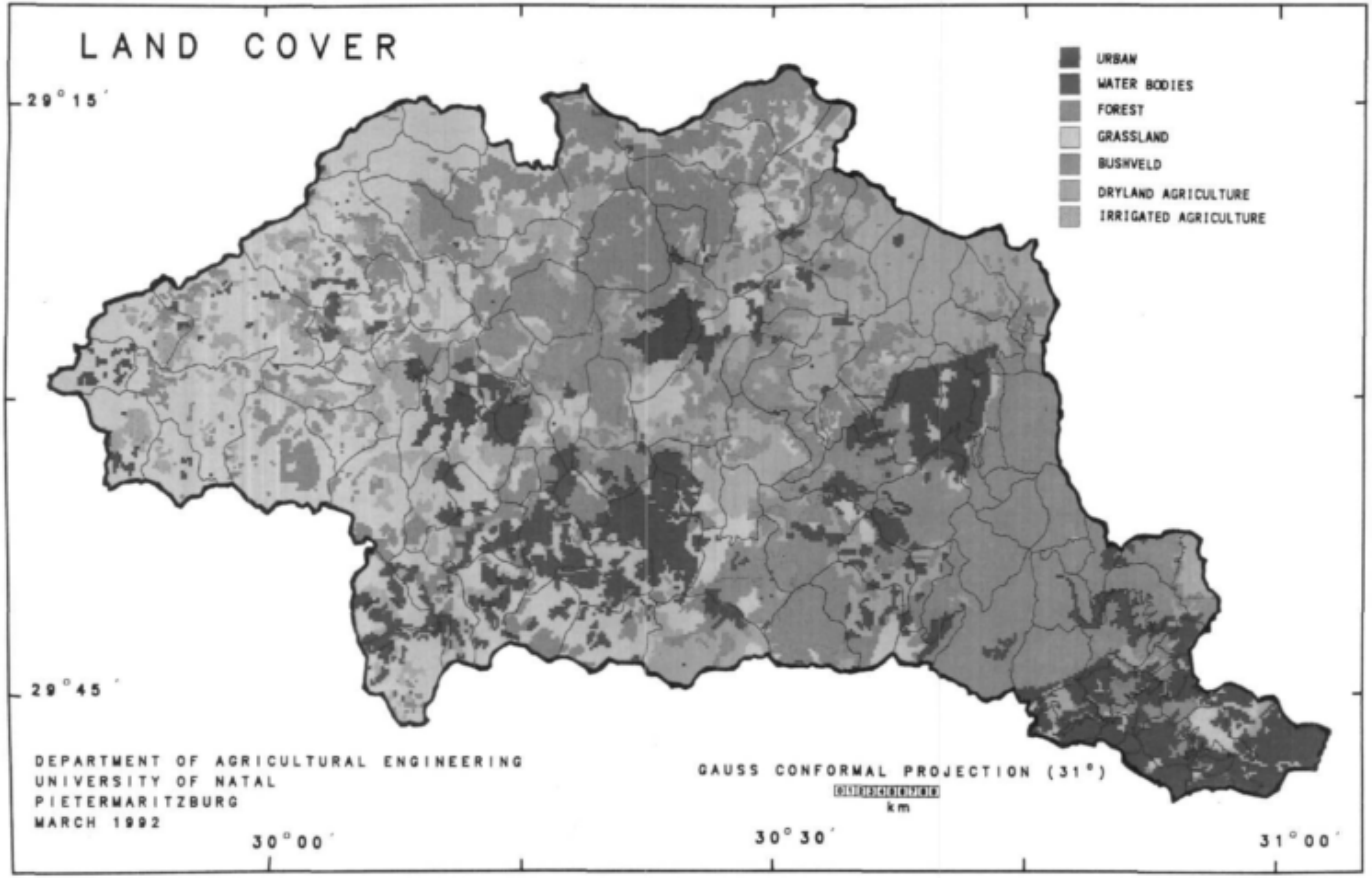


Figure 5.1 Land cover for the Mgeni catchment

43 Informal residential, rural in character

This includes scattered plots or smallholdings and dwellings with no services provided. They are rural rather than urban in character because they have some cultivation in the form of plots associated with the settlements and subsistence farming.

59 Open spaces/parkland

This category includes green belts, golf courses, municipal parks, open spaces and sports fields. The percentage impervious area would be in the region of 5% consisting of club houses and change rooms, etc. Vegetation would typically be irrigated with green cover generally all year round.

WATER BODIES

50 Dams/lakes

This class comprises larger dams or reservoirs, as identified in the Mgeni catchment by the INR, as well as farm dams (not identified by the INR survey), which are used principally for irrigation although some exist for recreational fishing.

53 Wetlands

Wetlands occur predominantly occur west of Nottingham at an altitude of 1840 m and are found at the source of the Mgeni. Vegetation in the wetland is predominantly grasses rather than reeds. Some of the wetlands have been dammed and others left in their natural state.

FOREST

36 Eucalypts

Eucalyptus grandis is the dominant species in the catchment although some plantations of *E.cloeziana* and *E.macarthurii* were found near New Hanover and Howick. No distinction was made between species for hydrological modelling purposes. Average stand age of 6 years was assumed.

37 Pines

Three varieties are grown in the Mgeni catchment, *Pinus patula, P.taeda* and *P.elliottii*. For modelling purposes these were all presumed to respond similarly hydrologically and had an assumed average age of 15 years.

39 Wattle

Black wattle, *Acacia mearnsii,* is grown on a large scale commercially by timber companies and by individual farmers. An average age of 5 years was assumed for the wattle plantations.

35 Indigenous

This land cover classification refers to the remnants of the *Podocarpus* forest in the north and west of the catchment and the coastal forest near, and inland from Durban. Also included in this category are some of the steep valley slopes of the Mgeni between Baynes Drift and Nagle dam.

60 Woodland

Tree cover exceeds 80% but is not 100% tree cover as in indigenous forests. It occurs as "valley scrub" or "woodland mosaic" (Moll, 1976) on the steep slopes of the Mgeni River and its tributaries.

34 Other

Where forest species other than those given above were found, hydrological properties of "general timber" (Schulze, 1989) were assigned for modelling purposes. This included areas under poplars (*Populus deltoides*), or where it was impossible to determine the forest species.

NATURAL GRASSLAND

47 Veld in fair condition

The hydrological characteristics of veld in fair condition were used for the INR classification of grassland, which varied from grazed *Themeda trianda* to *Aristida junciformis*. Non-arable areas or areas between arable blocks were also included in this classification.

BUSHVELD

56 Bushveld - Acacia tree bush savannah

This category includes tree bush savannah or wooded grassland with 10 to 80% cover by trees predominantly of the *Acacia sieberana* and *A.karroo* species. Bush encroachment occurs where trees have been cut or grassland overgrazed. This type of vegetation was described by Moll (1976) as "dry valley scrub" or "bushland mosaic".

57 Valley of a Thousand Hills

This land cover was seen as being unique to this region and was created from a combination of bush/veld vegetation and subsistence crops. The Valley of Thousand Hills represents an extremely dissected area with steep slopes and deep valleys. Land cover consists of a mosaic of dwellings, mainly subsistence cropped areas, bush-veld and woodland. Crops grown in this area include sugarcane and maize, and cattle grazing is important. The remnant vegetation of indigenous forest, which has been extremely disturbed, occupies about half of the area.

DRYLAND AGRICULTURE

1 Maize

Hydrological properties of dryland maize were used for this land cover as maize is seldom irrigated in the Mgeni catchment.

16 Sugarcane

Hydrological constants for "generalised" sugarcane (Schulze, 1989) were used as it was not possible to distinguish between dryland and irrigated areas of sugarcane, and sugarcane in the Mgeni catchment is predominantly grown without irrigation.

61 Other (Mixed crops)

Other crops found in the Mgeni catchment included those not mentioned above such as vegetables, or where it was not possible to distinguish between the different types of crops.

IRRIGATED AGRICULTURE

24 Pastures (perennial crop)

Perennial pastures were considered to be irrigated for modelling purposes. Where not irrigated, veld in fair condition (see above) was assumed.

5.2.3 Hydrological land cover information and processes

In order to use the above land cover classification for hydrological simulation it was necessary to derive hydrological variables with unique values in order to account for the above and below ground vegetation processes for each class. Hydrological information from the *ACRU* DSS for each land cover class is given in Appendix D.1 and the information for maize was selected (Table 5.2) as an example to explain how the hydrological variables account for the above and below ground processes. Above ground processes are taken into account by the crop coefficient (CAY), the leaf area index (LAI) and a value of vegetation or land cover interception in mm.rainday^{-1} (INT), all of which are input as monthly values but transformed into daily values through Fourier Analysis in the modelling system.

Interception, i.e. the process by which precipitation is "caught" by the land cover, stored temporarily as interception storage and then evaporated, is controlled by the variable INT, which for maize can be seen to be highest when the crop is fully developed. Interception continues when the crop has been harvested due to the residues and mulch left on the surface. It is only in September and October, when the land has been prepared by ploughing and the new crop has not yet emerged, that the interception loss per rainday is zero. Water from interception which remain stored on a particular day is evaporated back to the atmosphere the following day, using up energy available from potential evaporation (E_p) before the remaining E_p is used in the transpiration and soil evaporation processes. In the case of forests water is evaporated at a rate well in excess of available net radiation and potential evaporation (Rutter, 1967; Calder, 1982). Hence, an enhanced wet canopy evaporation rate (E_w) has been incorporated into *ACRU* for use when simulating under a forest land cover.

The leaf area index is defined as the planimetric area of the plant leaves relative to the soil surface area and is a determinand of the consumptive water use by plants as well as of shading of the soil, protection of soil from erosive raindrop impact and interception. When not available for a particular land cover, LAI can be determined from CAY using the Kristensen (1974) relationship (Schulze, 1989). In Table 5.2 for maize the LAI is greatest when the canopy is fully developed towards the end of the growing season.

The crop coefficient controls the maximum transpiration through the crop. Transpiration from the land cover is equivalent to the product of the reference evaporation (A-pan) and CAY for that day, when the plant is not subject to stress. A separate variable for each land cover controls the soil water content at which the plant becomes stressed, whereafter transpiration is reduced to below the maximum value. The maximum potential transpiration is a function of plant growth (October to February in Table 5.2) and is reduced to the equivalent of mean "bare soil" evaporation losses when the plant has senesced.

Table 5.2 Hydrological variables for maize

Land cover class	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 Maize (Mgeni/Mooi)	CAY	0.99	0.84	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.48	0.78
Planting date = Oct 15	LAI	5.05	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.50	3.00
Growing season = 140 Days	INT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74

Water extraction by the plant roots is the predominant below ground hydrological plant process. In *ACRU*, soil water extraction takes place simultaneously from both soil horizons and in proportion to the assumed active rooting masses within the respective horizons. ROOTA describes the fraction of active root mass in the topsoil horizon, which for maize is smallest when the plant is developed to maturity and the roots are well distributed and is considered to be unity with young plants, when there are only few active roots, which would all be in the topsoil horizon, or when the plant has senesced. On the premise that "roots look for water, water does not look for roots", there is a subroutine in *ACRU* whereby if the subsoil horizon is not stressed, but the topsoil horizon is, the subsoil's contribution to total evaporation is enhanced beyond that computed for its root mass fraction; similarly, if the subsoil horizon is stressed but the topsoil horizon is not, the topsoil's contribution to evaporation is enhanced.

In the present version of the *ACRU* modelling system no extraction from the intermediate groundwater zone takes place, because this zone is assumed to be at a greater depth than the active root depth. Where actual soil depths are greater than the effective root depth of the particular crop or land cover, the variable EFRDEP is used to limit the water budget calculations to consider the soil horizon to be as deep as the effective root zone.

In the Mgeni catchment many different land covers are often represented within a single subcatchment. The percentage of each land cover within each subcatchment was extracted from the Mgeni GIS and examples are shown in Appendix D.2. Subsequent automated area weighting, carried out within the *ACRU Menubuilder*, was used to obtain representative hydrological land cover variables for each subcatchment.

5.3 INCORPORATION OF AREAS WITH IMPERVIOUS LAND COVER INTO *ACRU*

Approximately 10% of the Mgeni catchment has land cover of an urban nature with varying proportions of impervious areas for each urban land cover. Although the urban hydrology components of the hydrological modelling system for the Mgeni catchment are being developed as a separate Water Research Commission funded project, it was necessary to accommodate urban areas with impervious land cover within the scope of this research project, in order to be able to simulate streamflow from subcatchments which included urban areas. The incorporation of routines to describe hydrologically those areas with impervious land cover into the hydrological modelling system for the Mgeni catchment should be viewed as initial steps in the direction of urban hydrological modelling routines into the *ACRU* modelling system, which does not lessen the need for the development and integration of more sophisticated urban modelling concepts in *ACRU*.

5.3.1 Concepts

In practice runoff from an impervious area can be partitioned into that part which flows directly to streamflow, and that part which flows onto a pervious area. Impervious areas are considered to be either:

a) directly adjacent to a water course, stormwater drain or channel, in which case runoff from the impervious area contributes directly to streamflow (adjunct impervious areas), or

b) disjunct from a water course, where runoff from the impervious area flows onto a pervious area and contributes to the soil water budget of the pervious area (disjunct impervious areas).

This concept is made possible in *ACRU* by entering into the *Menubuilder* that fraction of the urban area of the catchment that would contribute directly to streamflow and is thus an adjunct impervious area (ADJIMP) and that fraction of the catchment that is impervious but would contribute directly to the soil water budget of the pervious areas (DISIMP). Whatever the impervious area, there is a certain amount of precipitation intercepted by and stored on the surface of the layer as depression storage which does not contribute to runoff. This amount which is considered constant for both adjunct and disjunct impervious areas is entered into the *Menubuilder* as the parameter STOIMP with units in mm. The processes involving impervious areas are conceptualised in Figure 5.2.

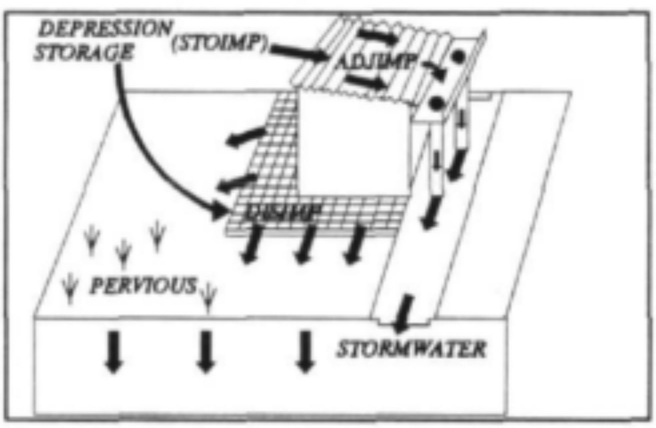


Figure 5.2 Conceptualisation of impervious areas considered in *ACRU*

5.3.2 Analogy with the SCS concepts of impervious areas

The concept of adjunct and disjunct impervious areas is analogous with the SCS concept of connected and unconnected impervious areas (United States Department of Agriculture, 1986) where runoff from a connected area flows directly into a drainage system and runoff from an unconnected area is spread over a pervious area as sheet flow. Instead of using an SCS runoff curve number (CN) to estimate runoff from the pervious area, the SCS refinement as used in the *ACRU* model and described by Schulze (1989) is followed, where the soil moisture deficit is used to estimate the potential maximum retention (S).

5.3.3 Evaporation from impervious areas

Rainfall stored on the impervious surface as depression storage is evaporated using the daily A-Pan evaporation rate. Where evaporation is insufficient to evaporate all the depression storage on the day of the rainfall event, this storage is carried over to the following day and the remaining amount of depression storage reduced accordingly.

Evaporation and transpiration from the pervious areas, considered in the soil water budget, is not increased to account for advective assistance from the impervious areas. It is assumed that the contribution of runoff from disjunct impervious areas to the water budget of the pervious areas will increase the soil-water content such that the total evaporation rate from the pervious areas will be increased as a result of the greater availability of water for total evaporation. This, together with the addition of evaporation from impervious depression storage, will result in total evaporation from an urban area being greater than simply the evaporation from the remaining pervious area.

5.3.4 Urban land cover default values

In the *ACRU Menubuilder* the facility exists to insert the fraction of the catchment which is an adjunct impervious area (ADJIMP) and a disjunct impervious area (DISIMP). The following values (Table 5.3) are, however, suggested as defaults of ADJIMP and DISIMP for different urban land covers when only estimates of impervious percentages are known from urban land cover descriptions. Note that when only a portion of the catchment is comprised of an urban land cover, the fractions ADJIMP and DISIMP are still defined as the impervious fractions of the entire subcatchment. Default interception storage is assumed to be 1 mm for all the urban land covers used in *ACRU*.

Table 5.3 Urban land cover classes used in *ACRU* and their default values

Land cover		Average per cent impervious area	ADJIMP	DISIMP
CBD / commercial		85	0.70	0.15
Industrial	- high density	70	0.40	0.30
	- medium density	50	0.30	0.20
	- low density	30	0.15	0.15
Formal residential	- high density	65	0.50	0.15
	- medium density	40	0.25	0.15
	- low density	20	0.05	0.15
Informal residential	- urban in character	30	0.00	0.30
	- rural in character	10	0.00	0.10
Residential parkland		05	0.00	0.05

Under the above method of accounting for responses from urban areas, the current hydrological land cover variables used in *ACRU* need to be updated to reflect total evaporation from only the pervious portions of the urban areas. The SCS (United States Department of Agriculture, 1986) suggests that the remaining pervious areas be considered lawn or pasture in good condition. It is believed that this is too general for southern African conditions where the pervious areas range from cover consisting of trees and shrubs in a low density residential area to veld in a poor condition in an informal residential area. Default hydrological land cover variables for the urban land cover classes are therefore included in Appendix D.

5.4 HYDROLOGICAL MODELLING WITH CHANGING LAND COVER

Hydrological analysis required for design and planning often fails to consider gradual environmental land cover changes and uses present or static land cover for long term simulations. According to Schulze (1981), it is important to consider land cover change because, one would, in most cases like to predict the environmental impacts of these changes before they occur and hydrological modelling is the most likely means by which the effects of changes can be simulated realistically. Braune and Wessels (1981) emphasize the need to analyse land cover trends carefully in considering water resources planning and call for the projection of land cover trends into the future for water resource analysis. The importance of considering land cover changes is assessed by comparing simulated streamflows using temporally static and then dynamic land cover with observed streamflow for the Lions river catchment of the Mgeni catchment (Tarboton and Cluer, 1991).

5.4.1 Obtaining land cover changes over time

Black and white aerial photographs from 1959, 1967, 1978 and 1990 covering the Lions river catchment (Figure 2.3) at scales ranging from 1:20 000 to 1:36 000 were used to obtain the spatial distribution of land cover for each of these points in time. From the photographs land cover was delimited into:

a) veld

b) forestry (with distinction between indigenous and commercial forest)

c) contoured agriculture

d) uncontoured agriculture

e) farm dams and

f) urban areas.

Care was taken to use only the central portion of each photograph to minimize distortion although the anomaly of an increase in veld area after 1979 (shown in Figure 5.3) was suggested by Tarboton and Cluer (1991) as possibly being due to inaccuracy in delimiting land cover from aerial photography and scale problems at the photograph boundaries. In deriving the hydrological land cover variables for each catchment at each point in time using the DSS contained in the *ACRU Menubuilder* (Schulze, 1989) the following were assumed from a field knowledge of the catchment:

a) the veld was in fair condition (i.e. lightly grazed, 50-75% cover)

b) commercial forest was *Eucalyptus grandis*

c) contoured agriculture was dryland maize

d) uncontoured agriculture was dryland or irrigated pastures and

e) urban areas were informal residential, but with an urban character.

The current irrigated area to reservoir surface area ratio was assumed constant to estimate the areas under irrigation from reservoir areas for the antecedent dates of interest. By interpolating linearly between the spatial land cover distributions (Table 5.4) for each date of photography, a dynamic land cover file was created for each subcatchment. The temporal land cover trends apparent in Table 5.4 are illustrated in Figure 5.3 for the catchment as a whole, but it should be remembered that the temporal land cover distributions for each individual subcatchment were actually used as model inputs.

5.4.2 Streamflow simulations

Streamflow was simulated from 1958 through 1988 and compared with streamflows observed at gauging station U2H007 at the catchment outlet. Two static simulations were carried out, the first assuming land cover temporally static from 1959 onwards (59 Static), and the second assuming a 1990 land cover static throughout the simulation period (90 Static). The dynamic simulation accounted for gradual land cover changes by using a temporally varying dynamic land cover file (from 1959 to 1990) which was updated for each subcatchment on an annual basis.

Statistics of performance of monthly summaries of daily streamflow for the three simulations compared with observed streamflow over the 31 year simulation period are shown in Table 5.5. By assuming static land cover with a spatial distribution as in 1959, total observed streamflow was over-estimated by 17.7% with an increasingly divergent trend as illustrated in Figure 5.4. Simulation using static land cover was inadequate in mimicking the decreasing trend in observed streamflow as a result of the increased streamflow reducing activities in the catchment with time (Figure 5.3). Although the regression coefficient in the '59 Static' simulation was better than in the other simulations, variance of simulated values was greater than variance of the observed values and the high base constant for the regression offset the higher correlation coefficient and caused over-simulation of streamflow.

Table 5.4 Land cover distribution for each Lions river subcatchment at discrete times (Tarboton and Cluer, 1991)

Subcatchment information	Year	Veld (km^2)	Forest (km^2)	Dryland Agriculture (km^2)	Irrigated Agriculture (km^2)	Dams (km^2)	Urban (km^2)
Subcatchment 1	1959	29.7	2.6	3.3	1.6	0.3	0.0
Area = 37.5 km^2	1967	28.0	4.9	2.2	2.0	0.3	0.1
MAP = 1031 mm	1978	26.6	3.3	0.0	6.5	1.0	0.1
Altitude = 1151 m.a.s.l	1990	20.0	5.4	1.5	9.1	1.4	0.1
Subcatchment 2	1959	78.0	8.6	23.6	0.5	0.0	0.0
Area = 110.7 km^2	1967	51.7	15.6	34.5	7.0	0.7	1.2
MAP = 928 mm	1978	44.4	12.0	37.4	14.3	1.1	1.5
Altitude = 1454 m.a.s.l	1990	61.7	14.0	13.1	18.9	1.8	1.2
Subcatchment 3	1959	47.9	3.7	7.8	1.6	0.1	0.2
Area = 61.3 km^2	1967	40.6	8.8	5.5	4.8	0.3	1.3
MAP = 947 mm	1978	23.9	9.9	18.0	7.5	0.6	1.4
Altitude = 1378 m.a.s.l	1990	28.4	11.8	12.7	6.8	0.6	1.0
Subcatchment 4	1959	26.3	13.8	14.4	0.7	0.1	0.0
Area = 55.3 km^2	1967	35.0	13.1	5.7	1.4	0.1	0.0
MAP = 1026 mm	1978	10.9	19.9	15.1	8.4	0.7	0.3
Altitude = 1254 m.a.s.l	1990	18.6	19.9	6.8	8.4	0.7	0.9
Subcatchment 5	1959	44.3	6.6	3.8	0.2	0.2	0.0
Area = 55.1 km^2	1967	36.0	10.4	6.9	0.9	0.9	0.0
MAP = 966 mm	1978	22.9	13.5	16.7	0.9	0.9	0.2
Altitude = 1409 m.a.s.l	1990	21.5	18.3	13.5	0.7	0.7	0.4
Subcatchment 6	1959	22.7	2.1	4.3	0.3	0.0	0.0
Area = 29.4 km^2	1967	18.3	4.7	5.8	0.5	0.1	0.0
MAP = 967 mm	1978	16.2	4.4	7.1	1.4	0.2	0.1
Altitude = 1214 m.a.s.l	1990	11.2	6.3	8.5	2.3	0.4	0.7
Totals for entire catchment	1959	248.9	37.4	57.2	4.9	0.7	0.2
	1967	209.6	57.5	60.6	16.6	2.4	2.6
	1978	144.9	63.0	94.3	39.0	4.5	3.6
	1990	161.4	75.7	56.1	46.2	5.6	4.3

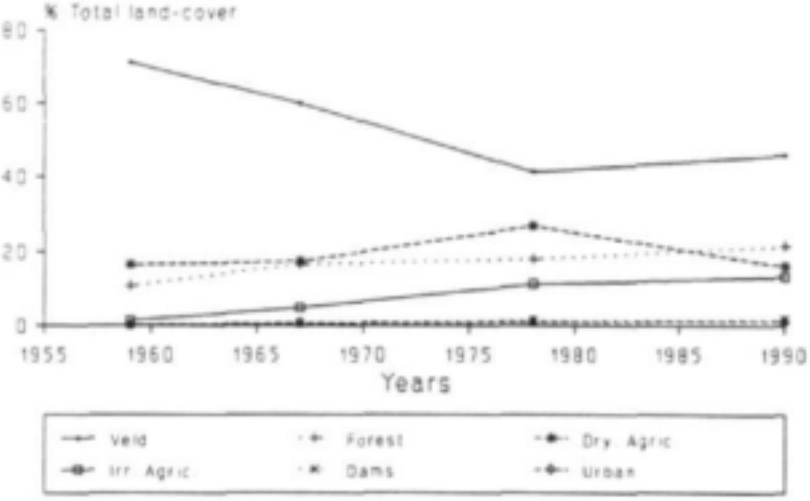


Figure 5.3 Land cover trends for the entire Lions river catchment over the period 1959-1990 (after Tarboton and Cluer, 1991)

Table 5.5 Statistics of performance of monthly summaries of daily streamflow using *ACRU* for static and dynamic land covers (Tarboton and Cluer, 1991)

Statistic	59 Static	Dynamic	90 Static
Total observed streamflow (mm)	5243.84	5243.84	5243.84
Total simulated streamflow (mm)	6174.34	4810.36	3582.06
Correlation coefficient	0.79	0.77	0.75
Regression coefficient	0.87	0.80	0.74
Base constant for regression (mm)	4.59	1.70	-0.77
Variance of observed values (mm)	371.77	371.77	371.77
Variance of simulated values (mm)	451.45	398.45	357.36
Coefficient of determination	0.62	0.60	0.56
Coefficient of efficiency	0.54	0.57	0.50

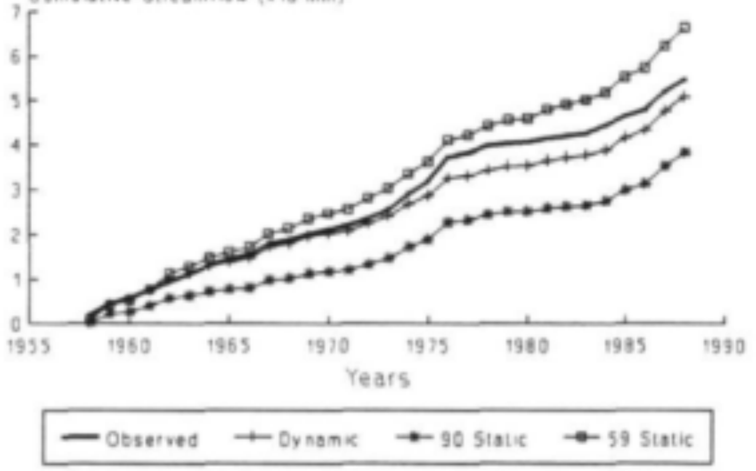


Figure 5.4 Comparison of long-term cumulative observed streamflow with that simulated using static and temporally dynamic land cover (after Tarboton and Cluer, 1991)

When the temporally dynamic land cover file was used, the hydrological simulation was improved to the extent that the total simulated streamflow was only 8.3 % less than the observed streamflow and variances in observed and simulated values were close to each other. The dynamic simulation mimicked observed streamflow almost exactly until 1972 (Figure 5.4), after which it under-simulated observed streamflow for 5 years before continuing parallel with observed streamflow for the remainder of the simulation period. This improved accuracy was obtained by recognizing the physical changes in land cover illustrated in Figure 5.3, and using a temporally dynamic land cover file as an input to the *ACRU* modelling system without other changes or parameter calibration (Tarboton and Cluer, 1991).

Frequently, no historical land cover information is available and current land cover is used for long-term hydrological simulations with historical climate data. The significant under-estimation of observed streamflow by 31.7 % (Table 5.4) when using the '90 Static' land cover highlights the inaccuracy of using current land cover information for long-term hydrological simulations and supports the arguments of Tarboton and Schulze (1991) that their underestimation in streamflow simulation in the Mgeni catchment over a 16 year period could have been due to the use of current land cover information. Increasing divergence of the cumulative simulated streamflow from the cumulative observed streamflow when using '90 Static' land cover (Figure 5.4), indicates that by not considering temporal land cover trends in long-term hydrological modelling, not only are the results likely to be inaccurate but the inaccuracies are amplified in time and for longer term analysis. Ironically the more critical the engineering design, the longer the data sets which are generally used in hydrological analysis!

CHAPTER 6

RESERVOIRS

Numerous reservoirs within a catchment can have a significant impact on the catchment water resources. Maaren and Moolman (1985) found that in the Mooi river catchment in the Natal Midlands there was significant reduction in streamflow with time over the years 1953 to 1985 resulting from the construction of farm dams during this period. It has been estimated by Tarboton and Schulze (1990) that potential streamflow into Midmar dam has been reduced by, on average, 13% or 13 million m^3 per annum as a result of the more than 400 small farm dams located upstream of the dam. In studying the potential impact of farm dams on the Ntinini river catchment in Northern Natal using the Pitman (1973) model, it was shown that several small dams impacted water resources more than a single large reservoir which yielded the same water supply. A knowledge of the geographical location as well as an estimate of reservoir capacity and surface area, for even the smallest of reservoirs, is thus an important input to any catchment modelling system. In this chapter details on the location of reservoirs and collection of data and information for all the reservoirs in the Mgeni catchment is presented, followed by an assessment of the accuracy of reservoir location using satellite imagery. The development of modelling routines to simulate the impacts of reservoirs on streamflow are discussed and methods used to estimate reservoir capacities from surface areas are evaluated.

6.1 LOCATION OF RESERVOIRS

In order to include the effect of reservoirs in modelling the hydrology of the Mgeni catchment, every effort was made to locate, and obtain data and information on, all reservoirs within the catchment.

6.1.1 Methods used and reservoirs located

Reservoirs were located using 1:50 000 topographical maps, 1:10 000 orthophotos, satellite images and field work. Data and information collected for each of the 1138 reservoirs located in the Mgeni catchment included its location and surface area at full capacity, and where possible the wall height, wall length, axis length, basin slope, dam shape and storage capacity when full. Figure 6.1 shows the location of reservoirs in the Mgeni catchment while the other reservoir information is presented in Appendix E.1. From the summary of the frequency distribution of reservoir surface area presented in Table 6.1 it can be seen that the majority of reservoirs (631) are relatively small impoundments with a surface area of less than 0.5 ha. Five large dams are located in the catchment (Table 6.2) with a combined surface area of 5577 ha, equivalent to 74% of the total reservoir surface area. Small dams (less than 5 ha surface area) make up 55 % of the remaining area under reservoirs, highlighting the need to consider them in hydrological simulations.

Table 6.1 Detection of reservoirs by satellite in the Mgeni catchment : Statistics

Reservoir Surface Area (ha)	Number of Reservoirs	Total Surface Area (ha)	Located by Satellite (No)	(%)
> 10	22	6064	18	84
5 - 10	27	204	24	92
2 - 5	96	304	77	81
1 - 2	153	233	77	51
0.5 - 1	209	156	10	5
< 0.5	631	153	18	3
Totals	1138	7114	224	

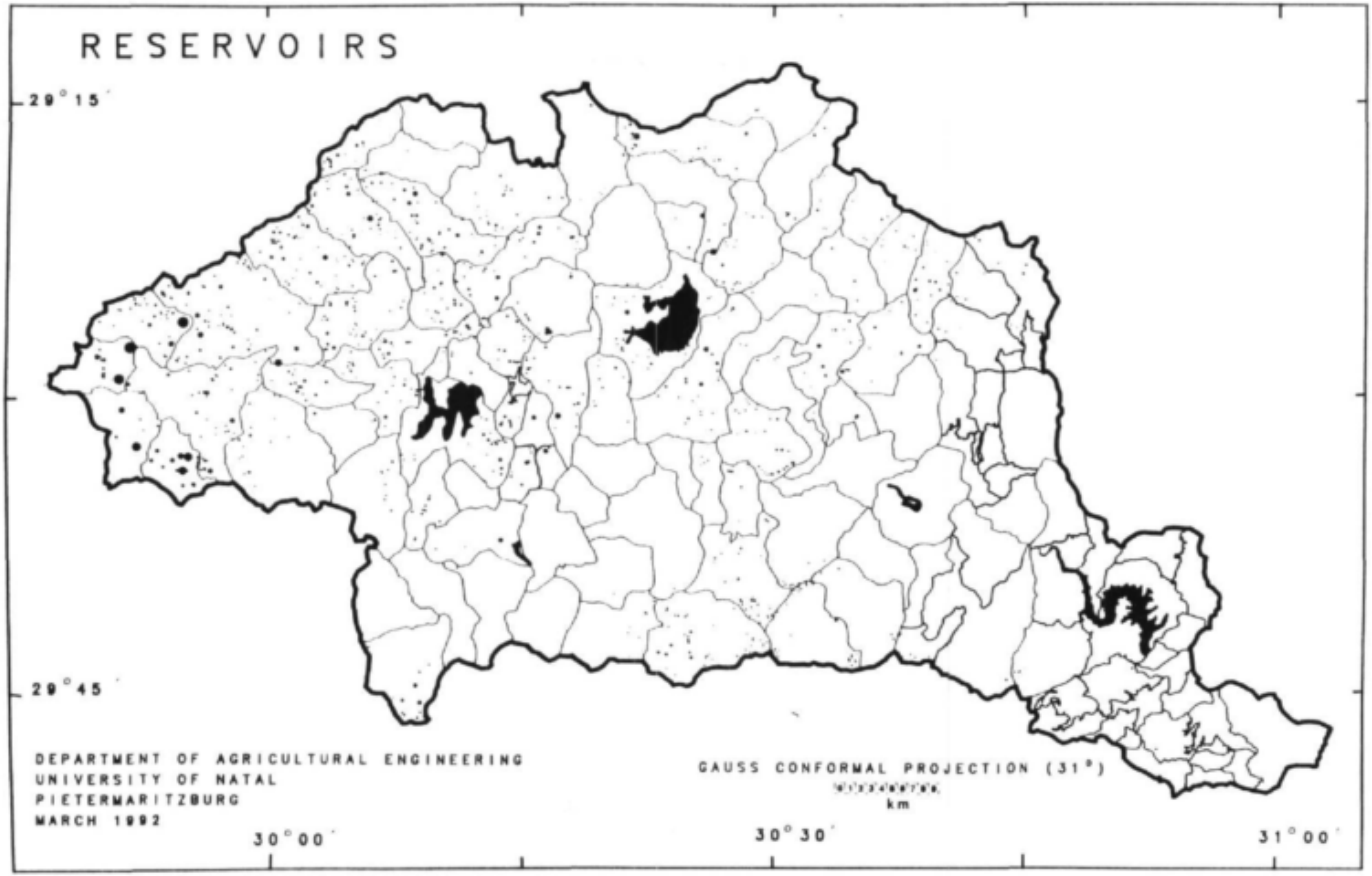


Figure 6.1 Location of reservoirs in the Mgeni catchment

Table 6.2 Surface area and full capacity of major reservoirs within the Mgeni catchment

Dam	Area (ha)	Capacity ($m^3.10^6$)
Albert Falls	2352	289.2
Midmar	1564	177.1
Inanda	1440	251.0
Nagle	156	23.2
Henley	65	5.4
Total	5577	745.9

6.1.2 Accuracy of satellite imagery for the location of reservoirs

Satellite imagery has great potential for the location of reservoirs because the technique can be automated, covers large areas and facilitates periodic or regular updates of reservoir inventories (Howman, 1988). Several problems, however, exist due to similar reflectances from substances other than water bodies and low resolution of imagery. Hence it is considered important to present details on the accuracy of satellite imagery used to locate reservoirs in the Mgeni catchment.

Information obtained from processing of February 1987 LANDSAT satellite images covering the Mgeni catchment (Howman, 1991) included location of each reservoir and an estimation of its surface area. Of the 347 reservoirs detected in the Mgeni catchment through satellite imagery, the existence of 224 was verified using 1:50 000 topographical maps, 1:10 000 orthophotos and field checks where necessary. Reservoirs larger than 2 ha were located successfully with an identification rate of between 81 and 92% (Table 6.1) while the satellite identification rate of the over 800 dams with an area of less than 1 ha was poor (3 to 5% success). The sharp drop in identification of the reservoirs with an area of less than 2 ha indicates the location of these reservoirs to be at the threshold of resolution identifiable by the LANDSAT satellite imagery (80 m).

Table 6.3 Accuracy of reservoir detection in terms of surface area when detected using LANDSAT satellite imagery

1) All reservoirs	No. of dams	Area(ha)	% of Total
Total in catchment	1138	7114	-
Detected by LANDSAT	347	6177	87
LANDSAT dams verified	224	5948	84
2) Excluding major dams	**No. of dams**	**Area(ha)**	**% of Total**
Total excluding 5 major dams	1133	1537	-
Indicated by LANDSAT	342	777	51
LANDSAT dams verified	219	548	36

In terms of surface area, satellite imagery detected 87% (with an 84% verification) of the total surface area in the Mgeni catchment under reservoirs (Table 6.3). If one excludes the five major dams from the area of reservoirs located by satellite imagery only 51% of the remaining area under reservoirs was located by the satellite imagery of which 36% was accurate. An example of the problem of detecting even large reservoirs is the detection of Shongweni dam in Natal where the satellite image indicated the dam to have an area of 5 ha whereas the true area is 143 ha, the error being due to algal blooms and water weed obscuring the water surface (Howman, 1991). The need for field verification when using satellite images cannot be stressed enough. Field verification in the Mgeni catchment indicated that 224 of the 347 "detected" water bodies were actually reservoirs, the remainder being, *inter alia*, forest, shadow or burned fields (Table 6.4). It can thus be concluded that although satellite images can be used to locate reservoirs, care should be taken to verify the results. Furthermore, the location of small reservoirs, below a threshold resolution for them to be identified by satellite imagery, is inherently inaccurate by this technique.

Table 6.4 Field verification of reservoirs indicated by LANDSAT satellite imagery

Dams detected	347
Verified	224
Parts of dams	31
Forest	28
Shadow	22
Forest in shadow	24
Wetlands	11
Ploughed and burned fields	4
Pools	2
Sewage works	1
Of 224, 127 not on 1:50 000 topo sheets Of 127, 33 not on 1:10 000 orthophotos	

6.2 RESERVOIR MODELLING ROUTINES

Reservoirs not only impact on the runoff and streamflow from a catchment but are points from which water is extracted and to which water can be transferred. The reservoir yield analysis routines in *ACRU* execute a separate water budget for a reservoir assumed to be situated at the outlet of a subcatchment. In the Mgeni catchment with many small reservoirs located internally within catchments it becomes impractical to delineate subcatchments such that a reservoir is located at the outlet of each subcatchment. Hence a modelling system was developed to account for multiple/internal reservoirs within delineated subcatchments.

6.2.1 Internal reservoirs

The concept of placing a reservoir at the outlet of a subcatchment is sound for a small catchment (Figure 6.2a) but when applied to larger subcatchments with internal reservoirs (Figure 6.1b) the concept is no longer sound, as reservoirs (i) and (ii) would be lumped to form a reservoir with the capacity of (i)+(ii) at the subcatchment outlet. In this case runoff from the entire subcatchment flows into the reservoirs and would contribute to filling the reservoirs before there was streamflow from the subcatchment outlet.

Reservoir modelling routines were developed to allow internal reservoirs to be simulated more realistically for each subcatchment while still lumping the capacity of the reservoirs within the subcatchment, thereby obviating the need for an excessive subcatchment discretisation which would have been required for modelling, had each reservoir been at a subcatchment outlet. Internal reservoirs are catered for as illustrated in Figure 6.2c by using the concept of partial areas of each subcatchment contributing to runoff into the subcatchment. This concept is based on equation 6.1 where the partial area of the subcatchment that contributes runoff directly into the internal reservoirs is estimated (PCCDAM), and the remainder of stormflow runoff would contribute to streamflow out of the catchment.

$$\text{QUICKF} = \text{QUICKF} * (1 - \text{PCCDAM} + \text{PCCDAM} * \text{DAMPER}) \qquad (6.1)$$

where QUICKF = stormflow runoff
PCCDAM = per cent catchment contributing to runoff into internal reservoirs
DAMPER = per cent lumped reservoir is of full capacity

In order to take into account the possibility of many reservoirs at different capacity stages it is assumed that when the lumped reservoir is empty, subcatchment runoff is equal to runoff from the fraction of the subcatchment not contributing runoff into the internal reservoirs. As the capacity within the lumped reservoir increases so the runoff fraction not flowing into the internal reservoirs is allowed to increase linearly (Figure 6.3) until when the lumped reservoir is at full capacity, when subcatchment runoff is equal to runoff from the entire subcatchment. This follows the assumption that with many reservoirs, as soon as they start filling there will be overflow from the smaller reservoirs until they are all overflowing when the largest of them is at full capacity. Using the reservoir information described in section 6.1 above, the cumulative surface areas and capacities of reservoirs within each of the 123 subcatchments were used as the

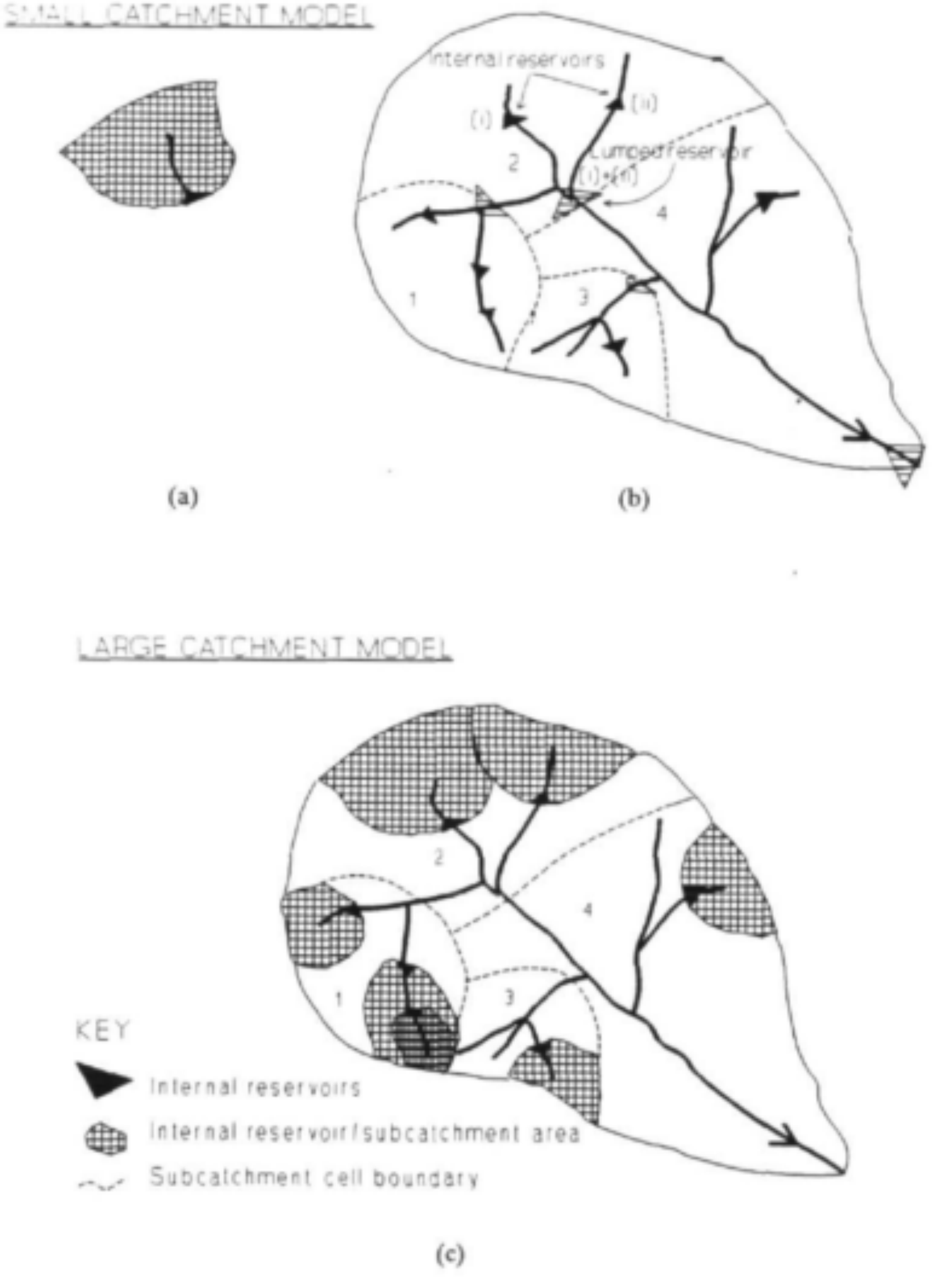


Figure 6.2 Reservoir modelling concepts: (a) small catchment model, (b) small catchment model applied to large catchment, (c) internal reservoirs concept in large catchment

surface area and capacity of a "lumped" reservoir for modelling purposes. The locations of the reservoirs were examined to obtain an estimate of the proportion of the catchment contributing runoff into the lumped reservoir. Area and capacity of the lumped reservoir for each subcatchment are given in Appendix E.2.

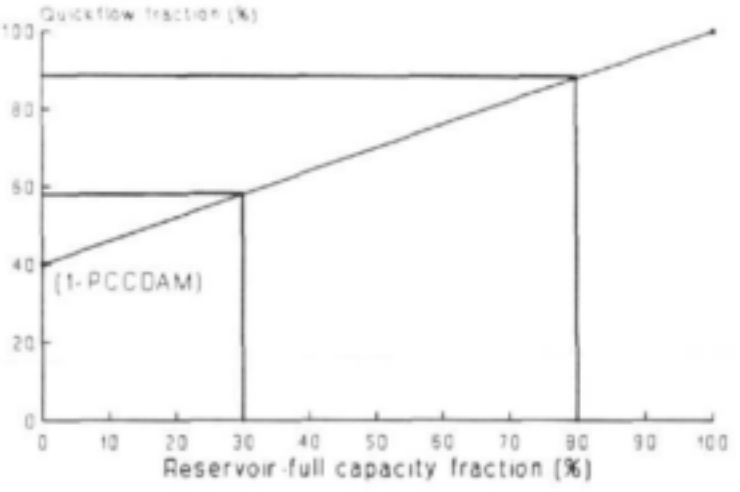


Figure 6.3 - Fraction contributing to quickflow runoff relative to lumped reservoir capacity

6.2.2 Area and capacity estimations

In order to carry out reservoir water budgeting the *ACRU* hydrological modelling system requires an estimate of reservoir surface area at full capacity, its storage at full capacity and a surface area:capacity relationship. Where the surface area:capacity relationship is not known, the modelling system assumes a triangular pyramid shape reservoir with uniform side slopes and longitudinal profile, and calculates an area:capacity relationship for the reservoir using data on the reservoir wall length (Schulze, 1989). In most cases the reservoir shape is not that of a triangular pyramid, however, and often, especially when located using satellite imagery or aerial photography, only the surface area of the reservoir is known.

Existing reservoir surface area:capacity algorithms were investigated and new algorithms developed to cater for the seven generalized reservoir shapes in Figure 6.4. Columns (a) and (b) of Figure 6.4 show the reservoir area:capacity algorithms developed for the different shapes where capacity is first expressed as a function of reservoir axis length, surface area and basin slope, i.e. f(LAS), and then as a function of axis length, maximum depth of the wall and wall length, i.e. f(LDW). Full capacities estimated using these algorithms were compared with known capacities for 16 dams in the Mgeni catchment and capacities estimated using the Agricultural Technical Services (Schultz, 1979) area:capacity relationship, *viz.* f(ATS), as well as the relationship developed by Maaren and Moolman (1985), *viz.* f(AMM), for dams in the Mgeni catchment. Figure 6.5 shows the relationship between capacity estimated using each of the four methods and the actual reservoir capacities. Because of the high R-squared value (0.931) for estimation using the Maaren and Moolman (1985) relationship, it was decided to use their area:capacity relationship for reservoir modelling in the Mgeni catchment. Capacities were, however, calculated for all the reservoirs in the Mgeni catchment using each of the four methods wherever possible. A sample of the reservoir information which forms part of the Mgeni GIS is shown in Appendix E.1

The length, area, slope method of estimating capacity was perceived as holding potential for use with remotely sensed reservoir information as this method also displayed a high R-squared value (0.921) when compared to known capacities. Surface area and axis length could be determined from the remotely sensed information and the basin slope (per cent) could be obtained using the location of the reservoir on a contour map (1:50 000 topographical map or 1:10 000 orthophoto).

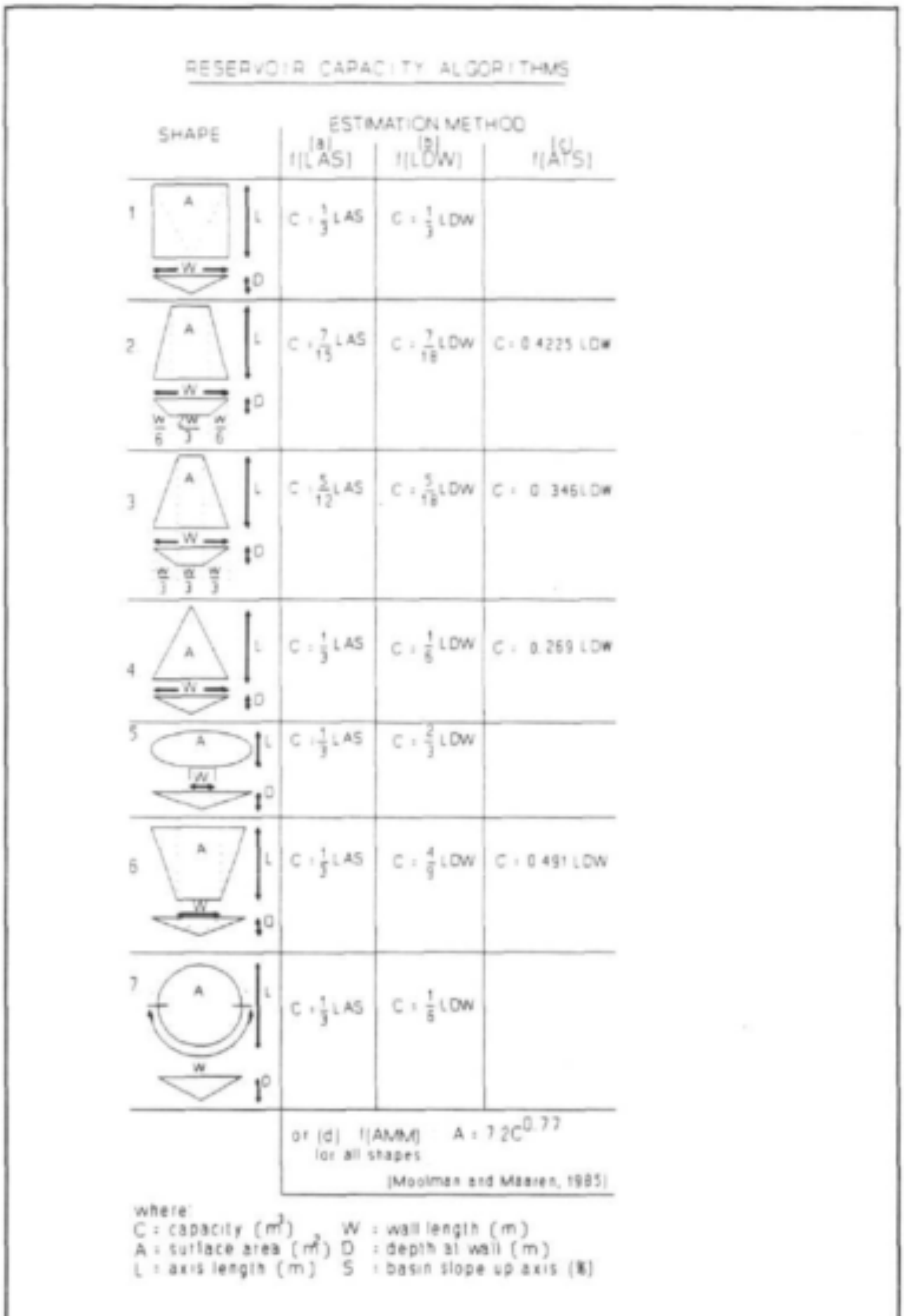


Figure 6.4 Algorithms for estimating reservoir capacity for different shaped reservoirs

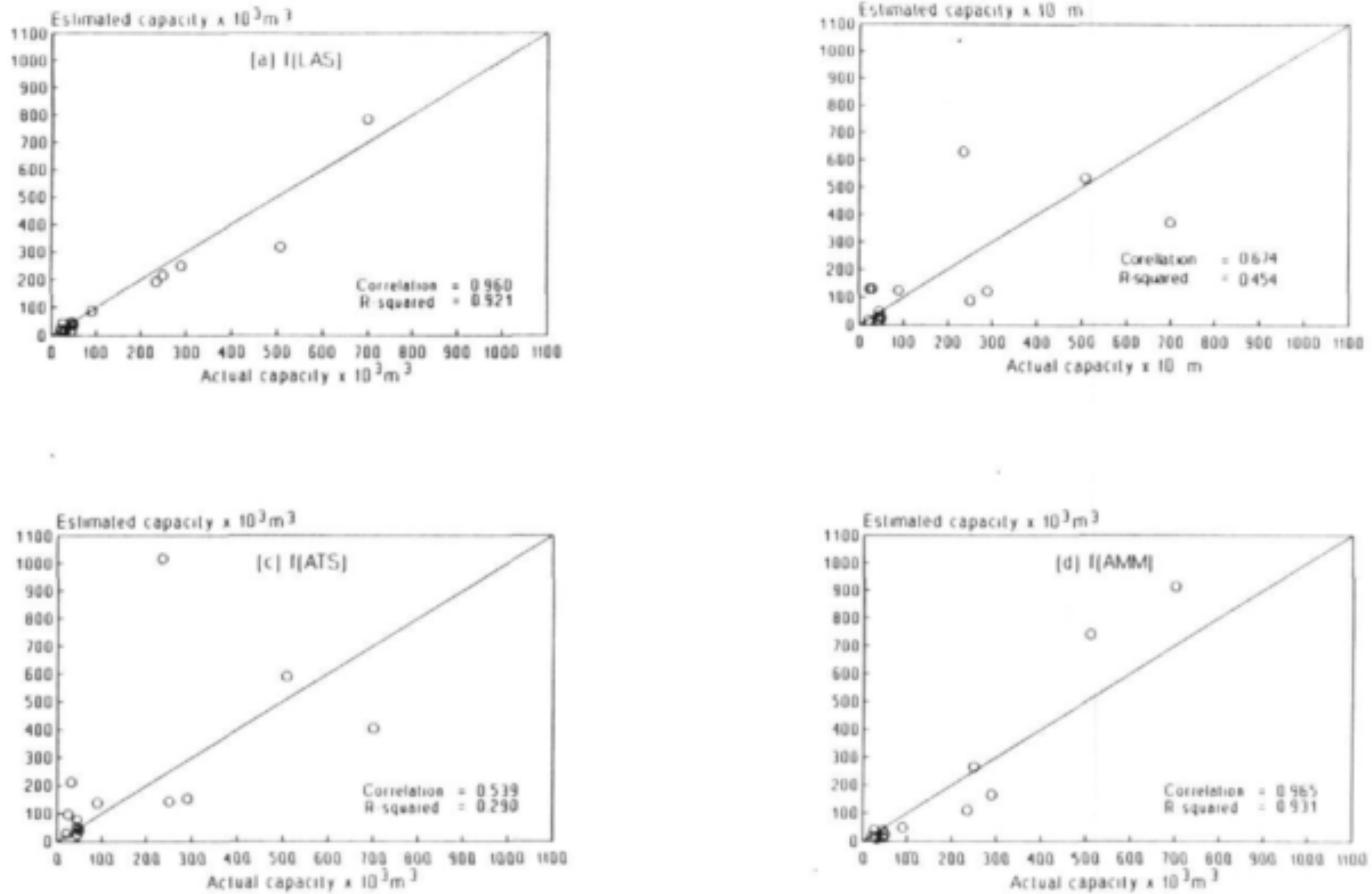


Figure 6.5 Correlations of observed versus estimated reservoir capacities when capacity is estimated: (a) as a function of length, area and slope, (b) as a function of length, depth and width, (c) by Agricultural Technical Services equations (Schultz, 1979), (d) as a function of area (Maaren and Moolman, 1985)

CHAPTER 7

WATER TRANSFERS

In the Mgeni catchment water transfers take place in the form of small scale transfers within subcatchments or large scale transfers between subcatchments. Small scale transfers are predominantly for purposes of irrigation while large scale transfers consist mainly of extractions from large storage reservoirs for municipal supplies and discharges into rivers from urban effluent.

7.1 SMALL SCALE TRANSFERS

Small scale water transfers for irrigation purposes can be divided into irrigation extractions and return flows.

7.1.1 Irrigation extractions

Irrigation extractions are dependent on the area under irrigation and the irrigation requirements of the crop being irrigated. According the INR land cover survey approximately 2% (or 91 km^2) of the Mgeni catchment is irrigated. Bromley (1989a), however, reported that in many cases the irrigated areas could not be distinguished from the satellite imagery used in the land cover survey. In order to obtain more detailed information on irrigation extractions a request was made to the agricultural engineering consultants, Murray Biesenbach and Badenhorst Inc. (MBB), who had already been commissioned by the DWAF to collect irrigation related information in the Mgeni catchment upstream of Midmar dam, to collect additional data and information for the DAE to use in this project. The data and information requested with regard to irrigation extractions included the following:

a)	Dams	-	location
		-	area
		-	capacity
b)	Water abstractions	-	location of pumps
		-	abstraction rates
		-	extraction canals
		-	boreholes
c)	Irrigation	-	area under summer irrigation and crop type
		-	area under winter irrigation and crop type
		-	application method, i.e. irrigation system
		-	scheduling method

When the survey by MBB is complete, it is expected that this information will be available in a GIS compatible format to be incorporated into the Mgeni GIS. The *ACRU* modelling system is configured to use this type of information to determine irrigation requirements and water abstractions. The areas under irrigation as determined by the INR are being used until the MBB irrigation information is available.

The *ACRU* modelling system already has irrigation subroutines that accommodate water supply for irrigation from either a supply reservoir, a river, the combination of reservoir and river, or by supply canal from a source outside the catchment. A separate water budget is carried out for the irrigated area and transfer losses in supplying water to the irrigation area, on-farm losses and losses due to irrigation inefficiencies are accounted for.

7.1.2 Irrigation return flows

Areas under irrigation on occasion generate "deep percolation" water which drains out beneath the active root zone, either when over-irrigation has taken place or when soil water in the root zone is displaced downwards by rain falling on a wet (e.g. recently irrigated) soil. In *ACRU* an option exists for this water to return to the river system as irrigation return flow, which then supplements streamflows downstream. Owing to frequent over-irrigation these return flows, with their associated leachates, may contribute to a progressively worsening salinisation problem for downstream users in irrigation projects along a river course.

7.2 LARGE SCALE TRANSFERS

Large scale transfers within the Mgeni system, which was considered downstream as far as the inlet to Inanda dam in this project, are primarily abstractions from the large supply reservoirs for municipal and industrial water supply, and effluent discharges from sewage works back into the rivers. The main abstractions and effluent disposals within the Mgeni system are illustrated in Figure 7.1 and synthesized in the *ACRU* modelling system by means of draft from the reservoirs and amounts pumped back into the rivers. Some daily abstraction and effluent return data and information was collected but daily records were incomplete over the desired simulation period (1960 to 1989). Consequently monthly totals of abstractions and return flows were obtained from the relevant authorities (*viz.* UW, DWAF, Howick Municipality and the Pietermaritzburg City Engineers Department) and converted to daily values in the modelling system. Values of abstraction and effluent return fluctuate seasonally and increase gradually with the population increase over time. To account for this, abstraction and effluent return volumes were updated in *ACRU* on a monthly basis, by means of a "dynamic file" for each point at which the abstraction or effluent discharge changed over time. A selected dynamic file is presented in Appendix F.

Water abstraction and effluent returns are summarised in Table 7.1, which also gives some indication of the range in the quantity of transfers. By far the greatest abstraction is from Nagle dam which supplies water to Durban. Water abstracted from Henley dam on the upper reaches of the Msunduzi river is supplied to Edendale and the H. D. Hill Water Works in Pietermaritzburg. In times of high flows, water can be diverted from the Henley dam inlet and released into the Msunduzi at a point downstream of the dam. The balance of Pietermaritzburg's water supply is extracted from Midmar dam which also supplies Howick with water. Releases and overflow from Midmar dam flow down the Mgeni to Albert Falls dam, which acts as a balancing dam and releases water to Nagle dam further downstream to meet the water requirements of the Durban metropolitan area. Water will also be supplied to Durban from Inanda dam in the future.

The major effluent disposal within the system is into the Msunduzi from Darvill sewage works with a small effluent discharge from Howick into the Mgeni upstream of the Howick falls. Return flows to the system below Inanda dam were not considered within the scope of this project.

The *ACRU* hydrological modelling system for the Mgeni catchment has the ability to incorporate additional transfer data (e.g. new or future transfers from Mearns dam or Impendle dam to Midmar dam) by means of the dynamic file which can be invoked at any point in time when required the modelling system.

Table 7.1 Summary of large scale water abstractions, transfers and returns within the Mgeni system

Abstractions from -	Transfer to -	Quantity (Ml/d)
Midmar dam	Pietermaritzburg Howick	33-117 0.5
Henley dam	Pietermaritzburg Edendale Diversion	22-43 2 1.7
Nagle dam	Durban	200-450
Effluent from -	Return to -	
Darvill	Msunduzi	16-60
Howick	Mgeni	0.25

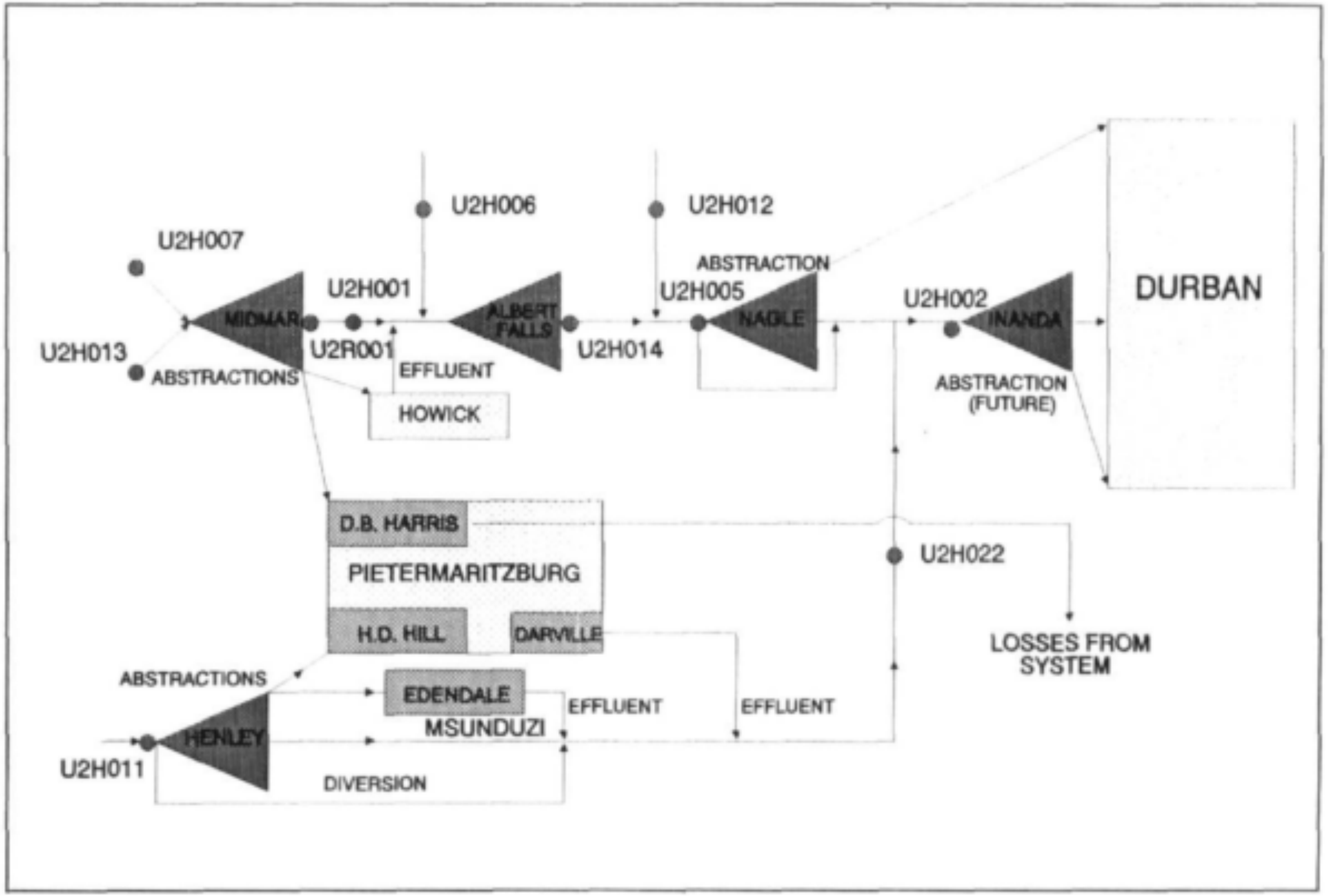


Figure 7.1 Mgeni catchment system showing large scale reservoir abstractions, inter-basin transfers and effluent discharges

CHAPTER 8

SOILS

Spatial and vertical information on soils is essential for hydrological modelling, as it is the capacity of the soil to absorb, retain and release, i.e. redistribute, water. As such, soil is a prime regulator of hydrological responses within a catchment. This chapter discusses soils information in terms of soil properties required for hydrological modelling and the sources of soils information in the Mgeni catchment. The interpretation of soils information from the Soil and Irrigation Research Institute (SIRI) Land Type maps to obtain soil properties for hydrological modelling is explained, and model development to automate the "translation" of soils information into hydrological variables is presented.

8.1 SOILS INFORMATION

Soils mapping and collection of soils information is generally carried out by pedologists rather than hydrologists, who view soils from different perspectives. The pedologist or agriculturalist, for example, interprets the soils map, together with a functional soil classification, according to agricultural potential and constraints while the hydrologist has to use the same map and classification to assess hydrological attributes of soils.

8.1.1 Soil properties required for hydrological modelling

Marked spatial differences in the rates and lags of hydrological processes occur both within a catchment and between catchments as a consequence of hydrological responses associated with different soil properties. The minimum set of soil properties required for hydrological modelling using the *ACRU* modelling system includes the following:

a) depths of the top- and subsoil horizons (m)

b) soil water retention at wilting point for top- and subsoil horizons ($m.m^{-1}$)

c) soil water retention at field capacity for top- and subsoil horizons ($m.m^{-1}$)

d) soil water retention at saturation (porosity) for top- and subsoil horizons, values of which may be perturbed by tillage practices, ($m.m^{-1}$)

e) daily fractions of redistribution of soil water from top- and subsoil horizons when the topsoil's water content is above field capacity

f) daily fractions of redistribution of soil water from subsoil out of the active root zone when the subsoil's soil water content is above field capacity and

g) information on changes of clay distribution within the soil profile, which by implication of the above must be gleaned from soil texture classes, clay percentages and sequences of horizons within soil series.

8.1.2 Source of soils information

The prime source of soils information in southern Africa is the Soil and Irrigation Research Institute (SIRI) of the State Department of Agricultural Development, which is presently carrying out a countrywide Land Type survey with the aims of delineating Land Types at 1:250 000 scale (with fieldwork at 1:50 000), defining each Land Type, and analysing, in-depth, soil profiles within Land Types (SIRI, 1987). Results of this survey, which will eventually cover all of South Africa, are published in the form of regional analyses at 1:250 000 scale once they are completed. For each region the analyses comprise a Land Type map and a memoir containing tabulated Land Type information.

Land Type maps covering the Mgeni catchment had, by the end of 1991, not yet been published, but copies of the unpublished field maps at a scale of 1:50 000 were kindly made available to this project from the Cedara office of SIRI (Smith-Baillie, 1991) and digitised by the DAE. The 226 Land Types found in the Mgeni catchment were grouped into similar Land Types as shown in Figure 8.1. SIRI made the computerised inventories for each Land Type within the Mgeni catchment available to the DAE for inclusion in the Mgeni information base. An example of a Land Type inventory from the computer files is shown in Table 8.1.

Table 8.1 Example of computerised SIRI inventory for Land Type C6

```
LANDTYPE C6
A     C6   E3582   9999   180A L Smith-Baillie
B     C6  2930   9999
C     C6Hoofsaaklik sandsteen van die Formasie Vryheid, Groep Ecca, met klein oppervlaktes
C     C6van doleriet.#
C     C6Mainly sandstone of the Vryheid Formation, Ecca Group, with small areas of dolerite.
D     C6 3  25 4- 12 250-  400  X 4  35 2-  6 100-  500X-Z
D     C6 5  40 1-  6  50-  500  X
E     C6                                  GEEN
F     C6 Ms10                     200- 40015-25          R          3
G     C6 3  20                                    Afi/meSaLm-SaClLm
F     C6 Gs16                     300- 50015-30        so;R         1
G     C6 3  30                                    AfiSaLm-SaClLm
F     C6 My10                     350- 55015-30        so;R         0
G     C6 3   4                                    Afi/meSaLm-SaClLm
F     C6 Hu36Hu37                 800-120015-30     20-40R          0
G     C6 3  16 4    6                             BSaClLm-SaCl
F     C6 Sd21Sd31                 800-120020-30     35-50R          0
G     C6 3  10 4    2                             BSaCl-Cl
F     C6 Sw30Sw31                 450- 65015-25     20-40vp;so;R    0
G     C6 3  20 4   13                             BSaClLm-SaCl
F     C6 Sw40Sw41                 450- 65015-25     20-40vp;so;R    0
G     C6 4   5                                    BSaClLm-SaCl
F     C6 Va30Va31                 500- 75015-25     20-40vp         0
G     C6 4  28                                    BSaClLm-SaCl
F     C6 Va40Va41                 500- 75015-25     20-40vp         0
G     C6 4  18 5    7                             BSaClLm-SaCl
F     C6 Ss26                     400- 55015-25     25-50pr         0
G     C6 4   8 5    6                             Afi/meSaLm-SaClLm
F     C6 Es16                     400- 55015-2515-2525-50pr         0
G     C6 4   4 5    5                             Efi/meSaLm-SaClLm
F     C6 Oa36Oa37                1000-120020-30     20-40R          0
G     C6 4  10 5   15                             BSaClLm-SaCl
F     C6 Oa46Oa47                1000-120020-30     20-40R          0
G     C6 4   6 5   10                             BSaClLm-SaCl
F     C6 Du10                    1000-120020-30          R          0
G     C6 5  25                                    ASaClLm
F     C6 Ka20                     300- 45020-30          gc         0
G     C6 5  10                                    ASaClLm
F     C6 E                                                          4
G     C6 5   2
F     C6 S                                                          2
G     C6 5  20
```

8.2 INTERPRETING THE SOILS INFORMATION FOR HYDROLOGICAL PURPOSES

The Land Type inventories provide largely descriptive information on soils, including: underlying geology, terrain types, soil form and series, depth and textural classification. In order to use soils information contained in the Land Type inventories for hydrological modelling it was necessary establish a set of working rules to interpret the Land Type information and by inference obtain the required soil hydrological properties.

8.2.1 Determination of depths of top- and subsoil horizons from Land Type information

The active root depth of a soil profile is taken to be the total soil profile depth as given in the Land Type inventories, with a depth of 1 200 mm assumed when a depth of 1 200 mm + is denoted. For computational purposes a minimum total profile depth of 250 mm is assigned, except for areas designated as rocks.

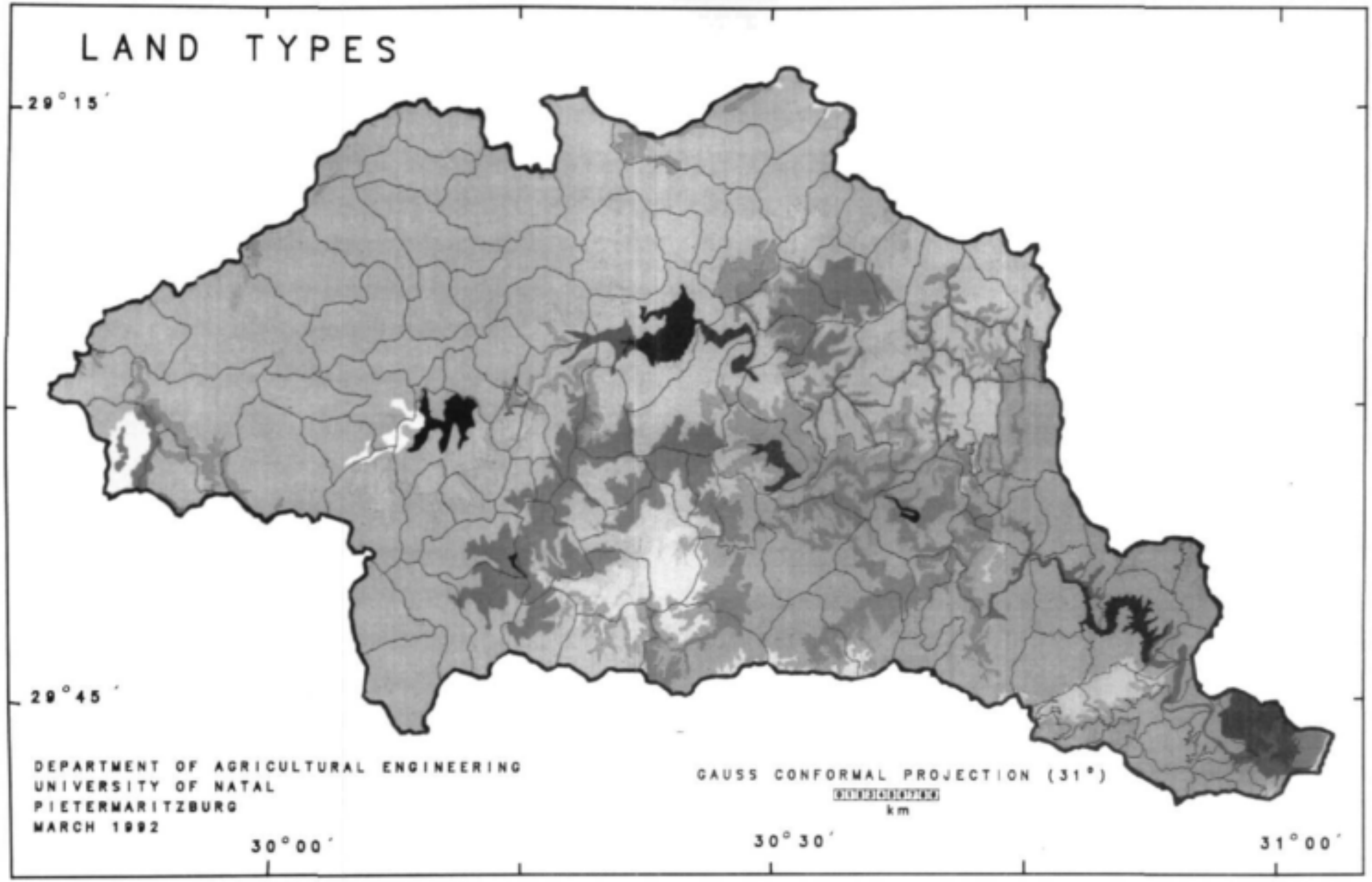


Figure 8.1 Land Types of the Mgeni catchment

RED-YELLOW APEDAL, FREELY DRAINED SOILS

- Aa — With a humic horizon
- Ab — Red, dystrophic and/or mesotrophic
- Ac — Red and yellow dystrophic and/or mesotrophic
- Ad — Yellow, dystrophic and/or mesotrophic
- Ah — Red and yellow, high base status, usually < 15% clay

PLINTHIC CATENA: UPLAND DUPLEX AND MARGALITIC SOILS RARE

- Ba — Dystrophic and/or mesotrophic; red soils widespread
- Bb — Dystrophic and/or mesotrophic; red soils not widespread
- Bd — Eutrophic; red soils not widespread

PLINTHIC CATENA: UPLAND DUPLEX AND/OR MARGALITIC SOILS COMMON

- Ca — Undifferentiated

ONE OR MORE OF: VERTIC, MELANIC, RED STRUCTURED DIAGNOSTIC HORIZONS

- Ea — Undifferentiated

GLENROSA AND/OR MISPAH FORMS (other soils may occur)

- Fa — Lime rare or absent in the entire landscape
- Fb — Lime rare or absent in upland soils but generally present in low-lying soils

GREY REGIC SANDS

- Hb — Regic sands and other soils

MISCELLANEOUS LAND CLASSES

- Ia — Undifferentiated deep deposits
- OO — Major dams

Experience-based working rules (Angus and Schulze, 1990) used to determine a total soil profile depth and to partition the total depth into respective depths of top- and subsoil horizons are summarized by flowchart in Figure 8.2.

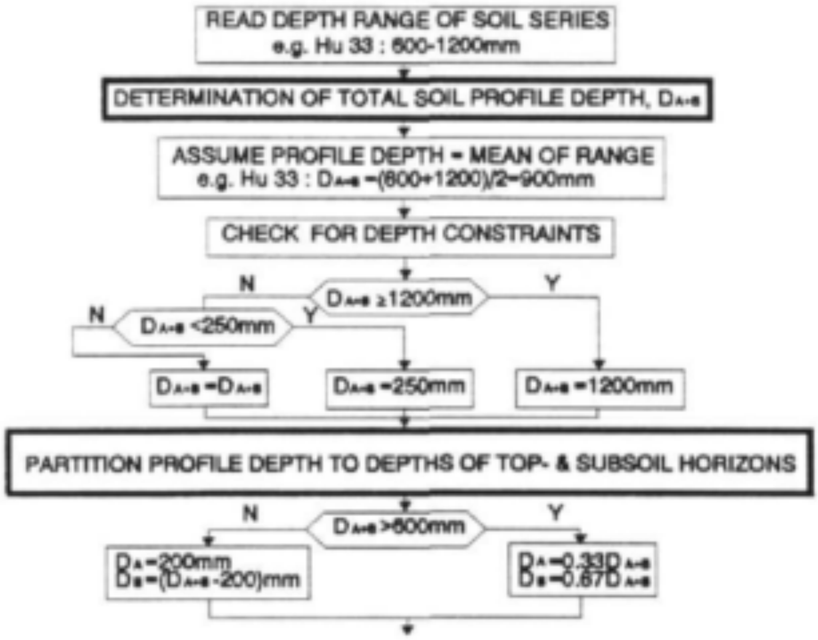


Figure 8.2 Flowchart depicting working rules on determining respective depths of top- and subsoil from Land Type information (after Angus and Schulze, 1990).

8.2.2 Determination of wilting point and field capacity values for top- and subsoil horizons

Values of the soil water retention constants at wilting point and field capacity for top- and subsoil horizons of a soil series will depend, *inter alia*, on soil texture, organic carbon content, bulk density, instability of the soil in regard to swell/shrink properties and change of clay content with depth. In regard to the change of clay content with depth, Schulze Hutson and Cass (1985) defined five clay distribution models for southern Africa, depicting no change with depth, a steady increase and three cases of abrupt textural change (Figure 8.2). Working rules for rates of clay content change for the five clay categories (0-6% clay, 6-15%, 15-35%, 35-55% and >55% clay) used in soil series delimitation by MacVicar *et al.* (1977) were drawn up by Schulze *et al.* (1985) and to each of the 501 soil series identified in South Africa, *inter alia*, a clay model/class and typical texture class were assigned, as in the example in Table 8.2. The complete version of Table 8.2 is published in Schulze *et al.*(1989).

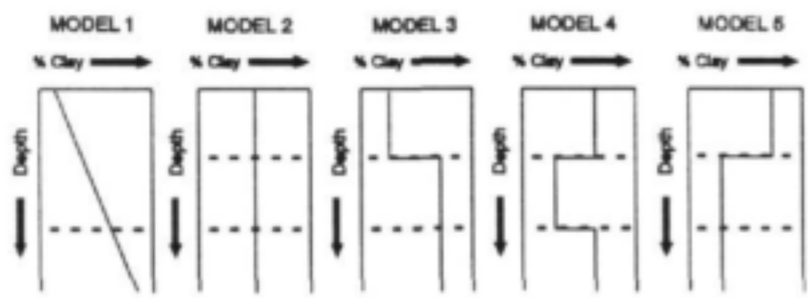


Figure 8.3 Clay distribution models for southern Africa (Schulze *et al.*, 1985)

Table 8.2 Example of hydrological classification of soil series for southern Africa (after Schulze *et al.*, 1989)

Soil Form	Code	Soil Series	Clay Distribution Model/Class	Typical Textural Class	Interflow Potential	SCS Soil Grouping
KROON-STAD	Kd 14	Mkambati	3e	SLm/SClLm	XX	C/D
	Kd 10	Rocklands	3b	LmS/SLm	XX	C/D
	Kd 18	Uitspan	3h	SClLm/SCl	XX	C/D
	Kd 21	Umtentweni	3c	LmS/SClLm	XX	C/D
	Kd 19	Volksrust	3k	SCl/Cl	XX	D
LAMOTTE	Lt 10	Alsace	2a	LmS	X	A/B
	Lt 21	Burgundy	2a	LmS	XX	B
	Lt 14	Chamond	2b	SLm	X	A/B
LONGLANDS	Lo 30	Tayside	1a	S	XX	C
	Lo 31	Vaalsand	1b	SLm	XX	C
	Lo 12	Waldene	1c	SClLm	XX	C
	Lo 13	Winterton	1d	SCl	XX	C
MAGWA	Ma 12	Frazer	1e	Cl	O	A/B
	Ma 11	Magwa	1d	SCl	O	A/B
	Ma 10	Milford	1c	SClLm	O	A
MAYO	My 10	Mayo	5c	SClLm	O/X	C
	My 11	Msinsini	5d	SCl	O/X	C/D

Table 8.3 Estimations of soil water content (θ) at wilting point and field capacity by clay distribution model (after Schulze *et al.*, 1985)

Clay Distribution Model/Class	θ at Wilting Point, WP ($m.m^{-1}$)		θ at Field Capacity, FC($m.m^{-1}$)	
	Topsoil WP1	Subsoil WP2	Topsoil FC1	Subsoil FC2
1a	.064	.065	.158	.171
b	.083	.091	.180	.201
c	.112(.127)	.158(.211)	.213	.277
d	.173(.226)	.226(.320)	.282	.354
e	.231(.320)	.265(.383)	.348	.398
2a	.067	.062	.162	.168
b	.089	.084	.187	.193
c	.138(.169)	.133(.169)	.242	.248
d	.202(.273)	.197(.273)	.315	.321
e	.250(.352)	.245(.352)	.370	.376
3a	.067	.084	.162	.193
b	.067(.054)	.110(.132)	.162	.222
c	.067(.054)	.142(.185)	.162	.259
e	.089(.091)	.133(.169)	.187	.248
h	.138(.169)	.181(.247)	.242	.303
k	.202(.273)	.245(.352)	.315	.376
5a	.067	.057	.162	.156
b	.089	.068	.187	.175
c	.138	.092	.242	.202
d	.202	.124	.315	.239

( ) Bracketed values refer to unstable soils

For each clay model/class estimates of soil water content were then made according to equations and simplifying assumptions developed by Hutson (1984) and Schulze *et al.* (1985). These are illustrated in Table 8.3. This information, gleaned from Tables 8.2 and 8.3 can be used to estimate wilting points and field capacities for top- and subsoils by soil series. Other methods/equations for these estimations are described in Schulze (1989).

8.2.3 Determination of porosity values and saturated soil water redistribution rates

The amount of water held by a soil at porosity i.e. at saturation, is used to determine soil water deficits, which affect stormflow response and will depend largely on the soil's

a) texture class, which reflects its percentages of the sand, silt and clay fractions, its

b) bulk density, which generally varies with depth and its

c) state of tillage, by which bulk density of the tilled layer is changed.

"Saturated" soil water redistribution takes place from top- to subsoil and subsoil to below the active root zone when the respective upper horizons' soil water content exceeds field capacity. For "tank" type models such as the version of *ACRU* used in this study of the redistribution is expressed as a fraction of the amount of water above field capacity draining to a lower horizon in a day. This fraction is governed largely by the soil texture of the lower of the two respective horizons into which soil water is moving by gravity. Texture related saturated redistribution fractions (per day) and porosity values derived from various sources in the literature are presented in Table 8.4.

Table 8.4 Porosity ($m.m^{-1}$) and soil water redistribution fractions (of "excess" water) by soil texture class (after Schulze, George and Angus, 1987; Buitendag 1990)

Texture Class	Topsoil	Subsoil	Tilled Layer		Saturated Soil Water Redistribution Fractions
			Fresh	End of Season	
Clay	.470	.482	.549	.538	.25
Loam	.512	.462	.589	.524	.50
Sand	.446	.430	.559	.503	.80
Loamy Sand	.452	.432	.562	.505	.70
Sandy Loam	.486	.448	.582	.524	.65
Silty Loam	.530	.500	.619	.575	.45
Sandy Clay Loam	.435	.435	.523	.486	.50
Clay Loam	.474	.456	.576	.541	.40
Silty Clay Loam	.489	.473	.544	.528	.35
Sandy Clay	.393	.423	.529	.492	.40
Silty Clay	.476	.470	.547	.536	.35

8.3 "TRANSLATION" OF LAND TYPE INFORMATION FOR APPLICATION IN THE MGENI MODELLING SYSTEM

In order to be usable for the hydrologist all the sets of information contained in Tables 8.2 (for all 501 series), 8.3 and 8.4 as well as the working rules established, for example, in Figure 8.2 plus many more working assumptions and inferentially determined equations have been amalgamated into an interactive soils Decision Support System (DSS) incorporated into the *ACRU* modelling system. This DSS is linked to the Land Type inventories (as illustrated by the example in Table 8.1) by a suite of computer programs which facilitate a "translation" of the Land Type inventory information into hydrologically useful variables. Land Type information can be "translated" at the level of:

a) individual soil series of a terrain unit(s) within a Land Type, or of

b) averaged values for individual Land Type(s), or at the level of

c) a defined catchment, which is made up of various percentages (adding to 100%) of a number of Land Types delimited within it.

For the Mgeni catchment the GIS was used to combine the subcatchment boundaries and spatial soils information to obtain a summary of the Land Types and their relative proportions within each subcatchment. These values were keyed directly into the soil DSS, to obtain a "translation" of the Land Type information into the hydrological soil variables required by the *ACRU* modelling system. An example of output of such a hydrological "translation" for Mgeni subcatchment U23723 in which six Land Types were delimited (*viz*. C289,...,D2) is given in Table 8.5.

Table 8.5 Example of a hydrological "translation" of Land Type inventory information for the Mgeni catchment (Schulze, Angus and Guy, 1991)

CATCHMENT NAME: U23723XX

LANDTYPE (%)

C289	26.27	C917	42.52	C919	5.10
C926	3.50	C918	11.66	D2	10.94

TERRAIN UNIT SOILS INFORMATION AND HYDROLOGICAL PROPERTIES

TERRAIN UNIT	AREA (%)	SLOPE (%)	SLOPE LENGTH M	ROCK (%)	EROSION (%)	STREAMBEDS (%)	MARSH (%)
1	11.32	3.	366.	4.9	0.0	0.0	0.0
2	0.25	45.	153.	18.0	0.0	0.0	0.0
3	85.12	17.	560.	4.4	1.4	0.0	0.0
4	0.0	0.	0.	0.0	0.0	0.0	0.0
5	3.64	11.	50.	0.0	0.0	24.0	0.0

TERRAIN UNIT	DEPAHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO2	ABRESP	BFRESP	K-FACTOR
1	254.4	405.6	.175	.199	.283	.321	.419	.461	0.37	0.25	0.20
2	200.0	115.9	.150	.146	.255	.263	.411	.440	0.33	0.25	0.24
3	279.4	486.4	.167	.196	.273	.317	.424	.454	0.38	0.29	0.20
4	0.0	0.0	.000	.000	.000	.000	.000	.000	0.00	0.00	0.00
5	119.8	141.2	.081	.112	.134	.170	.235	.239	0.25	0.24	0.24

OVERALL SUBCATCHMENT SOILS INFORMATION AND HYDROLOGICAL PROPERTIES

SLOPE (%)	SLOPE LENGTH (M)	ROCK (%)	EROSION (%)	STREAMBEDS (%)	MARSH (%)
.16	520.	4.3	1.2	0.8	0.0

DEPAHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO2	ABRESP	BFRESP	K-FACTOR
271.1	464.9	.165	.193	.270	.313	.417	.448	0.38	0.28	0.20

DEPAHO, DEPBHO	= Depths of top- and subsoil horizons (mm)
WP1, 2	= Soil water content at permanent wilting point ($m.m^{-1}$) for top- and subsoil horizons
FC1, 2	= Soil water content at field capacity ($m.m^{-1}$) for top- and subsoil horizons
PO1, 2	= Soil water content at porosity ($m.m^{-1}$) for top- and subsoil horizons
ABRESP, BFRESP	= Redistributions fractions of "excess" water (per day), top- to subsoil and subsoil to drainage
K-FACTOR	= Soil erodibility factor for the Universal Soil Loss Equation

CHAPTER 9

STREAMFLOW

The term streamflow embraces the combination of surface and near-surface generated runoff and subsurface generated baseflow and is thus the prime hydrological indicator of water quantity. One of the main objectives of modelling the hydrology of the Mgeni catchment was to simulate realistically and objectively the streamflow throughout the Mgeni catchment, and all the data collection, processing and model development discussed in the previous chapters was towards the end of better streamflow simulation at any point within the catchment. Streamflow records are vital to verify the ability of the hydrological modelling system selected to simulate observed flows accurately, before the modelling system is used to simulate impact scenarios which likely development might have on streamflow.

9.1 AVAILABLE STREAMFLOW DATA

Streamflow data in the Mgeni catchment were used not only to verify simulated values but also to enhance the quality of the simulation. An option was introduced into *ACRU* whereby observed streamflow could be used in preference to simulated streamflow as an input to downstream subcatchments. Where streamflow data were missing, suspect or the gauging weir had been overtopped and such data had been flagged, simulated streamflow took precedence over the observed data. The model user also still has the option to use simulated streamflow in preference to observed values where desirable.

The spatial location of point measurement stations for both streamflow (gauging weir) and water quality are illustrated in Figure 3.1 and listed in Table 9.1. All the processed daily streamflow data for the Mgeni catchment up to December 1990 have been extracted from the DWAF files through the CCWR. Although there are many sites at which point water quality observations are made (grab samples) there is a paucity of measured streamflow data and even at sites with streamflow measurements the data were often unreliable or missing. As a result the *ACRU* hydrological modelling system was verified with data from the gauges with the best streamflow data, *viz.* at U2H007, U2H013, U2H006 and U2H012.

9.2 SIMULATION OF STREAMFLOW

In the *ACRU* modelling system the generated streamflow comprises *baseflow* and *stormflow*, with the stormflow component consisting of a *quickflow* response (i.e. stormflow released into the stream on the day of the rainfall event) and a *delayed stormflow* response (Schulze, 1989). Baseflow is derived from a groundwater store which is recharged by drainage out of the lower active soil horizon when its water exceeds field capacity. Figure 2.2 shows these streamflow components diagrammatically.

9.2.1 Estimation of stormflow

Stormflow estimation is based on the SCS procedure, designed to use daily rainfall input as the driving mechanism. The concept of the SCS stormflow routine is based on the principle that the runoff potential is, *inter alia*, an inverse function of the soil's relative wetness. The SCS stormflow equation is as follows:

$$Q_s = \frac{(P - I_a)^2}{P - I_a + S_s} \quad for \;\; P > I_a \qquad (9.1)$$

where Q_s = stormflow volume (mm)
P = daily rainfall amount (mm)
I_a = initial abstractions (mm) before stormflow commences, and consisting mainly of interception, initial infiltration and depression storages and
S_s = potential maximum retention (mm) which is equated to the soil water deficit.

Table 9.1 Inventory of streamflow and water quality measuring points in the Mgeni catchment (various sources)

Gauging Station Number	Data Code		Latitude			Longitude			Years of record
			Deg	Min	Sec	Deg	Min	Sec	
U2H001	A01		29	29	13	30	14	16	12/1948-12/1990
U2H002	A01	Q01	29	39	00	30	48	00	01/1936-04/1975
U2H003		Q01	29	45	32	30	56	07	
U2H005	A01	Q01	29	35	05	30	56	15	11/1950-09/1989
U2H006	A01	Q01	29	22	50	30	35	39	01/1954-12/1990
U2H007	A01	Q01	29	26	23	30	16	00	07/1954-12/1990
U2H011	A01	Q01	29	38	44	30	09	34	12/1957-11/1990
U2H012	A01	Q01	29	26	13	30	15	11	08/1960-12/1990
U2H013	A01	Q-1	29	30	39	30	29	47	08/1960-12/1990
U2H014	A01	Q01	29	25	58	30	07	56	09/1964-12/1990
U2H015	A01	Q01	29	41	28	30	25	20	11/1971-08/1987
U2H016		Q01	29	33	21	30	49	54	
U2H018		Q01	29	34	24	30	14	58	
U2H019	A01		29	32	45	30	14	49	01/1977-06/1977
U2H020	A01		29	32	47	30	16	49	01/1978-12/1989
U2H021		Q01	29	25	18	30	16	51	
U2H022	A01	Q01	29	39	39	30	25	13	09/1983-12/1990
U2H023		Q01	29	36	11	30	38	52	
U2H024		Q01	29	48	50	30	25	59	
U2H025		Q01	29	49	16	30	52	34	
U2H026		Q01	29	48	00	30	53	24	
U2H027		Q01	29	48	50	30	51	00	
U2H028		Q01	29	49	49	30	54	41	
U2H029		Q01	29	48	51	29	52	52	
U2H030		Q01	29	49	23	30	57	09	
U2H031		Q01	29	49	08	30	57	47	
U2H032		Q01	29	48	12	30	57	25	
U2H033		Q01	29	49	11	30	57	45	
U2H034		Q01	29	48	20	30	57	52	
U2H035		Q01	29	48	23	30	30	00	
U2H036		Q01	29	49	50	30	54	10	
U2H037		Q01	29	29	13	30	09	23	
U2H038		Q01	29	24	32	30	22	11	
U2H039		Q01	29	27	55	30	20	40	
U2H040		Q01	29	26	26	30	19	49	
U2H041		Q01	29	36	27	30	27	00	
U2H042		Q01	29	39	31	30	41	02	
U2H043		Q01	29	35	52	30	37	40	
U2H044	A01	Q01	29	33	08	30	11	19	08/1988-12/1990
U2H045	A01	Q01	29	32	44	30	10	18	11/1989-12/1990
U2H046	A01	Q01	29	32	32	30	07	28	12/1989-12/1990
U2H047		Q01	29	36	08	30	24	49	
U2H048	A01	Q01	29	29	42	30	12	16	10/1979-11/1990
U2H054	A01			42	29	30	52	04	04/1989-11/1990

A = Upstream gauge plate
Q = Water quality sampling point

The SCS method adapted for use in southern Africa (Schulze, 1984; Schmidt and Schulze, 1987) is used to estimate stormflow in *ACRU*. In order to eliminate the necessity of estimating both I_a and S_s, I_a may be expressed in terms of S_s by the empirical relationship

$$I_a = cS_s$$

where c = coefficient of initial abstraction.

The equation used to estimate stormflow thus becomes

$$Q_s = \frac{(P - cS_s)^2}{P + S_s(1 - c)} \qquad (9.2)$$

The potential maximum retention of the soil, S_s, is conceived as a soil water deficit and is taken as the difference between water retention at porosity and the actual soil water content just prior to the rainfall event. The critical soil depth for which the soil water deficit is calculated for runoff generation is a variable in order to attempt to account for different dominant runoff producing mechanisms prevailing in subcatchments and for different infiltration rates. For further details on the adaptations of the SCS stormflow equation for use in *ACRU* the reader is referred to Schulze (1989).

9.2.2 Estimation of baseflow

Two response coefficients are applied in the generation of baseflow in *ACRU*. The first relates to the *drainage rate* of water out of the bottom subsoil horizon store, when its soil water content exceeds field capacity, into the intermediate groundwater store. This response rate is a function of soil texture and suggested values are given in Schulze, George, Lynch and Angus (1989). The second response coefficient concerns the *baseflow release* of water from the intermediate/groundwater store into the stream. Suggested values are given in Schulze (1989) and experience has shown that this baseflow release "decay" is not constant so when the groundwater store is large, baseflow release is enhanced, and when the groundwater store is low, baseflow release is reduced.

9.3 STREAMFLOW HYDROGRAPH ROUTING

In simulating daily streamflow, one of the assumptions in the version of *ACRU* developed originally for streamflow simulation in small catchments, was that stormflow generated on a particular day passed the catchment outlet on the same day. This assumption is not usually true of large catchments such as the Mgeni in which the river network plays an important role in transporting the water to the catchment outlet. Thus a flow routing submodel has been incorporated into *ACRU* which enables continuous hydrograph simulation to improve the temporal distribution of the simulated daily flow.

Methods for routing streamflow along river reaches and through reservoirs may be classified broadly as either hydraulic or hydrological (Viessman, Lewis and Knapp, 1989). Both techniques use the principle of conservation of mass. Hydraulic techniques are more complex and were developed for spatially-varied systems using an equation of motion, customarily the momentum equation. Hydrological routing techniques, which use a conceptual approach, are typically simpler techniques developed for spatially lumped systems (Wilson and Ruffini, 1988). It has been shown, *inter alia*, by Price (1974) that the simpler and less data intensive hydrological techniques perform generally as well as the hydraulic techniques. Thus hydrological routing techniques were implemented as an option in the *ACRU* modelling system.

9.3.1 River reach routing

The Muskingum method for channel routing is the most widely used hydrological routing technique (Wilson and Ruffini, 1988). Cunge (1969) related the parameters required for the Muskingum method to physical characteristics of the channel system by noticing similarities between the Muskingum method and the numerical approximation of a diffusion wave model. Thus the Muskingum-Cunge flow routing method, although classified as a hydrological method, gives results comparable with those using hydraulic methods. In using physically based estimates for model parameters, the Muskingum-Cunge method operates in accordance with the *ACRU* modelling philosophy and was thus selected for incorporation into the modelling system.

Invoked only for distributed catchment modelling, the flow routing submodel first disaggregates the simulated daily stormflow by using the SCS unit hydrograph (Schmidt and Schulze, 1987) and one of four regionalised rainfall distribution patterns identified for southern Africa by Weddepohl (1988). The daily rainfall amount is distributed according to the rainfall distribution type, divided into shorter durations and 15 incremental triangular hydrographs are computed and summed to give the stormflow hydrograph. The daily amount of simulated baseflow is then added to the storm hydrograph, assuming a linear change in baseflow rate over the day which ranges from the baseflow rate generated on the previous day to baseflow rate generated on the current day.

The hydrograph from a subcatchment is then routed through the reach downstream of the subcatchment using the Muskingum equation (9.3) and the routed hydrograph forms the inflow to the next subcatchment. The routing process is completed in a similar manner for all the subcatchments until the outflow hydrograph from the entire catchment has been generated. Routing equations used in *ACRU* are as follows:

$$Q_{(n+1)} = C_1 I_{(n+1)} + C_2 I_n + C_3 Q_n \qquad (9.3)$$

where:

$$C_1 = \frac{-KX + 0.5\Delta t}{K - KX + 0.5\Delta t}$$

$$C_2 = \frac{KX + 0.5\Delta t}{K - KX + 0.5\Delta t}$$

$$C_3 = \frac{K - KX - 0.5\Delta t}{K - KX + 0.5\Delta t}$$

and

Q_n	=	outflow from river reach at time = n ($m^3.s^{-1}$)
I_n	=	inflow to river reach at time = n ($m^3.s^{-1}$)
K	=	the storage time constant for the reach (s)
X	=	dimensionless weighting factor that varies between 0 and 0.5
Δt	=	user defined routing interval

The computation of negative outflows ($Q_{(n+1)}$) in equation 9.3 is avoided if the limits on Δt given in equation 9.4 are adhered to (Viessman *et al*., 1989), *viz*.

$$2KX < \Delta t < 2K(1-X) \qquad (9.4)$$

Compliance with equation 9.4 gives rise to conflicting requirements (Bauer, 1975). The smaller the value of Δt, the closer the finite difference approximation of the continuous hydrograph. However, equation 9.4 requires the value of Δt to be large relative to the value of the wave travel time, K. This conflict may be solved by sub-dividing the reach into appropriate sub-reaches and routing the flow through a series of sub-reaches. The accuracy of the method relies on the accurate estimation of parameters relating channel storage volume to inflow and outflow rates (Wilson and Ruffini, 1988). In the absence of observed flow data, either the wave travel time down the reach may be estimated and a default value of X assumed, or the physically based Muskingum-Cunge method may be used for parameter estimation, as shown in equations 9.5 and 9.6, *viz*.

$$X = \frac{1}{2}\left(1 - \frac{q_0}{S_0 v_c \Delta l}\right) \tag{9.5}$$

where

q_0	=	reference discharge per unit channel width ($m^3.s^{-1}.m^{-1}$)
S_0	=	dimensionless channel bottom slope
v_c	=	wave celerity ($m.s^{-1}$)
	=	zV
z	=	constant, depending on channel dimensions
V	=	reference velocity ($m.s^{-1}$)
Δl	=	routing reach length (m)

$$K = \frac{\Delta l}{v_c} \tag{9.6}$$

A problem in implementing equation 9.5 is deciding on the reference velocity and hence réference discharge to be used in the calculation. Wilson and Ruffini (1988) have suggested using equation 9.7 to calculate the reference flow rate, *viz*.

$$Q_0 = Q_b + \frac{1}{2}(Q_p - Q_b) \tag{9.7}$$

where

Q_o	=	reference flow rate ($m^3.s^{-1}$)
Q_p	=	peak flow rate ($m^3.s^{-1}$)
Q_b	=	base flow rate ($m^3.s^{-1}$)

Three parameter estimation options are available to the user for river reach routing and these are outlined briefly below:

a) Single reach routing: user input Δt, K and X

Flow is routed through a single reach, using user-defined values of the routing period (Δt) and the Muskingum parameters (K and X).

b) Multiple reach routing: user input Δt, K and X

Flow is routed through a series of sub-reaches in order to comply with requirements stipulated by equation 9.4, using user-defined values of Δt, K and X. Thus the number of sub-reaches used is calculated as shown in equation 9.8, viz.

$$NREACH = \frac{K}{\Delta t} \tag{9.8}$$

where $NREACH$ = number of sub-reaches.

For each sub-reach $K = \Delta t$, with the routing time being adjusted if necessary for routing through the last remaining sub-reach.

c) Multiple reach routing: user input Δt and channel dimensions

Flow is routed through a series of sub-reaches in order to comply with requirements stipulated by equation 9.4 using user-defined values of the routing period (Δt), channel geometry and channel slope. Equations 9.5 and 9.6 are used to estimate the Muskingum parameters (K and X) using equation 9.7 to define the reference flow rate. Equation 9.8 is used to calculate the number of sub-reaches necessary.

If the downstream subcatchment contains a reservoir, the hydrograph is routed through the reservoir before it becomes inflow to the next subcatchment.

9.3.2 Reservoir routing

The storage indication (modified-Puls) routing method was selected for routing flow through reservoirs. This method involves solving the continuity equation as given in equation 9.9, where the unknowns for a particular routing interval are written on the left hand side of the equation, in conjunction with a storage-discharge relationship for the reservoir, *viz.*

$$\frac{2S_{(n+1)}}{\Delta t} + Q_{(n+1)} = I_{(n+1)} + I_n + \left(\frac{2S_n}{\Delta t} - Q_n\right) \qquad (9.9)$$

The spillway discharge relationship used is given in equation 9.10 (Chow, Maidment and Mays, 1988).

$$Q = C_d B H^{\left(\frac{3}{2}\right)} \qquad (9.10)$$

where

- Q = flow rate over an uncontrolled spillway ($m^3.s^{-1}$)
- C_d = dimensionless coefficient of discharge, input by the user
- B = width of spillway (m), input by the user
- H = depth of storage above spillway crest (m)

The reservoir surface area:storage relationship used in *ACRU* may either be input by the user, based on a basin survey, or calculated using methods described in Chapter 6. Using the selected surface area:storage relationship, the relationship between storage and depth of flow over the spillway is obtained by calculating the surface area for a particular depth, and then using the surface area to calculate the storage above the spillway crest. By combining equation 9.10 with the derived storage:depth relationship, an exponential equation is fitted to the storage indication curve ($2S/\Delta t+Q$ vs Q) and equation 9.9 is then solved in a sequential step-wise manner to route the flow through the reservoir.

9.4 APPLICATION OF STREAMFLOW HYDROGRAPH ROUTING TO THE MGENI CATCHMENT

Founded on an event-based routing model developed and tested by Caldecott (1989) the continuous hydrograph simulation submodel incorporated into the *ACRU* modelling system (Smithers and Caldecott, 1991) was applied to the 175 km^2 catchment upstream of the Henley dam in the Mgeni catchment both with and without invoking the flow routing submodel. Although the effect of invoking the routing submodel is not always apparent in the statistics of performance, it can be used to improve the temporal distribution of simulated daily runoff as illustrated in Figure 9.1. Streamflow hydrograph routing has not, as yet, been applied to the entire Mgeni catchment but initial verification and development of the streamflow routing routines have been completed. It is envisaged that streamflow routing will be extended to other areas of the Mgeni catchment in Phase II of the project.

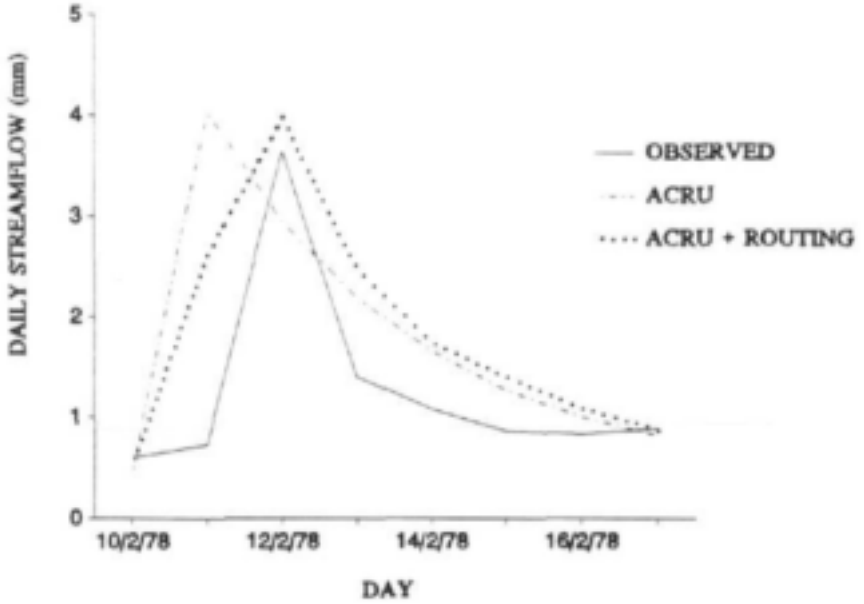


Figure 9.1 Daily values of streamflow from the Henley dam catchment, illustrating the effect of hydrograph routing on daily streamflow simulation (after Smithers and Caldecott, 1991)

CHAPTER 10

MGENI GEOGRAPHICAL INFORMATION SYSTEM

Geographical information has been used in hydrological modelling for many years but recent developments in the capabilities and speed of computer hardware together with appropriate software applications have greatly facilitated the manipulation, processing and display of spatial information using Geographical Information Systems (GISs). In a GIS, geographically spatial information is integrated into a single system, permitting interactions and processes previously not achieved easily, to be carried out between different spatial sets of data and information. The Mgeni GIS is perceived as being not only the interface between the geographical information and the hydrological modelling system (HMS), but also the mechanism which links and integrates the spatial information, discussed in the preceding chapters, into a unified system, thereby enabling the interfacing between the GIS and HMS (cf. Figure 1.3). In this chapter GIS concepts are discussed, followed by details on the sources of geographical information used in the Mgeni catchment. The establishment of the Mgeni GIS is presented and processes to interface the GIS with the *ACRU* HMS are discussed.

10.1 GIS CONCEPTS

In essence, a GIS can be defined as a set of hardware/software tools for inputting, collecting, storing, verifying, searching, retrieving, maintaining, transforming, analyzing and displaying spatial data from the real world for a particular set of purposes. The successful operation of a GIS depends not only on its hardware and software components, but also on the quality of data on which it is built and the skill of the people operating it.

While a map is a graphic representation of geographical features or other spatial phenomena which occur in the environment, a "coverage", "layer" or "image" within a GIS is a digital version of a map wherein map features are stored as simple points, lines or polygons. Since a map contains information describing the attributes of the various geographical features represented, either in the form of labels or symbolically with an attached key to the symbols, each coverage has associated information describing the attributes of each point line or polygon represented. In the same way that different maps are used to display different information, each coverage in a GIS contains a different set of information. The advantage of using a GIS is that one has base coverages which typically contain only one geographical feature per coverage, e.g. there could be one coverage containing rivers, another containing land cover information and a third containing altitude information. The GIS can then be used to "create" coverages by combining base coverages into a single coverage. This concept is illustrated by means of Figure 10.1. which has two base coverages, the first containing a delimited subcatchment and the second a coverage of land cover. To create a coverage containing the land cover within the delimited subcatchment the two coverages are combined resulting in a new coverage containing the desired information. At the same time the attributes of the coverages are combined so that a summary of the information in the new coverage can be generated, as given in Table 10.1.

Table 10.1 Example of land cover information within a subcatchment obtained by combining subcatchment and land cover coverages

Land cover	Area (km^2)	Area (%)
Dams	1.24	4.16
Grassland	24.67	82.51
Wetlands	3.99	13.33
Subcatchment	29.90	100.0

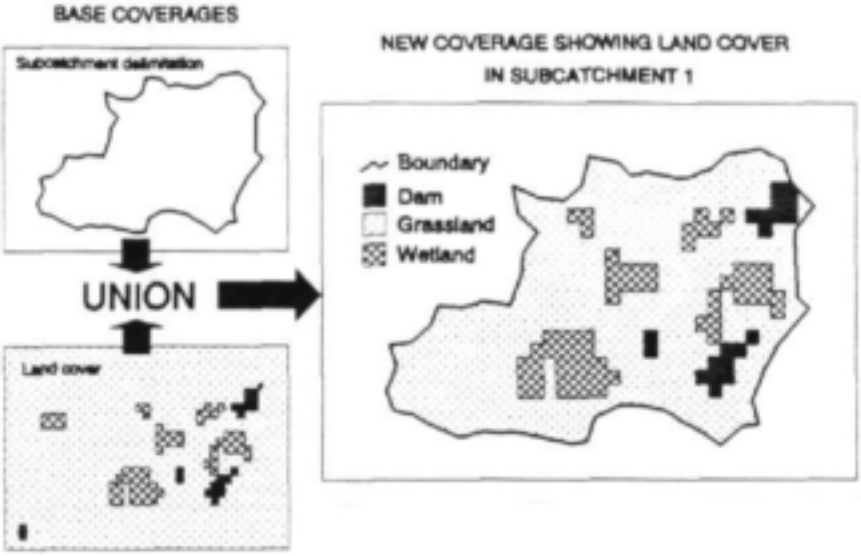


Figure 10.1 Concept of combining coverages within a GIS

10.2 SOURCES OF GEOGRAPHICAL INFORMATION FOR USE IN THE MGENI GIS

Data and information in the form of coverages were brought together in the Mgeni GIS and used in the synthesis of coverages from which information was extracted for use in the *ACRU* hydrological modelling system. Several sets of geographical data covering southern Africa had already been developed by the DAE through previous and current Water Research Commission (WRC) funded projects and were available for use in this project. These data sets of spatially distributed point measurements included:

a) daily time series of rainfall

b) monthly summaries of daily rainfall and

c) daily time series of temperature.

From these data and the sources listed in Table 10.2 the following information had been created at a one by one minute of a degree spatial grid covering the entire or parts of southern Africa:

d) mean and median monthly and annual precipitation

e) altitude

f) distance from the sea

g) monthly means of minimum and maximum daily temperature.

Within the scope of this project altitude data at a spatial resolution of 250 by 250 metre was obtained from the Directorate of Surveys and Mapping for the rectangular region encompassing the Mgeni catchment and land cover information was captured for the catchment by the INR (Bromley, 1989a) using, *inter alia*, remote sensing, aerial photography and ground truthing. SIRI Land Type information was digitized from field maps at a scale of 1:50 000. Table 10.2 gives a full list of the different coverages of geographical information which had been obtained for the period up to 1991, while the methods used in their collection and processing have already been discussed in Chapters 3 to 9.

Table 10.2 Coverages of geographical information collected for the Mgeni catchment (after Tarboton, 1991b)

Coverage	Geographical information	Information sources	References
Altitude grid	Gridded altitudes at 250 x 250 m interval	Chief Directorate Surveys and Mapping, Private Bag, Mowbray	
Point rainfall	Location of 186 daily rainfall stations in and around catchment	SAWB and SIRI data obtained through the CCWR	Dent, Lynch & Schulze, 1987
Rainfall grid	Gridded median monthly totals of daily rainfall at 1'x 1' of a degree interval	CCWR rainfall database from Natal Univ., Dept. Agric. Engineering database	Dent, Lynch & Schulze, 1987
Point temperature	Location of stations with measurements of maximum and minimum daily temperature	SAWB and SIRI data obtained through the CCWR	
Temperature grid	Gridded means of daily maximum and minimum temperatures for each month at 1'x 1' of a degree interval	Univ. Natal, Dept. Agric. Engineering database	Schulze & Maharaj, 1991
Evaporation grid	Gridded mean A-pan equivalent potential evaporation for each month at 1'x 1' of a degree interval	Univ. Natal, Dept. Agric. Engineering database	Schulze & Maharaj, 1991
Rivers	Digitized river courses for Mgeni and main tributaries	1:250 000 topographic maps	
Weirs	Point measurements of quantity (gauging weirs) and quality (grab or continuous samples)	Department of Water Affairs and Forestry database	
Soils	Digitized Land Types	SIRI 1:50 000 field maps, SIRI Land Type memoirs and computerised data base	Smith-Baillie, 1991
Land cover	27 land cover classes	SPOT satellite images (FCC) (1987) Supplementary aerial photography 1:50 000 topographic maps (1973-1982) 1:10 000 orthophotos (1973-1982)	Bromley, 1989a
Reservoirs	Location, surface area, capacity & critical dimensions	LANDSAT multispectral images (1987) 1:50 000 topographic maps (1973-1982) 1:10 000 orthophotos (1973-1982) Field verification	Howman, 1991
Subcatchments	Subcatchment delimitation according to physiographic boundaries	1:50 000 topographic maps, Quaternary subcatchment boundaries	Pitman, Middleton & Midgley, 1981

10.3 ESTABLISHMENT OF THE MGENI GIS

At the outset of this research project three commercially available GIS software packages were investigated with a view to creating a GIS for the Mgeni, *viz.*

a) SPANS,

b) UNIGIS, and

c) ARC/INFO.

At that stage, although no commercial GIS package had been purchased nor obtained for the project, the Mgeni GIS was conceived in that data collection was initialised and data manipulation skills were developed through the use of "in-house" software to manipulate and display the geographical data. Altitude, land cover, temperature and precipitation data and information were incorporated successfully into the Mgeni GIS using in-house software and the CCWR mainframe computer for their digitizing, manipulation and display.

During the course of 1990 an evaluation copy of the UNIGIS package was made available to the project by the Aircraft Operating Company and this IBM compatible DOS-PC based software was used to capture the SIRI Land Type information for the catchment by digitizing the Land Type delineations from the 1:50 000 field maps. This proved to be a time consuming process owing to the complexity of the Land Type information and the fact that these maps were still in a research stage and had not been "edge matched". The complexity and quality of the maps also implied that they could not be scanned digitally which, with the facility to carry out raster editing, is perceived as a future method of to capture digital data more quickly while at the same time eliminating some of the digitizing errors.

In the latter part of 1990 two copies of PC ARC/INFO were offered to the DAE by the DWA within the scope of their collaborative research program. The Land Type information captured by the UNIGIS package was transferred to the ARC/INFO system by means of the common interchange format (DXF) and all the relevant spatial data pertaining to the Mgeni catchment system were transferred from the CCWR mainframe system into the ARC/INFO system. This was carried out by means of the ASCII import option and GENERATE of ARC/INFO, which caters for the transfer of vector and point information from one system to another. Once the data transferral was complete the ARC/INFO system was used for further analysis, processing and display of the geographical data and information contained in the Mgeni GIS. Processes to interface the GIS containing the Mgeni catchment coverages (Table 10.2) and the *ACRU* modelling system are described in greater detail in the following section.

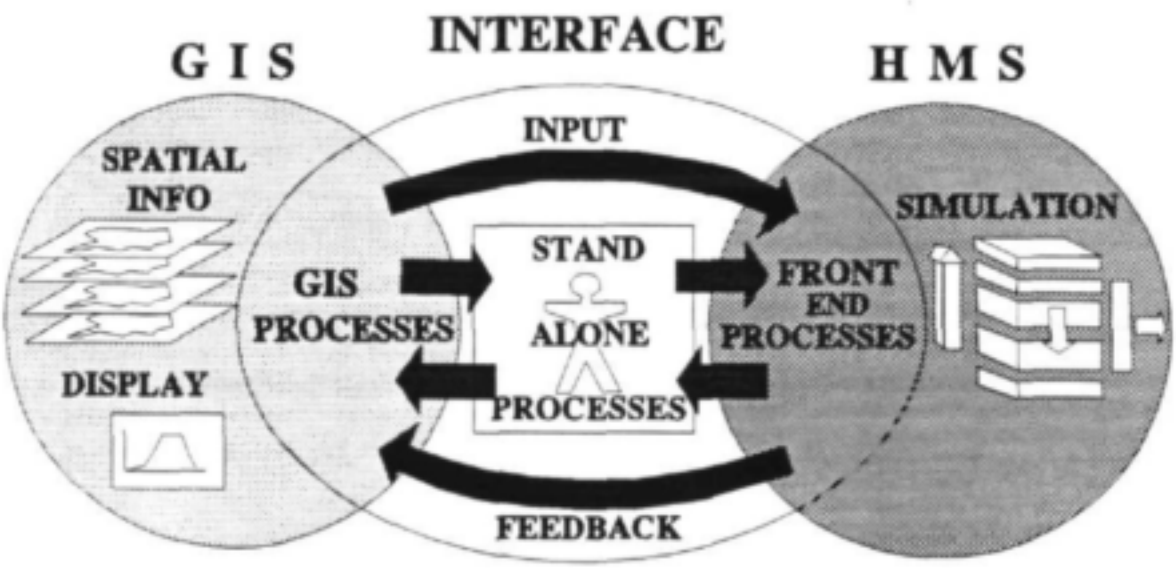


Figure 10.2 GIS - hydrological modelling system (HMS) interface concept (Tarboton, 1991b)

10.4 INTERFACING THE MGENI GIS AND THE *ACRU* HYDROLOGICAL MODELLING SYSTEM

Geographical information systems and hydrological modelling systems are separate entities that require interfacing to enable communication between the two systems for meaningful hydrological simulation and effective use of the geographical information. Interfacing between the Mgeni GIS and the *ACRU* model, within the distributed hydrological modelling system for the Mgeni catchment (Figure 1.3), is the means by which the systems can communicate and interact. Essentially the GIS/HMS interface conceptualized in Figure 10.2 consists of the derivation of meaningful hydrological input variables for the HMS from the geographical information and the feedback of hydrological output to the GIS for display purposes.

Interfacing processes can take place either within the GIS package or as stand alone interfacing programs or as front end processing which forms part of the HMS. One or more or different combinations of these interfacing processes may be used to derive particular input variables or to display output. Often the interfacing processes is not yet completely automated and the human element forms part of the interfacing process, i.e. output from one process is input manually to another process.

10.4.1 GIS processing

GIS processing included combining the different coverages listed in Table 10.2 using the methods described in the "GIS concepts" section above to obtain coverages with the desired input information. For distributed hydrological modelling in the Mgeni catchment it was necessary to combine the subcatchment coverage with each of the coverages containing the input information required by the modelling system. In some cases the major inputs themselves were a combination of other coverages. For example the base coverages of altitude, temperature, and distance from the sea were combined using regression equations (cf. Chapter 4) to obtain a coverage containing an estimated monthly means of A-pan equivalent evaporation at 1' x 1' of a degree intervals. Combining this A-pan evaporation coverage with the subcatchment images resulted in a coverage of estimates of month by month mean A-pan evaporation for each of the 123 subcatchments.

Variables obtained in this manner were input into the *ACRU Menubuilder* (Schulze, George, Lynch, and Angus, 1989) for front end processing before they were used in simulation by the *ACRU* HMS. Reservoir coverage information contained in the GIS included the location, surface area, capacity, wall length, wall height, shape and valley slope for each reservoir (cf. Chapter 6). GIS processing involved the calculation of combined total surface areas and capacities for all the reservoirs in each subcatchment. The fraction of each subcatchment that contributed direct runoff into the reservoirs was estimated manually and entered into the *Menubuilder* together with the combined reservoir surface areas, capacities and a representative reservoir area/capacity relationship.

GIS processing of spatial soils and land cover information involved obtaining their relative representation within each subcatchment by combining the soils or land cover coverage with the subcatchment coverage as described in 10.1 above. Table 10.1 shows the result of the GIS processing of land cover information for Subcatchment 1 in the Mgeni catchment. Similar processing of the soils coverage results in the percentage representation of each Land Type within each subcatchment. Further processing of the percentage representations of soils and land cover information to obtain hydrological variables for each subcatchment was performed in the stand alone and front end processing sections of the interface.

10.4.2 Stand alone processing

Stand alone processing at the GIS/HMS interface for the Mgeni catchment involved the use of a soils DSS, described in Chapter 8, to translate representative Land Type information for each subcatchment into hydrological variables for each subcatchment. Median monthly totals of daily rainfall obtained by GIS processing for each subcatchment, were used with selected driver stations (Tarboton, 1991a) and a stand alone program to generate daily rainfall files for each subcatchment with a format that could be read directly by the *ACRU* modelling system.

Manual inputs to the *Menubuilder* can also be considered as a further example of stand alone processing at the GIS / HMS interface. Although the *ACRU Menubuilder* (Schulze *et al.*, 1989) can stand alone it is used as a front end program to the *ACRU* modelling system to prepare input information in a format that can be read directly by the modelling system. Further discussion of the *Menubuilder* as a front end process follows.

10.4.3 Front end processing

Interfacing at the front end of the hydrological modelling system is carried out predominantly by the *ACRU Menubuilder*, which is a user friendly interactive program (involving human input) that creates an input data file for the *ACRU* agrohydrological modelling system. The *Menubuilder* contains a HELP facility and performs internal checks for realistic input values, issuing warning or error messages if input beyond a physically acceptable range is keyed in. It contains a DSS with pre-programmed values, *inter alia*, for soils and land cover information.

An example of front end processing is the conversion of the percentage representation of each land cover output from the GIS, to vegetation variables that can be used directly in the *ACRU* HMS. Interfacing the percentage cover obtained from the GIS for Subcatchment 1 displayed in Table 10.1 to the hydrological variables displayed in Table 10.3 involved entering a land cover code and the percentage land cover into the *Menubuilder*. Area weighting of pre-defined hydrological properties (Appendix E.1) was carried out in the *Menubuilder* to obtain weighted monthly values for each variables, *viz*. crop coefficient, vegetation interception and the proportion of roots in the topsoil (A) horizon.

Table 10.3 Hydrological variables obtained by entering land cover percentages into the *Menubuilder* for Subcatchment 1

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop coefficient	0.67	0.67	0.67	0.57	0.34	0.24	0.23	0.23	0.31	0.50	0.56	0.66
Interception loss ($mm.rainday^{-1}$)	1.12	1.12	1.12	1.03	0.94	0.94	0.94	0.94	1.03	1.12	1.12	1.12
Proportion of roots in A horizon	0.91	0.91	0.91	0.95	0.98	1.00	1.00	1.00	1.00	0.96	0.91	0.91

Another aspect of front end processing is the updating of variables that change with time. A dynamic file indicating dates of change and variables that change is read directly by *ACRU* to account for gradual or sudden physical changes in a subcatchment. Front end processing can also be considered to include pre-simulation and post-simulation processing within the HMS. In the *ACRU* modelling system, pre-simulation processing uses harmonic (Fourier) analysis within the program to generate daily values from monthly means for many variables including A-pan equivalent, evaporation and vegetation variables. Post-simulation processing at the front end of the hydrological modelling system includes writing of hydrological output to selected formats for display with either stand alone packages or with the GIS.

10.4.4 Future for GIS / HMS interfacing

Present interfacing processes between GISs and hydrological modelling, as demonstrated for the Mgeni catchment, have the potential to make effective use of spatial information and transform it into representative variables for hydrological simulation. Automation and minimizing of the human element is perceived as a requirement for future interfacing. It is suggested that in the Mgeni Phase II project stand alone programs be reduced to a minimum or eliminated completely by incorporation into either the GIS or the hydrological modelling system, culminating in a system whereby GIS information required by the HMS and outputs from the HMS are transferred to and fro transparent to the modellers. It is suggested that the GIS be used more for the outputting of results from the HMS in the form of graphical displays, in the future.

CHAPTER 11

RESULTS

The hydrological modelling system for the Mgeni catchment was set up to enable simulation over the 30 year period from 1960 to 1989; however, selected statistics of daily and monthly streamflow over shorter periods are presented in for selected subcatchments with observed streamflow to show the ability of the modelling system to synthesize observed flows. Simulation over the 30 year period is not presented because changing land cover over this period would affect the simulation statistics as indicated in the section on "Hydrological modelling with changing land cover" in Chapter 5, and historical land cover information was not collected for the entire catchment. Predominantly "external" subcatchments without the major reservoirs were selected for model verification due to the complications of simulating streamflow through the large reservoirs where the operation strategy was not known.

11.1 STREAMFLOW SIMULATION FOR SELECTED CATCHMENTS

11.1.1 Streamflow simulation in Quaternary catchment U231

Results of observed and simulated streamflow in Quaternary catchment U231 comprising Subcatchments 1 to 6 in the upper Mgeni with a cumulative area of 293.17 km^2 are presented in Table 11.1. Observed streamflow is from gauging weir U2H013 situated at the outlet of Subcatchment 6. Simulation was over the 16 years from 1971 to 1986 using present land cover information. Totals of monthly and daily observed and simulated streamflows for U2H013 are different because of the way the model handles missing data. If observed streamflow data are missing for a particular day, that day is omitted from the statistical analysis for purposes of assessing daily model performance, while the entire month is omitted from the monthly analysis of performance even if only one day in that month had missing data.

Table 11.1 Results of observed vs simulated streamflow and selected statistics of performance for Quaternary catchment U231 of the Mgeni catchment (after Tarboton and Schulze, 1991)

Statistics for U2H013 1971 - 1986	Daily simulation	Monthly totals of daily simulation
Total observed streamflow (mm)	3993.61	3945.97
Total simulated streamflow (mm)	3561.47	3527.80
Mean observed streamflow (mm)	0.68	20.77
Mean simulated streamflow (mm)	0.61	18.57
Correlation coefficient	0.76	0.92
Students' 't' value	87.89	31.12
Regression coefficient	0.83	0.86
Base constant for regression (mm)	0.05	0.75
Variance of observed values (mm)	1.17	656.28
Variance of simulated values (mm)	1.38	576.70
% difference in standard deviation	-10.14	5.53
Coefficient of determination	0.57	0.84
Coefficient of efficiency	0.96	0.90

Total simulated streamflow was 11% less than the observed streamflow for the simulation period. Good correlation between observed and simulated streamflows is shown by the high correlation coefficients for both daily and monthly simulations (i.e. monthly totals of daily values). According to Students' 't' test the correlation is significant at the 99.5 percentile level. Figure 11.1 shows the close correlation between observed and simulated annual streamflows over the 16 year simulation period. Plots of daily observed and simulated streamflows at weir U2H013 for January 1986 and monthly values for the year 1985 are shown in Figures 11.2 and 11.3. The underestimation of observed streamflow, revealed in the statistics, can be seen in the daily plot which also shows the observed streamflow peak to lag the simulated streamflow peak, indicating that simulated catchment response time is less than actual response time. Application of the routing routines, presented in Chapter 9 and verified for the Henley catchment, would likely have reduced this lag effect.

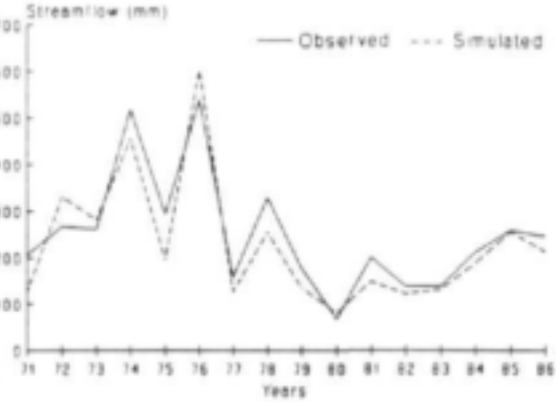


Figure 11.1 Annual totals of daily observed vs simulated streamflow for Quaternary catchment U231 (Tarboton and Schulze, 1991)

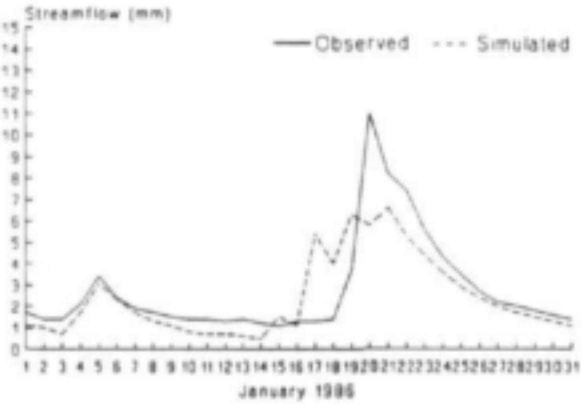


Figure 11.2 Daily observed vs simulated streamflow for Quaternary catchment U231 (Tarboton and Schulze, 1991)

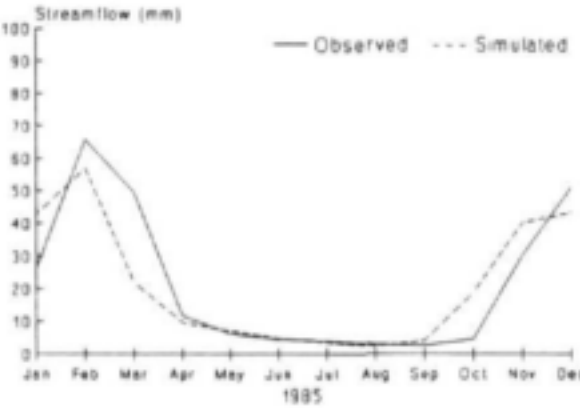


Figure 11.3 Monthly totals of daily observed vs simulated streamflow for Quaternary catchment U231 (Tarboton and Schulze, 1991)

11.1.2 Streamflow simulation in Quaternary catchment U232

Results and statistics of observed versus simulated streamflow for Quaternary catchment U232, i.e. the Lions river catchment, are presented in Table 11.2. The catchment is comprised of Subcatchments 9 to 14 with a cumulative area of 356.76 km^2 and gauging weir U2H007 is located at the outlet of the Subcatchment 14. The results are similar to those for Quaternary catchment U231, with an 11% under-simulation of streamflow over the 16 year period from 1971 to 1986. As expected in the absence of flood routing, the monthly totals of daily simulations display improved statistics of performance over those of the daily simulations *per se*.

Table 11.2 Results of observed vs simulated streamflow and selected statistics of performance for Quaternary catchment U232 of the Mgeni catchment (after Tarboton and Schulze, 1991)

Statistics for U2H007 1971 - 1986	Daily simulation	Monthly totals of daily simulation
Total observed streamflow (mm)	2461.08	2461.08
Total simulated streamflow (mm)	2170.71	2170.71
Mean observed streamflow (mm)	0.42	13.83
Mean simulated streamflow (mm)	0.37	12.20
Correlation coefficient	0.75	0.88
Students' 't' value	87.21	24.84
Regression coefficient	0.64	0.64
Base constant for regression (mm)	0.10	3.29
Variance of observed values (mm)	0.59	439.07
Variance of simulated values (mm)	0.42	234.25
% difference in standard deviation	15.40	29.96
Coefficient of determination	0.57	0.78
Coefficient of efficiency	0.55	0.76

11.1.3 Streamflow simulation in Quaternary catchment U233

Quaternary catchment U233, i.e. the Karkloof river catchment, is comprised of Subcatchments 17 to 23 with a cumulative area of 335.53 km^2. Results and statistics of the simulation over the 5 years from 1985 to 1989 are presented in Table 11.3. Total daily simulated streamflow matches closely total daily observed streamflow while monthly simulated streamflow over-simulates observed monthly flows by 10%. Correlation statistics of daily flows are poor while monthly totals of daily flows display better statistics. It should be stressed again that these are "first run" comparisons with no parameter optimising to seek improved fits.

Table 11.3 Results of observed vs simulated streamflow and selected statistics of performance for Quaternary catchment U233 of the Mgeni catchment

Statistics for U2H006 1985 - 1989	Daily simulation	Monthly totals of daily simulation
Total observed streamflow (mm)	1837.36	1227.62
Total simulated streamflow (mm)	1869.83	1348.13
Mean observed streamflow (mm)	0.51	11.58
Mean simulated streamflow (mm)	0.52	12.72
Correlation coefficient	0.55	0.80
Students' 't' value	39.10	13.41
Regression coefficient	0.62	0.67
Base constant for regression (mm)	0.21	4.50
Variance of observed values (mm)	0.67	201.05
Variance of simulated values (mm)	0.85	141.30
% difference in standard deviation	-13.07	16.17
Coefficient of determination	0.30	0.63
Coefficient of efficiency	0.98	0.93

11.1.4 Streamflow simulation upstream of Henley dam

Four subcatchments are located upstream of Henley dam, *viz.* Subcatchments 62 to 65 with a cumulative area of 177.76 km^2. Observed streamflow is under-simulated by 14% for both daily and monthly totals of daily streamflow over the period from 1970 to 1985 (Table 11.4). This under-simulation is believed to be caused by the use of static present land cover, as was suggested by Tarboton and Schulze (1991) for Quaternary subcatchment U231. Again, for reasons already named, monthly simulation statistics are better than their daily counterparts.

Table 11.4 Results of observed vs simulated streamflow and selected statistics of performance for Quaternary catchment U237 upstream of Henley dam

Statistics for U2H011 1970 - 1985	Daily simulation	Monthly totals of daily simulation
Total observed streamflow (mm)	1221.99	1085.10
Total simulated streamflow (mm)	1054.98	933.13
Mean observed streamflow (mm)	0.68	19.73
Mean simulated streamflow (mm)	0.59	16.97
Correlation coefficient	0.76	0.83
Students' 't' value	49.26	10.93
Regression coefficient	0.96	0.82
Base constant for regression (mm)	-0.07	0.84
Variance of observed values (mm)	0.90	386.72
Variance of simulated values (mm)	1.44	373.14
% difference in standard deviation	-26.66	1.77
Coefficient of determination	0.58	0.69
Coefficient of efficiency	0.31	0.68

11.1.5 Streamflow simulation in Mgeni catchment upstream of Nagle dam

The Mgeni catchment downstream to Nagle dam is comprised of Subcatchments 1 to 60 with a contributing area of 2518.43 km^2. Results and statistics of performance for the 5 year simulation from 1985 to 1989 presented in Table 11.5 indicate daily streamflows to be over-simulated by 21% and monthly totals of daily flows to be over-simulated by 9%. Correlation between simulated and observed values is poor, and believed to be due to the timing of releases from the upstream dams (Midmar and Albert Falls). In this simulation operating strategies of the dams were not known and were therefore not incorporated in simulations.

Table 11.5 Results of observed vs simulated streamflow and selected statistics of performance for the Mgeni catchment upstream of Nagle dam

Statistics for U2H005 1985 - 1989	Daily simulation	Monthly totals of daily simulation
Total observed streamflow (mm)	482.62	379.02
Total simulated streamflow (mm)	585.39	413.27
Mean observed streamflow (mm)	0.34	10.24
Mean simulated streamflow (mm)	0.41	11.57
Correlation coefficient	0.48	0.47
Students' 't' value	20.55	3.16
Regression coefficient	0.51	0.23
Base constant for regression (mm)	0.24	8.80
Variance of observed values (mm)	0.74	151.60
Variance of simulated values (mm)	0.83	36.54
% difference in standard deviation	-6.03	50.91
Coefficient of determination	0.23	0.22
Coefficient of efficiency	0.98	0.94

11.2 FREQUENCY ANALYSIS OF STREAMFLOW AT SELECTED POINTS IN THE CATCHMENT

The value of simulating the hydrology of the Mgeni catchment is to be able to assess the probability of receiving certain water yields at points of interest in the catchment. Naturally the water flow into reservoirs is of interest and the water yield from the whole catchment is of interest. Streamflow was simulated for all the subcatchments upstream of Inanda dam over a 10 year period from 1980 to 1989. Streamflow volumes for dry years (10th percentile of non-exceedence, i.e. driest year in 10), wet years (90th percentile of non-exceedence, i.e. wettest year in 10) and years with median flows (50th percentile) are presented in Table 11.6 for inflows into the four major dams in the catchment, the Msunduzi tributary and the Mqeku tributary. Since Midmar dam and Albert Falls dam are "nested" upstream of Nagle dam, streamflow into Inanda is comprised of outflow from Nagle dam, the contribution from the Msunduzi and Mqeku tributaries and runoff from the subcatchments immediately adjacent to Inanda dam and between Nagle and Inanda dams.

Table 11.6 Simulated streamflow for selected points in the Mgeni catchment at 10th, 50th and 90th percentile levels of non-exceedence probability

Point of interest	Streamflow			
	($m^3 \times 10^6$)			(mm)
	10th %ile	50th %ile	90th %ile	50th %ile
Midmar dam inlet	16.7	132.5	239.6	154.9
Albert Falls dam inlet	90.7	160.1	407.4	102.6
Nagle dam inlet	118.5	283.4	455.0	112.5
Msunduzi tributary	115.9	234.8	320.7	266.4
Mqeku tributary	19.7	43.4	117.1	156.9
Inanda dam inlet	435.7	722.2	993.9	182.4

Median streamflow at each point of interest is of the order of 15% (ranging from 10 to 20%) of the catchment MAP except streamflow from the Msunduzi catchment which is approximately 30 % of the catchment MAP. It would appear that streamflow from the Msunduzi catchment is over-estimated although the fact that it contains large urban areas (Pietermaritzburg and Vulindlela) and little forestry may account for the high water yield. Runoff from urban areas in the Msunduzi catchment is investigated in greater detail through the use of scenarios of possible future development in Chapter 12.

CHAPTER 12

IMPACT OF POTENTIAL DEVELOPMENT SCENARIOS ON STREAMFLOW RESPONSES

The hydrological modelling system for the Mgeni catchment was developed as a tool to aid developers and planners in managing the water resources of the Mgeni catchment. Scenarios play an important part in planning because they can quantify the implications of possible future developments in an area. In the context of this project the effect of three scenarios of possible future developments within the Mgeni catchment are evaluated in terms of their impacts on the quantity of streamflow generated from selected portions of the catchment. Anticipated agricultural development is assessed first using a scenario that quantifies the impact of the construction of numerous farm dams on downstream runoff. Thereafter a scenario evaluates the impacts of possible future afforestation practices on streamflow. Finally a scenario featuring possible future increases in formal and informal urban settlements quantifies an impact of urbanization on streamflow in the Msunduzi tributary of the Mgeni catchment.

12.1 SCENARIO 1: IMPACTS ON STREAMFLOW OF FARM DAMS

The catchments upstream of Midmar dam (Figure 12.1) were selected for the assessment of the impact of farm dams because a major portion of the mean annual runoff (MAR) of the entire Mgeni catchment is generated within this area which, being subject to little industrial development, provides good quality water (Breen, Akhurst and Walmsley, 1985). However, the fact that in excess of four hundred farm dams have been construction in this area, stimulated the development of a scenario to assess the impacts of farm dams on water resources. In this scenario the impact of farm dams on water yield from the Midmar catchment is assessed by comparing runoff and streamflow simulated with the present reservoirs upstream of Midmar dam hypothetically removed and a simulation with the dams in place. A 16 year simulation period from 1971 to 1986 was used. For the simulation without reservoirs, areas under irrigation remained unchanged but irrigation was extracted from streamflow rather than from the reservoirs.

Figure 12.1 shows the system layout for the Midmar catchments used to simulate the streamflow into Midmar dam before the construction of the 459 reservoirs presently located upstream of Midmar dam as shown in Figure 6.1. The total surface area of the reservoirs upstream of Midmar dam is 874 ha and the cumulative capacity 23 million m^3, which is approximately 13% of the capacity of Midmar dam of 178 million m^3.

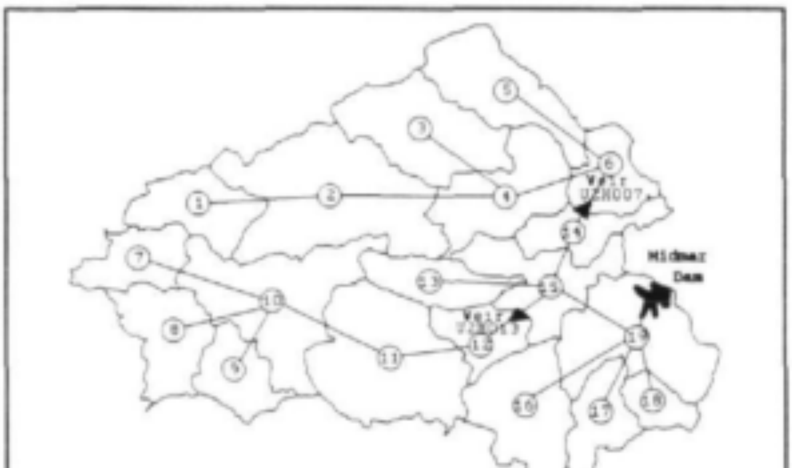


Figure 12.1 Midmar catchment discretisation and system layout (Tarboton and Schulze, 1991)

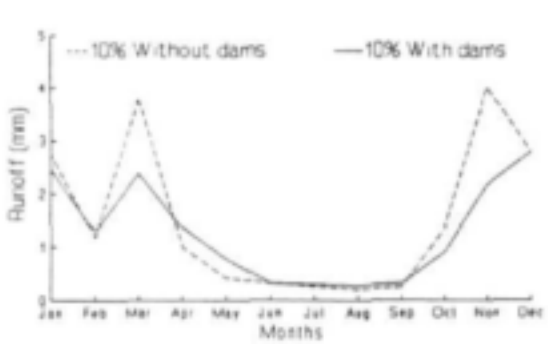
Table 12.1 illustrates the range of change in runoff from particular subcatchments and streamflow which includes contributions from upstream subcatchments, for the subcatchments upstream of Midmar subject to Scenario 1. The results indicate that the construction of small farm dams had the impact of reducing runoff from most subcatchments, the reduction being as high as 33%. In some cases, e.g. Subcatchment 7 which is at high altitude (1848 m.a.s.l.) and has relatively lower evaporation losses and no irrigation from the reservoirs within the subcatchment, runoff from the subcatchment was increased after reservoir construction possibly because the reservoirs' water surface is more effective in producing runoff from rainfall than vegetative surfaces.

Table 12.1 Median annual runoff and streamflow for Scenario 1 with and without farm dams

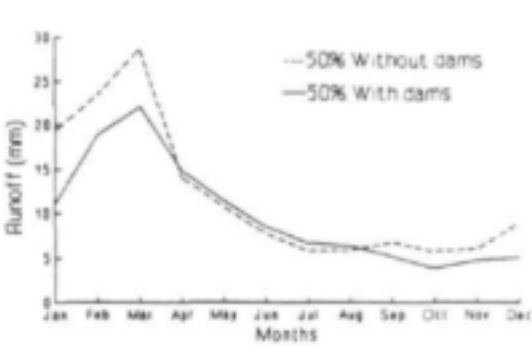
Subcatchment number	Without dams		With dams			
	Runoff (mm)	Streamflow (mm)	Runoff (mm)	(% change)	Streamflow (mm)	(% change)
2	130		98	-33		
6	134	140	125	- 7	119	-18
7	210		225	+ 7		
8	154	130	130	-24		
19	113	168	103	-10	158	- 6

Simulated streamflow from Subcatchments 1 to 6 was decreased by 18% from 140 to 119 mm after reservoirs were included. The net decrease in simulated median annual streamflow into Midmar dam from 168 to 158 mm implies that the present reservoirs upstream of Midmar dam have the effect of reducing median annual streamflow into the dam by 6%, i.e. the equivalent of $6x10^6m^3$.

The intra-annual variation in runoff from Subcatchment 8 under Scenario 1 is compared with that of the base simulation for dry years (10th percentile, i.e. driest year in 10) and years of median flow (50th percentile) in Figure 12.2. The range of runoff without reservoirs is greater in dry years, with more runoff in the wet months and less in the dry months than under Scenario 1 with reservoirs. For both the median year and in wet years (not shown) runoff with reservoirs is less than before their construction in the summer rainfall months from October through to March because the reservoirs intercept a portion of the runoff produced in the early part of the wet season. During the winter months with very little rainfall, runoff comprising predominantly seepage and controlled discharges, is more from Scenario 1 with reservoirs.



(a)



(b)

Figure 12.2 Intra-annual variation in runoff from Subcatchment 8 for base simulation and under Scenario 1 with and without farm dams in (a) dry years and (b) year of median runoff (after Tarboton and Schulze, 1991)

12.2 SCENARIO 2: IMPACTS ON STREAMFLOW OF DOUBLING OF AREA UNDER AFFORESTATION

For South Africa the Forestry Council in its Strategic Forestry Development Plan of 1989 (Directorate of Forestry, 1989) called for an increase in the area under forestry by some 38 000 ha p.a. from 1990 until the year 2010. This implies that there is likely to be a doubling of the present area under commercial afforestation over the next 20 years, much of it possibly in catchments such as the Mgeni with a MAP generally exceeding 850mm. In this scenario the impacts of increased afforestation upstream of Midmar dam are assessed by comparing water yield under present land cover with that when the area under forest upstream of Midmar dam is doubled. Simulation is again over the 16 year period from 1971 to 1986.

Figure 12.3 shows the present spatial distribution of forestry in the Mgeni catchment upstream of Midmar dam. Included are areas of pines, eucalypts, wattle, indigenous and mixed forest. Impacts of increased afforestation were assessed in Scenario 2 by assuming that subcatchments 1, 6, 8 and 12 were completely afforested to *Eucalyptus grandis* except for the wetlands and areas under reservoirs (Figure 12.4). This was equivalent to an increase in afforestation of 11 881 ha over and above the existing 11 845 ha of forestry within the Midmar catchment, or a doubling of area under afforestation.

Impacts of afforestation on runoff from Subcatchments 1, 6, 8 and 12 are illustrated in Table 12.2. Marked local reductions in runoff were simulated for the subcatchments in which the afforestation occurred, with the magnitude of runoff reduction being related to the MAP of the each subcatchment. An increase in percentage afforestation from 9 to 97% (i.e. entire catchment minus 3% dams) in the relatively wet Subcatchment 1 (MAP 1031 mm) resulted in a simulated 37% decrease in runoff while a similar increase in afforestation from 1 to 93% in the relatively dry (MAP 887 mm) Subcatchment 8 resulted in a simulated 72% decrease in runoff. Upstream of Subcatchments 6 and 12 the increased areas under afforestation were respectively 124% from 4845 to 10 833 ha and 169% from 3497 to 9391 ha and the streamflow reduction from these subcatchments was 12% in both cases. By doubling the area under afforestation in the Midmar catchment from 11 845 to 23 726 ha the median annual streamflow as simulated at the outlet of Subcatchment 19 into Midmar dam, was reduced by 10%, i.e. $9.2 \times 10^6 m^3$.

Table 12.2 Median annual runoff and streamflow for Scenario 2 with present land cover and doubling of area under afforestation

Subcatchment number	Present land cover		Doubling of area under afforestation			
	Runoff (mm)	Streamflow (mm)	Runoff (mm)	(% change)	Streamflow (mm)	(% change)
1	229		144	-37		
6	125	119	40	-68	105	-12
8	130		37	-72		
12	125	189	75	-50	164	-10
19	103	158			142	-10

In Figure 12.5 the seasonal variation in runoff from Subcatchment 8 under the afforestation Scenario 2 is compared with that of the simulation using present land cover for years with median (50th percentile) and high (90th percentile, i.e. wettest year in 10) flows. Subcatchment runoff is less under afforested conditions throughout the year for median, wet and dry (not shown) years. Runoff in the dry months of the year is close to zero even under wet conditions at the 90th percentile of non-exceedence (Figure 12.5 b) and the duration of the period with close to zero runoff is extended from 3 to 6 months for the a year of median runoff as illustrated in Figure 12.5(a).

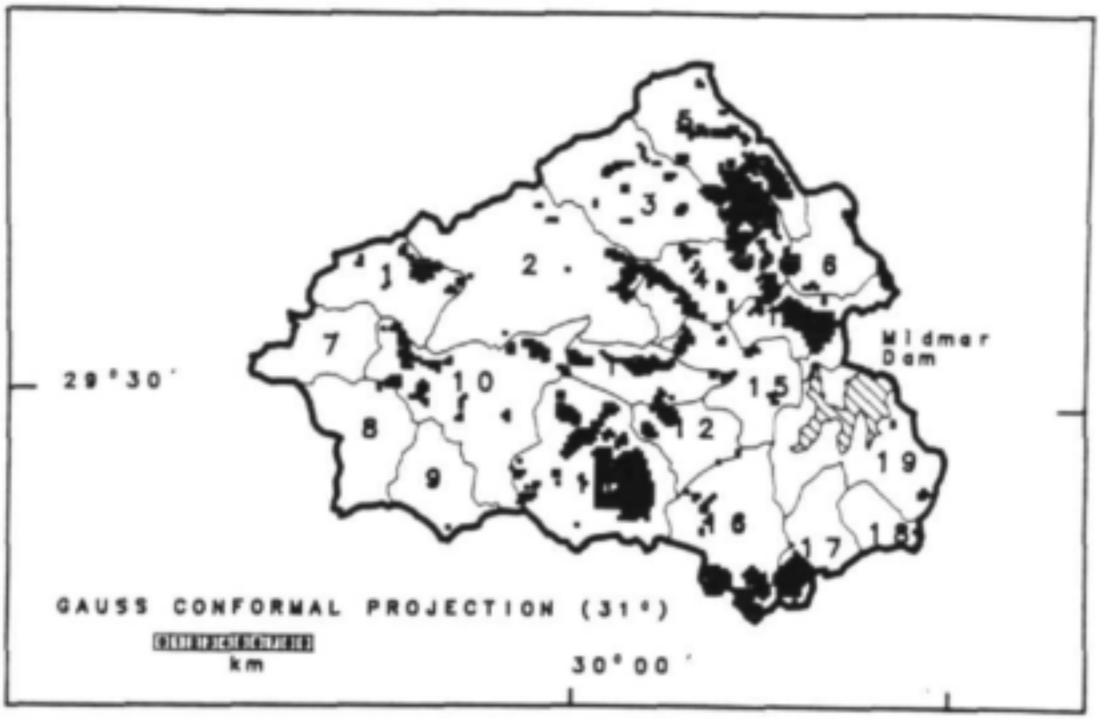


Figure 12.3 Spatial distribution of forestry upstream of Midmar dam under present land cover

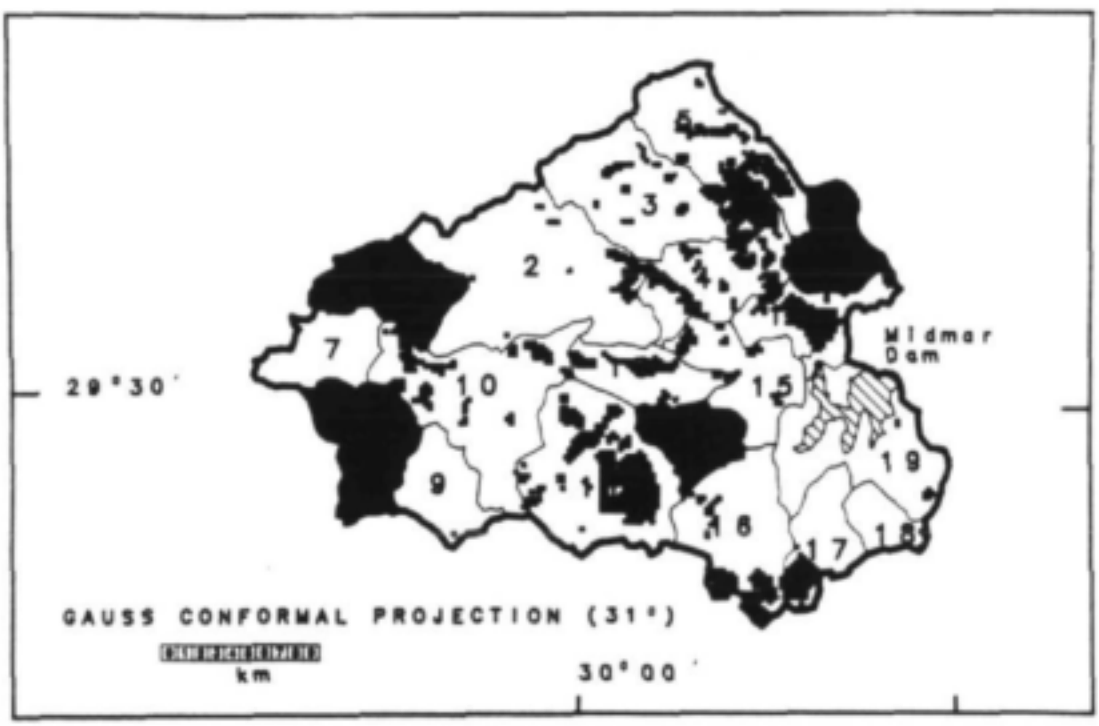
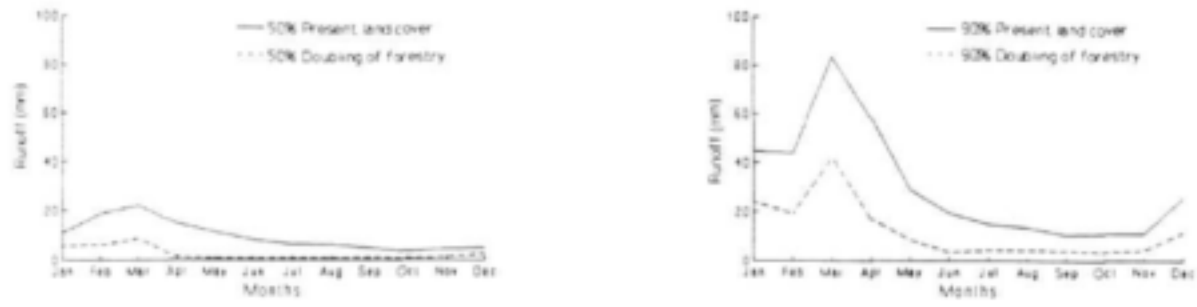


Figure 12.4 Spatial distribution of forestry for the scenario to double the area under forestry upstream of Midmar dam



(a) (b)

Figure 12.5 Intra-annual variation in runoff from Subcatchment 8 for simulation using present land cover and doubling of area under afforestation in (a) a year of median runoff and (b) the wettest year in 10 (after Tarboton and Schulze, 1991)

12.3 SCENARIO 3: IMPACTS ON STREAMFLOW OF URBANIZATION

It has been predicted in Water Plan 2025 (Horne Glasson Partners, 1989) that urbanization in the Pietermaritzburg-Durban area which falls within the Mgeni catchment, is expected to increase by 80% by the turn of the century, with more than 75% of the urban population in informal urban dwellings. Urbanization of this nature is likely to have a significant impact on water quality, but water quantity is also likely to be affected to a lesser degree. Water quality is, however, dependent on water quantity and as the focus of this project is on the development of a hydrological modelling system to simulate water quantity in the Mgeni catchment, it is appropriate to present a scenario in which the impact of likely future urbanization on water quantity is assessed. In Water Plan 2025 (Horne Glasson Partners, 1989) three scenarios of possible development in the Mgeni catchment, *viz*. "Status Quo", "Emergent Trends" and "High Road" are discussed in depth. The Status Quo and Emergent Trends represent the lower and upper limits of the probable development envelope and projections from these two scenarios were used to develop the urbanization scenarios for the Mgeni catchment that follow.

12.3.1 "Status Quo" conditions

In the Status Quo scenario an economic growth rate of 2.5% p.a. is projected with strict government control of the release of land for urban settlement. Decentralization away from the Durban Functional Region (DFR) and Pietermaritzburg Metropolitan Region (PMR) would be encouraged, unemployment would rise and the average monthly per capita income would decrease. Population figures for 1985 and 2025 presented in Table 12.3 indicate a 1.6 fold increase for the urban population in formal settlements and a five fold increase for the urban population in informal settlements over the 40 year period.

Table 12.3 Projected population under a "Status Quo" scenario (source Horne Glasson Partners, 1989)

Projected population (million)	1985	2025
Rural	0.40	0.41
Informal urban	1.06	5.30
Formal urban	2.18	3.49
Total	3.64	9.20

Using the projected population figures and a projection of the increase in industrial and commercial land (Horne Glasson Partners, 1989) present areas of formal and informal settlements and the CBD/commercial area were increased, in subcatchments 62 to 82 in the Msunduzi tributary (Figure 12.6), which includes Vulindlela and Pietermaritzburg, to obtain an urbanization scenario under Status Quo conditions. Table 12.4 shows the total area of each urban land cover class found in the Msunduzi catchment under present, Status shows the total area of each urban land cover class found in the Msunduzi catchment under present, Status Quo and Emergent Trends conditions. The increase in urban land cover under Status Quo conditions for each subcatchment from 62 to 82 are shown in Table 12.5. Increases in urban land cover were accompanied by corresponding decreases in the area under veld.

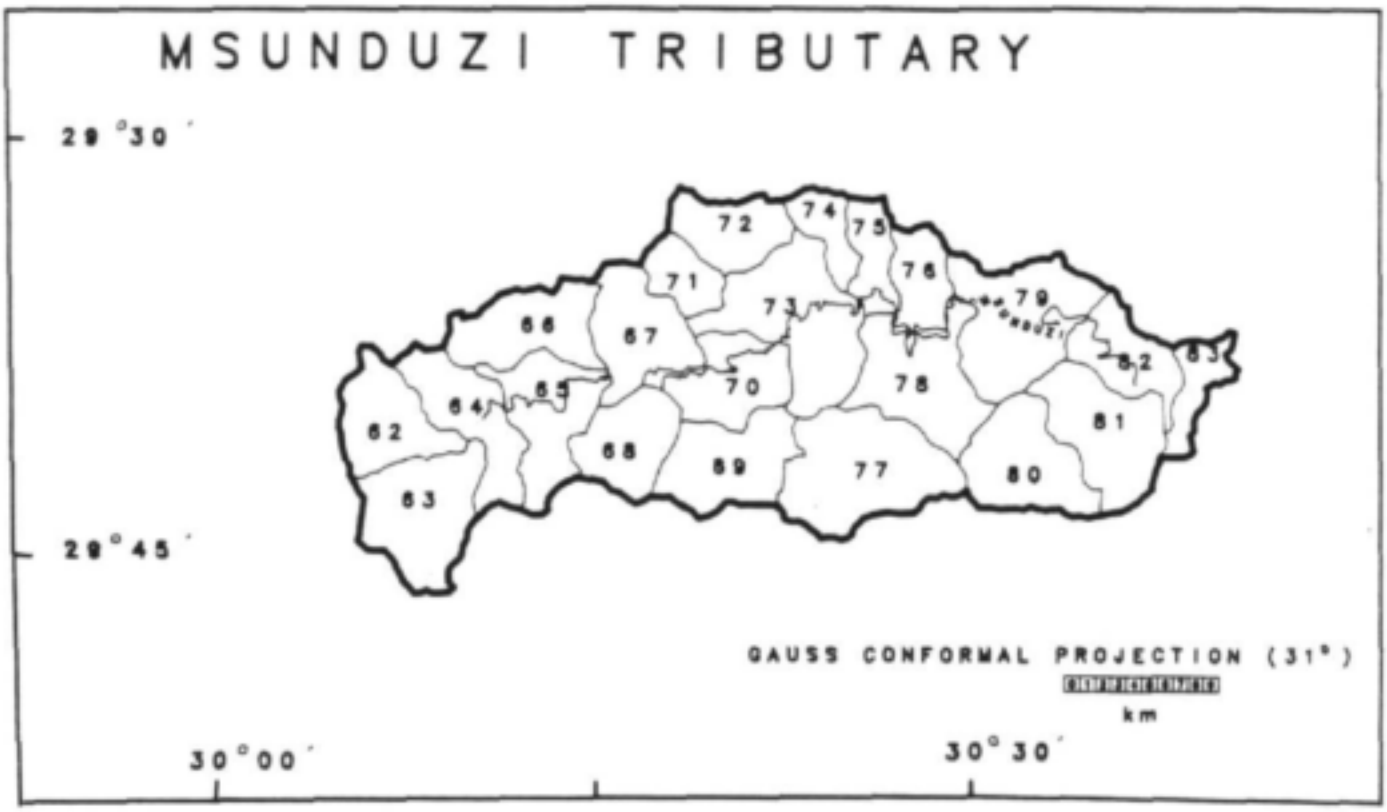


Figure 12.6 Msunduzi tributary catchment discretised into subcatchments

Table 12.4 Area of each urban land cover class found in the Msunduzi catchment under present land cover, "Status Quo" and "Emergent Trends" conditions

Scenario	Informal residential (km²)	Formal residential low density (km²)	Formal residential medium density (km²)	Formal residential high density (km²)	CBD commercial (km²)
Original land cover	29.0	27.0	11.4	20.6	26.3
Status Quo	84.5	42.7	17.6	32.9	34.2
Emergent Trends	133.9	48.1	20.2	37.3	34.2

Table 12.5 Increased urbanization for each subcatchment in the Msunduzi catchment for urbanization scenario under "Status Quo" conditions

Subcatchment number	Informal residential (% increase)	Formal residential low density (% increase)	Formal residential medium density (% increase)	Formal residential high density (% increase)	CBD commercial (% increase)
62	10.0	1.4			
63					0.1
64	1.0			1.4	
65	0.9				
66	35.2				
67	19.0		1.7	0.4	0.1
68	4.3				0.1
69	2.7				0.1
70	9.1	4.9		6.2	8.0
71			6.0	1.7	
72		9.2	1.3	1.8	
77		15.8	6.3	6.8	
74				22.0	4.5
75				0.6	0.1
76					
77					0.1
78				0.3	0.1
79	1.6				
80	1.6				0.3
81	14.7				
82	33.4				
Total Increase	191.4	58.1	54.3	59.7	30.0

12.3.2 "Emergent Trends" conditions

The Emergent Trends scenario is based on the same growth rate assumptions as those for Status Quo conditions, but owing to greater demand for land to house the poor there is likely to be a release of land to areas outside those which up to 1990 were defined as "group areas" and an expected densification within the previously defined "group areas". Population projections for the Emergent Trends scenario indicated in Table 12.6 represent an 10.3 fold increase in the informal urban population and a 1.8 fold increase in the formal urban population. Increased urban land cover under the Emergent Trend scenario calculated in the same way as those for the Status Quo scenario are presented in Table 12.7

Table 12.6 Projected population under an "Emergent Trends" scenario (source Horne Glasson Partners, 1989)

Projected population (million)	1985	2025
Rural	0.40	0.44
Informal urban	1.06	10.92
Formal urban	2.18	3.92
Total	3.64	15.28

Table 12.7 Increased urbanization for each subcatchment in the Msunduzi catchment for urbanization scenario under "Emergent Trends" conditions

Subcatch-ment number	Informal residential (% increase)	Formal residential low density (% increase)	Formal residential medium density (% increase)	Formal residential high density (% increase)	CBD commercial (% increase)
62	23.4	1.9			
63					0.1
64	2.1			1.7	
65	2.2				
66	50.2				
67	26.0		2.2	0.6	10.1
68	10.0				0.1
69	6.3				0.1
70	21.5	6.5		8.4	8.0
71			8.0	2.3	
72		12.3	1.6	2.5	
73		21.0	8.3	9.0	
74				29.7	4.5
75				0.7	0.1
76					
77					0.1
78				0.4	0.1
79	3.7				
80	3.6				0.3
81	34.4				
82	71.4				
Total	361.7	78.1	77.2	81.1	30.0

12.3.3 Impacts under "Status Quo" and "Emergent Trends" conditions

Simulated runoff for the 10 year period from 1980 to 1989 for present land cover, Status Quo and Emergent Trends conditions was compared for selected subcatchments in the Msunduzi catchment to assess possible impacts on streamflow of urbanization. Subcatchments 66 and 82 were selected because of their large increases in informal residential area and Subcatchment 74 because of its large increase in high density formal residential area under both Status Quo and Emergent Trends conditions.

Runoff from the selected subcatchments under present and Status Quo scenario conditions is compared in Table 12.8 at the 10th, 50th and 90th percentiles of non-exceedence. For both Subcatchment 66 and 82 runoff is increased due to the increase in area under informal settlements, the increase being more significant in dry years (10th percentile, i.e. the driest year in 10) and wet years (90th percentile, i.e. wettest year in 10) than in years of median flow (50th percentile). The increase in runoff from increased urbanization in the form of formal settlement under Status Quo conditions is negligible (0 to 2%), probably owing to the good vegetation cover associated with formal residential areas.

Under Emergent Trends conditions runoff from the subcatchments with increased areas under informal settlements is significantly more than under present conditions, especially in dry years (10th percentile) where runoff is increased by 92 and 70% for Subcatchments 66 and 82 respectively (Table 12.9). Runoff from formal urban settlements is also increased under the Emergent Trends scenario with the increase being greater in years of median flow than in both dry and wet years.

Table 12.8 Comparison of runoff from selected catchments in the Msunduzi catchment under present and "Status Quo" conditions

Subcatch-ment number	10 th percentile			50 th percentile			90 th percentile		
	Runoff (mm)		% increase	Runoff (mm)		% increase	Runoff (mm)		% increase
	Present conditions	Status Quo		Present conditions	Status Quo		Present conditions	Status Quo	
66	81	95	17	312	318	2	526	556	6
74	190	190	0	298	304	2	635	641	1
82	43	48	12	88	95	8	200	227	4

Table 12.9 Comparison of runoff from selected catchments in the Msunduzi catchment under present and "Emergent Trends" conditions

Subcatch-ment number	10 th percentile			50 th percentile			90 th percentile		
	Runoff (mm)		% inc-rease	Runoff (mm)		% inc-rease	Runoff (mm)		% inc-rease
	Present conditions	Emergent Trends		Present conditions	Emergent Trends		Present conditions	Emergent Trends	
66	81	156	92	312	388	24	526	639	21
74	190	194	2	298	332	11	635	683	8
82	43	73	70	88	132	50	200	284	42

Urbanization is likely to have impacts other than simply an increase in streamflow volumes. Figure 12.7 illustrates probable intra-annual runoff from Subcatchment 66 for years of median flows under present, Status Quo and Emergent Trends conditions. With increased urbanization, in the form of informal settlements, runoff in the high flow months (October to April) is likely to be increased and runoff in the low flow months (May to September) decreased. This trend was more pronounced in dry years and less pronounced in wet years (not illustrated). Intra-annual trends for Subcatchment 74, with increases predominantly in formal urbanization, were similar to those simulated for present conditions.

Figure 12.7 Intra-annual variation in median runoff from Subcatchment 66 under present conditions and subject to increased urbanization under "Status Quo" and "Emergent Trends" conditions

12.4 VALUE OF SCENARIOS

The problem of rapid and intensified agricultural and urban development in the Mgeni catchment was addressed by simulating quantitatively and objectively the impacts on water yield of potential development scenarios on a critical portions of the catchment. This hydrological simulation process provides water resources managers with information needed to make informed proactive planning decisions.

Agricultural development assessed in terms of more local impacts on runoff of present reservoirs within each of the 19 subcatchments, illustrated the variation in impact of reservoirs depending on subcatchment altitude, rainfall, land cover and reservoir demands. Simulated runoff from catchments without reservoirs was shown to be more variable than that from the same catchments with reservoirs. Present reservoirs upstream of Midmar dam were shown to have the overall impact of reducing median annual streamflows into the dam by 6%, i.e. $6x10^6m^3$.

ACRU was able to quantify the marked local reduction in runoff from subcatchments affected under a potential afforestation scenario. The degree of runoff reduction appeared to be related to the relative MAP of the areas afforested (Tarboton and Schulze, 1991). Runoff from afforested subcatchments was low even during wet years and the duration of the period of low runoff was extended into the summer rainfall months. The regional impact of a doubling of afforestation in the Midmar catchment was a 10%, i.e. a $9.2x10^6m^3$, reduction in streamflow into Midmar dam.

The Status Quo and Emergent Trends urban scenarios developed in 1989 may already be outdated in light of political developments after that date, and a "High Road" scenario (Sunter, 1987) with increased international political acceptability and an increase in the economic growth rate up to 5% may be a more likely scenario. The Status Quo and Emergent trends scenarios were, however, presented because they represented the upper and lower limits in the envelope of likely population increases. Simulated runoff increased significantly in selected subcatchments subject to increased informal settlements for both Status Quo and Emergent Trends conditions. The increase in simulated runoff from a subcatchment with increased formal settlement were less marked. Intra-annual trends in runoff from subcatchments with predominantly informal settlement development were impacted under the urbanization scenarios. Although the modelling system was able to simulate impacts on streamflow of urbanization, simulation of the impact on water quality related to these streamflows will be of greater value to water resources managers and is an area of possible future research.

CHAPTER 13

CONCLUSIONS AND RECOMMENDATIONS

The ***main aim*** of this project was to develop a distributed hydrological modelling system for the Mgeni catchment to aid in the integrated planning and development of the catchment by providing hydrological information to those responsible for management of the catchment's water resources.

Specific objectives were to:

* collect and process input data and information for the modelling system
* establish a GIS to facilitate management and manipulation of spatial information
* develop the hydrological modelling system to simulate catchment hydrology successfully in terms of water quantity
* verify the modelling system simulations against observed data where available
* transfer modelling techniques to ungauged catchments and
* simulate the impacts of likely development scenarios

The ***approach adopted*** was to select the *ACRU* modelling system as the basis on which the hydrological modelling system for the Mgeni catchment was developed. This "system" was conceptualized as including catchment data and information, processes developed to "translate" data and information into hydrological input variables, support programs and new routines, the *ACRU* model as the hydrological "system driver" and the Mgeni GIS which links the spatial information in a unified system and interfaces with the *ACRU* modelling system for hydrological simulation.

Achievements of the project can be summarized as follows:

* data collection and processing;
    - development of rainfall estimation techniques
    - estimation of A-pan equivalent evaporation from temperature surrogates
    - classification of catchment into hydrological land cover classes
    - digitization of SIRI Land Type maps
    - collection of detailed reservoir information for catchment
    - collection of water abstraction, transfer and effluent discharge data
    - collection of streamflow data for catchment

* establishment of Mgeni GIS incorporating coverages of;
    - subcatchment delimitation
    - system layout
    - land cover
    - Land Type
    - reservoir location and properties
    - point measurements of rainfall, evaporation, temperature, water quantity and water quality
    - annual, monthly and daily rainfall surfaces
    - annual and monthly evaporation surfaces

* development of the hydrological modelling system including;
    - improvement and automation of soils Decision Support System (DSS)
    - improvement of vegetation and land use DSS to include urban land cover

- development of routines to accommodate simulation with multiple reservoirs within subcatchments
- development and evaluation of techniques to estimate reservoir capacities from shape and other properties
- development of streamflow routing routines

* model verification for selected catchments including
    - simulation over 30 years using temporally changing land cover for Lions river catchment
    - Quaternary catchment U231
    - Quaternary catchment U232
    - Quaternary catchment U233
    - Quaternary catchment U237 above Henley dam
    - Mgeni catchment upstream of Nagle dam

* transfer of modelling techniques to ungauged catchments or catchments with poor streamflow data including the remainder of the catchments within the Mgeni catchment

* simulation of likely future development scenarios including
    - impacts on streamflow of construction of farm dams
    - impacts on streamflow of doubling of the area under afforestation
    - impacts on streamflow of increased urbanization including expansion of informal settlements under so called "Status Quo" and "Emergent Trends" conditions.

It is ***recommended*** that ***future research*** concentrate on the following aspects for further development of the hydrological modelling system in the second phase of this project:

* incorporation of new rainfall estimation techniques including
    - spatial rainfall estimation using radar
    - "real time" rainfall estimation

* finer disaggregation of subcatchments based on
    - resolution of accurate rainfall estimation
    - overlaying of climatic, land cover and soils coverages using the GIS

* incorporation of water quality routines to simulate the impact of
    - point source pollution
    - diffuse pollution

* automation and improvement of GIS / *ACRU* modelling system interfacing by
    - minimising the human element at the interface
    - incorporating stand alone processes into either the GIS or *ACRU* modelling system
    - utilizing the GIS for display of simulation results
    - development of the GIS / *ACRU* to enable interactive scenario assessment.

CHAPTER 14

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CHAPTER 15

APPENDICES

EXPLANATORY NOTE

Appendices A through G contain examples and extracts of the data and information collected for the Mgeni catchment, from which the inputs for the *ACRU* hydrological modelling system were extracted. This information is included to supplement the information presented in the body of the document and for reference to the format of the information which is available on computer compatible disk on request from the Department of Agricultural Engineering at the University of Natal. The *ACRU* menu used in simulating the hydrology of the Mgeni catchment is also available on disk.

The figures included in the body of this report that are coverages of the Mgeni catchment are also available on request from the Department of Agricultural Engineering at the University of Natal in the form of overlays at a scale of 1:250 000. Similar overlays of median monthly A-pan equivalent evaporation, and monthly maximum and minimum temperatures (not shown in the report) are also available on request.

LIST OF APPENDICES

A.1 RAINFALL STATION INFORMATION - EXAMPLES

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STATION   LAT     LONG    ALT. RECORD  COMPLETE      LOCATION/CONTACT          MAP
 I.D.                     (M)   SPAN  DATA YEARS
================================================================================
0238442 W 2952.3 2945.3 1559 1957 1990  22          SARNIA (BOS)              934.8
 64  LINES OF DATA                0238442 W        COMPLETE DATA YEARS: 63
         STATS ON GOOD  DATA
 MEAN 162.4 142.8 135.2  58.7  19.7  14.8  14.5  26.7  53.6  81.3 123.3 134.5 938.2
 MEDN 159.0 137.3 136.2  57.6  15.7   7.6   8.0  17.4  39.8  73.8 128.1 127.8 941.7
 STD   66.9  60.4  69.8  28.9  19.5  23.2  21.1  26.6  68.3  43.8  50.1  56.2 200.9
 C.V.  41.2  42.3  51.6  49.2  98.9 156.3 145.4  99.7 127.4  53.9  40.7  41.8  21.4
 SKEW   0.5   0.8   0.5   0.1   1.5   2.7   2.5   1.4   4.1   0.6   0.5  -0.3  -0.7
 YRS     34    34    35    34    33    34    34    34    33    34    33    34    35
          PERIOD OF RECORD        1957 MONTH  1 TO  1990 MONTH 12
      STATS ON ALL DATA
 MEAN 159.0 141.9 135.0  56.2  26.5  13.5  15.8  23.9  47.0  77.4 130.2 137.4 963.7
 MEDN 149.2 130.0 128.0  56.1  15.8   6.1   8.2  14.4  40.1  67.6 129.8 133.4 946.4
 STD   63.4  56.1  60.2  31.6  36.6  19.6  20.8  25.4  50.5  35.5  46.1  52.7 171.0
 C.V.  39.9  39.5  44.6  56.2 138.3 144.8 131.8 106.5 107.4  45.8  35.4  38.4  17.7
 SKEW   0.6   1.0   0.7   1.2   4.1   2.8   2.1   1.4   5.5   1.0   0.3   0.1  -0.3
 YRS     64    64    64    64    64    64    64    64    64    64    64    64    64
          PERIOD OF RECORD        1927 MONTH  1 TO  1990 MONTH 12

STATION   LAT     LONG    ALT. RECORD  COMPLETE      LOCATION/CONTACT          MAP
 I.D.                     (M)   SPAN  DATA YEARS
================================================================================
0238468 W 2948.7 2946.2 1501 1920 1990  56          BULWER (TNK)              955.4
 69  LINES OF DATA                0238468 W        COMPLETE DATA YEARS: 70
         STATS ON GOOD  DATA
 MEAN 152.6 145.5 126.4  57.2  23.3  15.0  12.7  25.5  46.5  82.5 107.6 135.3 899.8
 MEDN 161.0 145.4 122.1  48.0  13.3   2.9   6.8  15.3  37.8  78.7 111.1 145.5 930.1
 STD   94.5  73.3  78.8  38.9  27.3  24.1  17.9  29.3  54.0  49.1  65.0  78.0 285.7
 C.V.  61.9  50.3  62.3  68.1 117.1 160.9 141.0 114.7 116.1  59.6  60.4  57.7  31.7
 SKEW  -0.2  -0.1   0.1   1.0   2.0   2.1   2.0   1.4   4.4   0.3   0.0  -0.2  -0.5
 YRS     67    69    68    69    67    68    68    68    67    68    67    67    70
          PERIOD OF RECORD        1920 MONTH  1 TO  1990 MONTH 12
      STATS ON ALL DATA
 MEAN 152.8 145.3 125.1  57.6  23.3  15.0  12.7  25.5  46.5  82.5 107.6 135.3 904.9
 MEDN 158.8 145.4 119.3  49.5  12.8   2.6   6.8  15.3  37.8  78.7 109.9 145.5 930.1
 STD   95.2  73.8  78.6  39.0  27.3  24.1  17.9  29.3  54.0  49.1  65.0  78.0 284.6
 C.V.  62.4  50.8  62.8  67.8 117.1 160.9 141.0 114.7 116.1  59.6  60.4  57.7  31.4
 SKEW  -0.2  -0.1   0.2   1.0   2.0   2.1   2.0   1.4   4.4   0.3   0.0  -0.2  -0.5
 YRS     66    68    67    68    67    68    68    68    67    68    67    67    69
          PERIOD OF RECORD        1920 MONTH  1 TO  1990 MONTH 12
```

A.2 SUBCATCHMENT MEDIAN MONTHLY AND MEAN ANNUAL PRECIPITATION - EXAMPLES

SUB-CATCHMENT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MAP (all in mm)
1	155.2	127.2	117.3	46.2	15.5	3.2	5.0	15.1	33.9	69.6	102.5	130.6	902.4
2	157.2	126.5	121.8	47.7	14.4	2.5	5.1	17.1	34.2	70.3	103.6	126.3	904.2
3	170.4	136.1	133.6	53.4	15.1	2.9	6.9	20.0	38.9	76.7	116.0	139.2	996.1
4	174.2	141.7	135.2	53.4	17.7	3.7	7.9	19.8	42.4	81.8	121.4	149.6	1038.4
5	173.2	137.2	136.2	56.0	18.6	4.3	8.5	18.8	43.6	85.6	123.7	161.0	1060.6
6	153.4	124.6	124.1	52.1	17.6	4.5	8.4	17.1	40.9	79.7	116.6	152.5	981.6
7	162.4	135.6	132.3	55.3	17.5	4.3	8.6	16.5	42.4	85.0	123.3	162.6	1039.2
8	145.8	127.8	121.2	51.8	16.3	3.9	9.1	15.4	39.8	79.1	118.5	153.1	970.5
9	181.6	149.2	136.6	53.8	18.7	4.6	6.9	18.2	42.0	83.8	122.9	156.6	1071.6
10	155.2	129.6	121.8	49.3	16.1	4.6	7.0	16.0	38.9	77.7	113.2	144.2	958.1
11	152.0	133.1	118.5	49.0	16.6	5.4	7.3	15.8	39.8	80.0	116.3	146.1	957.6
12	157.2	144.1	126.7	55.3	16.5	4.6	7.8	17.5	44.9	86.4	128.8	164.4	1044.7
13	154.5	143.3	120.7	52.4	15.5	4.7	6.9	15.7	40.1	82.0	122.3	153.2	996.4
14	147.5	132.5	111.7	53.5	15.8	5.3	7.6	16.8	47.5	83.8	121.8	151.5	989.8
15	146.4	129.1	115.5	53.5	16.1	4.8	8.1	17.2	43.4	82.4	120.4	152.0	979.5
16	134.4	115.7	105.9	49.4	15.6	4.8	7.2	16.5	39.2	75.8	110.8	137.3	902.3
17	134.3	118.9	105.0	46.9	13.3	3.3	4.9	12.2	33.4	71.5	105.0	131.1	863.3
18	144.9	126.5	113.9	52.0	15.3	3.6	5.9	12.8	38.2	79.4	113.6	142.4	950.3
19	142.1	126.3	111.2	50.3	14.8	3.7	6.2	13.3	37.8	77.2	111.9	139.8	928.9
20	168.6	149.8	132.1	60.6	19.0	5.0	9.8	16.9	48.9	93.7	131.7	164.5	1123.3
21	151.9	136.8	117.3	53.9	16.0	4.6	7.4	15.6	43.6	83.7	121.5	151.4	1001.4
22	176.4	163.9	143.2	66.3	18.9	6.3	8.9	19.3	53.5	102.3	137.3	177.8	1209.3
23	146.7	127.6	109.8	54.1	15.9	5.2	7.6	17.1	46.8	85.7	117.5	145.7	981.9
24	156.3	133.0	114.6	58.1	17.1	4.9	7.1	19.2	49.3	94.4	127.5	156.5	1051.0
25	145.4	121.0	119.2	51.3	18.6	5.2	7.9	18.9	41.9	77.5	114.1	142.9	958.2
26	132.2	112.0	109.9	46.5	17.2	4.8	6.7	17.1	37.5	71.6	108.8	129.1	891.0
27	135.2	115.8	111.2	47.5	17.5	4.8	6.7	17.2	38.3	75.1	113.2	132.0	921.3

A.3 DRIVER STATION SELECTION FOR EACH SUBCATCHMENT

SUB-CATCHMENT	STATION1	STATION2	STATION3	STATION4	STATION5	STATION6
U23110	0238543A	0238662A	0268441W	0238636W	0268806A	
U23120	0238662A	0238543A	0238636W			
U23130	0238662A	0238636W	0238543A			
U23140	0238662A	0268806A	0239002W	0238543A	0238636W	
U23150	0239002W	0239097A	0268806A			
U23160	0239002W	0269147A	0239184A			
U23170	0239002W	0269147A	0239184A			
U23180	0269147A	0239184A	0269388A			
U23210	0268683A	0268806A	0268441W	0268862W	0238543A	
U23220	0268806A	0268862W	0268891W	0268683A	0269147A	0269114A
U23230	0269114A	0269111A	0268862W	0268891W	0269145A	0268806A
U23240	0269147A	0269145A	0269114A	0269295A		
U23250	0269111A	0269114A	0268891W	0269147A		
U23260	0269295A	0269147A	0269145A	0269111A		
U23270	0269147A	0269295A	0269145A			
U23271	0269147A	0269295A	0269145A			
U23310	0268891W	0269111A	0269043A			
U23320	0269493A	0269111A	0269043A			
U23330	0269111A	0269493A	0269043A			
U23340	0269295A	0269532A	0269647W	0269493A	0269111A	0269477A
U23350	0269111A	0269295A	0268891W	0269532A		
U23360	0269647W	0269493A	0269532A	0269111A		
U23370	0269532A	0269295A	0269477A	0269388A		
U23380	0269477A	0269532A	0269388A	0269626A	0269597W	
U23411	0239184A	0239097A				
U23412	0239184A	0239097A	0239483A			
U23413	0239184A	0239421W	0239483A	0239518W		
U23414	0239184A	0239421W	0239483A			
U23420	0269388A	0239421W	0269295A			
U23431	0269388A	0269477A	0239421W	0269295A		
U23432	0239421W	0269388A	0239482W	0239482A		
U23433	0239421W	0269388A	0239482W	0239482A		
U23434	0239483A	0239482W	0239482A	0239421W		
U23435	0239483A	0239482W	0239482A	0239421W		
U23440	0239483A	0239482W	0239482A	0239421W		
U23450	0239482W	0239482A	0269477A			
U23461	0269744S	0269532A	0269712W	0269626A		
U23462	0239482W	0239482A	0269597W	0239633A		
U23463	0269626A	0269597W	0269774A	0269744S	0269775W	
U23470	0269775W	0239812A	0239633A			
U23511	0269712W	0269744S	0269774A			
U23512	0269647W	0269712W	0269744S	0269774A		
U23513	0269774A	0269744S	0270023A	0270021W	0269712W	
U23521	0269647W	0270021W	0269712W			
U23522	0270164S	0270021W	0269647W	0270282W		
U23523	0270021W	0270023A	0270164S			
U23524	0270023A	0270021W	0270086A	0270260A		
U23531	0270260A	0270321A	0270021W	0270023A		
U23532	0270260A	0270205A	0270321A	0270321S		
U23533	0270086A	0270205A	0270023A	0270021W		
U23540	0270086A	0270023A	0270057A			
U23610	0270057A	0270086A	0239812A	0240031W		
U23621	0270057A	0270119W	0270086A	0270119S		
U23622	0240033A	0239812A	0240031W	0239784W		
U23623	0240031W	0240033A	0239812A			
U23630	0270321A	0270321S	0270205A			
U23640	0270205A	0270178S	0270119S	0270119W		
U23650	0270329S	0270178S	0270119W			
U23661	0270119W	0270178S	0240033A	0240031W		
U23662	0240185W	0240033A				
U23670	0240185W	0240284W				
U23711	0239097A	0239133A	0239133W			
U23712	0239196A	0239133A	0239225A	0239133W		
U23713	0239097A	0239133A	0239133W	0239184A		
U23714	0239518W	0239225A	0239577W			
U23715	0239518W	0239483A	0239184A	0239097A		
U23721	0239518W	0239577W				
U23722	0239518W	0239585W				
U23723	0239585A	0239585W	0239700A			
U23724	0239700A	0239518W				
U23725	0239574W	0239577W	0239518W	0239604W		

A.3 CONTINUED

SUB-CATCHMENT	STATION1	STATION2	STATION3	STATION4	STATION5	STATION6
U23726	0239574W	0239604W	0239633A			
U23727	0239577W	0239700A				
U23731	0239633A	0239604W	0239784W			
U23732	0239784W	0239812A	0239633A	0239604W	0240033A	
U23733	0239784W	0240033A	0239812A			
U23734	0239700A	0239705A	0239705S	0239676S	0239855A	0240014W
U23735	0239700A	0240014W	0240073W	0239784W		
U23736	0240185W	0240033A	0239784W			
U23737	0240073W	0240014W	0239855A			
U23738	0240073W	0240014W	0240284W			
U23739	0240185W	0240284W				
U23740	0240284W	0240404W				
U23810	0270321A	0270321S	0270472A	0270472S		
U23821	0270472S	0270472A	0270321A	0270321S		
U23822	0270329S	0270505S	0240753W			
U23831	0270329S	0270205A	0270321A	0270321S		
U23832	0270329S	0270505S	0270178S	0270472S		
U23840	0240753W	0240185W				
U23851	0270329S	0270505S	0270321A	0270321S		
U23852	0270329S	0270505S	0270321A	0270321S		
U23861	0270329S	0270178S	0270205A			
U23862	0240185W	0240753W	0270329S			
U23870	0240185W	0240753W	0270329S			
U23880	0240185W	0240757S	0240753W			
U23911	0240284W	0240073W	0240404W			
U23912	0240284W	0240404W	0240564W			
U23913	0240185W	0240404W	0240284W			
U23921	0240185W	0240753W	0240757S			
U23922	0240185W	0240757S				
U23930	0240404W	0240564W				
U23941	0240757S	0240753W				
U23942	0240404W	0240586W	0240757S			
U23943	0240586W	0240587A				
U23951	0240757S	0240753W				
U23952	0240757S	0241042S				

NB : Subcatchment numbering system as in ACRU menus

B A-PAN EVAPORATION STATION DATA AND INFORMATION

STATION-ID		LAT (MIN)	LONG (MIN)	ALT (M)	STATION NAME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	START	END	YRS
29063042	A	1746	1842	980	ELSTOB P,SUNNY	194.6	166.4	165.0	136.2	107.3	94.8	108.5	141.9	140.3	195.3	180.0	190.7	1979	1983	4
29123109	A	1752	1869	660	MAYFIELD, STANG	160.0	141.4	138.0	123.0	103.7	91.8	102.8	120.1	133.3	149.7	137.2	170.1	1980	1986	5
29123114	S	1752	1874	359		187.1	162.0	163.8	129.8	121.6	111.9	122.7	143.7	146.3	174.3	177.9	191.6	1967	1986	18
29133002	A	1753	1802	1371	WESTON COLLEGE,	163.5	149.6	145.7	116.6	95.7	84.0	94.8	120.1	129.0	152.4	167.2	175.6	1975	1982	7
29133017	A	1753	1817	1420	NETENI, RIETVLE	172.9	144.9	143.3	117.0	100.5	84.6	94.3	124.0	145.2	168.7	132.8	172.9	1982	1986	4
29143036	S	1754	1836	1118		182.9	150.3	161.2	134.0	127.7	116.5	131.1	163.0	162.5	178.5	164.5	195.3	1980	1986	6
29143037	W	1754	1837	1066	0270194	170.1	148.8	149.1	121.1	117.6	104.8	120.9	148.6	157.5	177.2	164.2	183.6	1973	1987	15
29183107	S	1758	1867	151		195.3	171.7	169.5	130.3	111.8	93.0	105.3	129.1	144.2	173.3	173.3	200.8	1970	1987	16
29202943	A	1760	1783	1539	MESHLYNN,KAMBER	165.4	139.1	133.3	120.0	101.3	86.0	96.1	126.1	131.0	136.4	156.0	170.5	1979	1982	3
29213041	A	1761	1841	1023		167.4	147.4	145.7	117.6	102.6	94.1	107.3	130.0	140.8	163.6	160.5	175.5	1971	1982	11
29243025	S	1764	1825	710		201.5	157.4	150.1	130.8	117.8	96.6	119.1	159.4	174.0	168.2	168.6	197.8	1982	1986	4
29253005	A	1765	1805	1110	DUNLOP R,CAVERS	177.8	160.3	155.0	123.0	93.8	87.0	101.6	127.1	129.0	158.1	178.0	169.5	1979	1982	3
29273111	S	1767	1871	148		179.2	157.2	145.5	112.6	89.7	71.4	79.4	99.9	123.0	154.8	161.6	181.9	1972	1986	15
29293034	S	1769	1834	960		177.0	154.4	148.2	122.0	108.5	99.5	112.5	136.0	153.0	171.2	166.1	188.7	1972	1985	14
29322953	A	1772	1793	1699	IVANHOE, IMPEND	158.8	137.2	134.6	110.4	94.9	79.8	86.2	119.7	134.4	135.8	136.0	155.6	1981	1986	5
29323017	A	1772	1817	1067	CEDARA AGR RES	159.0	137.7	138.2	104.7	93.7	81.7	94.1	123.0	137.4	150.7	144.8	166.5	1960	1982	23
29343108	S	1774	1868	71		180.0	160.9	160.8	121.0	98.6	77.4	87.3	104.8	122.6	153.1	157.8	181.3	1966	1986	18
29373004	A	1777	1804	1540	ELANDSHOEK, BOS	175.7	144.2	136.4	112.2	102.3	80.4	96.1	115.5	158.3	146.5	139.5	177.5	1982	1986	3
29403024	A	1780	1824	775	UKULINGA AGR RE	155.0	145.1	148.8	127.8	122.2	117.0	126.1	140.9	141.9	160.0	156.6	176.1	1966	1983	10
29423102	S	1782	1862	96	EXPERIMENT STAT	182.1	159.2	151.2	115.0	94.2	79.2	86.0	102.5	119.4	147.8	157.2	185.6	1927	1987	23
29453008	A	1785	1808	1375	SEVONTEIN, ELAN	191.2	167.1	166.4	162.0	131.3	107.0	124.0	155.0	197.3	159.7	152.3	186.0	1983	1986	3
29453024	A	1785	1824	860	NATAL EST., THO	154.5	141.9	143.2	125.5	111.6	97.5	107.0	132.8	143.5	159.7	157.0	173.6	1981	1986	6
29583038	S	1798	1838	658		156.0	138.1	140.7	118.2	104.3	96.2	109.5	123.2	131.5	153.8	149.2	165.6	1967	1986	16

LAT = Latitude in minutes S of the Equator
LONG = Longitude in minutes E of 0°

C. TEMPERATURE STATION DATA AND INFORMATION - EXAMPLES

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 STATION   LAT    LONG   ALT. GOOD REC POS     LOCATION/CONTACT              M.A.T.          ORIGINAL   M.A.P.
 I.D.     (DEG. & MIN.)  (M)  DATA IN DATABASE                                                          I.D.
=========================================================================================================================
0238616 W 2946.0 2951.0 1250    9     739                                                                -1.0
 238616  MX 25.9 25.8 24.5 23.6 21.4 19.4 18.3 21.3 22.9 23.9 24.6 25.3   23.1   238616  AV 20.3 20.3 19.1
16.9 14.0 11.7 10.7 13.5 15.7 17.5 18.6 19.6   16.5   238616  MI 14.6 14.7 13.6 10.3  6.6  3.9  3.0  5.8
8.7 11.1 12.6 13.9    9.9

 STATION   LAT    LONG   ALT. GOOD REC POS     LOCATION/CONTACT              M.A.T.          ORIGINAL   M.A.P.
 I.D.     (DEG. & MIN.)  (M)  DATA IN DATABASE                                                          I.D.
=========================================================================================================================
0238616 R 2946.0 2951.0 1250   10    3250               LONG EL                                RES0040    -1.0
RES0041  MX 30.3 30.6 29.4 27.4 25.7 24.4 23.9 24.8 26.4 28.0 29.3 30.1   27.5  RES0041  AV 24.5 24.2 22.6
20.7 18.3 16.3 15.8 17.3 19.7 21.7 23.3 24.2   20.7  RES0041  MI 18.7 17.8 15.9 13.9 10.9  8.1  7.7  9.8
12.9 15.5 17.2 18.3   13.9

 STATION   LAT    LONG   ALT. GOOD REC POS     LOCATION/CONTACT              M.A.T.          ORIGINAL   M.A.P.
 I.D.     (DEG. & MIN.)  (M)  DATA IN DATABASE                                                          I.D.
=========================================================================================================================
0238662 A 2932.0 2953.0 1699   12    2635               IVANHOE,IMPENDHLE                      ATS0265  1059.0
ATS0265  MX 21.8 22.9 20.7 17.0 17.8 15.8 15.4 17.0 19.7 19.7 19.9 22.6   19.2  ATS0265  AV 16.8 17.4 15.4
11.9 11.4  8.9  8.9 10.2 13.5 14.3 14.3 17.1   13.3  ATS0265  MI 11.9 12.0 10.1  6.7  4.9  2.1  2.4  3.5
7.3  8.9  8.7 11.6    7.5

 STATION   LAT    LONG   ALT. GOOD REC POS     LOCATION/CONTACT              M.A.T.          ORIGINAL   M.A.P.
 I.D.     (DEG. & MIN.)  (M)  DATA IN DATABASE                                                          I.D.
=========================================================================================================================
0239097 A 2937.0 3004.0 1540   78    2611               ELANDSHOEK, BOSTON                     ATS0235  1007.3
ATS0235  MX 26.8 27.5 25.5 23.9 21.0 19.7 20.2 20.6 21.9 23.5 24.6 26.3   23.5  ATS0235  AV 20.0 20.7 18.8
16.8 13.9 11.9 12.1 13.2 14.7 16.2 17.6 19.4   16.3  ATS0235  MI 13.3 13.9 12.0  9.8  6.9  4.2  4.0  5.7
7.5  9.0 10.6 12.6    9.1
```

D.1 LAND COVER SUMMARY FOR EACH SUBCATCHMENT - EXAMPLES

SUBCATCHMENT NO: 1 AREA(KM2): 30.01

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
47	FAIR VELD	24.57	81.89
50	RESERVOIR	1.48	4.92
53	WETLAND-GRASSES	3.97	13.23

SUBCATCHMENT NO: 2 AREA(KM2): 41.67

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
1	MAIZE	3.18	7.64
24	PASTURES-PERRENNIAL CROP	4.50	10.81
37	PINE FOREST(15YRS)	0.36	0.87
47	FAIR VELD	28.37	68.09
50	RESERVOIR	0.58	1.39
53	WETLAND-GRASSES	2.33	5.60
61	MIXED CROPS-MGENI	2.34	5.61

SUBCATCHMENT NO: 3 AREA(KM2): 29.54

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
1	MAIZE	1.54	5.20
24	PASTURES-PERRENNIAL CROP	1.05	3.54
34	TIMBER-GENERALIZED	0.18	0.62
37	PINE FOREST(15YRS)	0.06	0.21
47	FAIR VELD	25.43	86.07
50	RESERVOIR	1.25	4.23
57	BUSH/VELD/SUBS CROPS	0.06	0.21

SUBCATCHMENT NO: 4 AREA(KM2): 82.53

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
1	MAIZE	0.04	0.05
24	PASTURES-PERRENNIAL CROP	1.54	1.86
34	TIMBER-GENERALIZED	1.49	1.81
35	INDIGENOUS FOREST	3.63	4.40
36	EUCALYPTUS PLANTATION	1.24	1.50
37	PINE FOREST(15YRS)	1.84	2.23
39	WATTLE PLANTATION	1.04	1.26
47	FAIR VELD	67.41	81.68
50	RESERVOIR	0.57	0.69
61	MIXED CROPS-MGENI	3.73	4.52

SUBCATCHMENT NO: 5 AREA(KM2): 83.76

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
1	MAIZE	0.62	0.74
24	PASTURES-PERRENNIAL CROP	1.22	1.46
34	TIMBER-GENERALIZED	0.12	0.14
35	INDIGENOUS FOREST	1.25	1.49
36	EUCALYPTUS PLANTATION	0.94	1.12
37	PINE FOREST(15YRS)	18.67	22.29
47	FAIR VELD	59.03	70.48
61	MIXED CROPS-MGENI	1.82	2.18
50	RESERVOIR	0.10	0.12

SUBCATCHMENT NO: 6 AREA(KM2): 25.66

ACRU CODE	LAND COVER DESCRIPTION	AREA(KM2)	AREA(%)
1	MAIZE	2.97	11.57
24	PASTURES-PERRENNIAL CROP	1.32	5.14
34	TIMBER-GENERALIZED	0.19	0.73
36	EUCALYPTUS PLANTATION	0.05	0.21
37	PINE FOREST(15YRS)	2.06	8.03
39	WATTLE PLANTATION	0.25	0.97
47	FAIR VELD	17.39	67.74
61	MIXED CROPS-MGENI	1.39	5.43
50	RESERVOIR	0.04	0.17

D.2 HYDROLOGICAL INFORMATION FOR EACH LAND COVER CLASS

CROP NO			J	F	M	A	M	J	J	A	S	O	N	D
1	MAIZE - UMGENI/MOOI	CAY	0.99	0.84	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.48	0.78
	Planting date = Oct 15	LAI	5.05	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.50	3.00
	Growing season = 140 days	INT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
		ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
16	SUGARCANE - GENERALISED	CAY	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
		LAI-1.00												
		INT	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
		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
24	PASTURES - PERENNIAL CROP	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
		LAI	3.00	2.50	4.05	0.65	0.40	0.40	0.40	0.50	0.65	1.20	3.60	4.00
		INT	1.40	1.40	1.40	1.40	1.20	1.00	1.00	1.20	1.30	1.40	1.40	1.40
		ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
34	TIMBER - GENERALISED	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
		LAI-1.00												
		INT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
		ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
35	INDIGENOUS FOREST - ZULULAND	CAY	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.80	0.85	0.90	0.90	0.90
		LAI	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
		INT	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
		ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
36	EUCALYPTUS PLANTATION - ass-	CAY	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
	umed age 8 years	LAI	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
		INT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
		ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
37	PINE FOREST - assumed age 15	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	years	LAI	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90
		INT	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3./50	3.50	3.50	3.50
		ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
39	WATTLE PLANTATION - assumed	CAY	0.90	0.90	0.89	0.88	0.87	0.87	0.87	0.87	0.88	0.89	0.90	0.90
	age 8 years	LAI	3.00	3.00	3.00	3.00	2.75	2.75	2.75	2.75	2.75	3.00	3.00	3.00
		INT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
		ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
43	SUBSISTENCE CROPS - SCATTERED	CAY	0.80	0.70	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.60
	Planting date = Nov 1	LAI-1.00												
		INT	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.80
		ROOTA	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
47	FAIR VELD - ALL AREAS	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
		LAI	0.90	0.90	0.90	0.59	0.31	0.10	0.10	0.10	0.23	0.45	0.59	0.90
		INT	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.20
		ROOTA	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
48	RESIDENTIAL FORMAL, HIGH DEN-	CAY	0.75	0.75	0.75	0.65	0.40	0.20	0.20	0.20	0.30	0.60	0.65	0.70
	SITY - pervious portion	LAI	1.30	1.30	1.30	0.90	0.21	0.20	0.20	0.20	0.10	0.74	0.90	1.09
		INT	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
		ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
49	RESIDENTIAL FORMAL, MED DEN-	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
	SITY - pervious portion	LAI	3.00	2.50	4.05	0.65	0.40	0.40	0.40	0.50	0.65	1.20	3.60	4.00
		INT	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.10	1.20	1.30	1.40
		ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
53	WETLAND - GRASSES	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.40	0.40	0.40	0.50	0.60	0.70
		LAI	1.30	1.30	1.30	0.40	0.21	0.20	0.20	0.20	0.10	0.74	0.90	1.09
		INT	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		ROOTA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
56	BUSH/VELD	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.35	0.35	0.55	0.65	0.80	0.80
		LAI-1.00												
		INT	2.00	2.00	2.00	1.70	1.50	1.30	1.30	1.30	1.00	1.60	1.80	2.00
		ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80
57	VALLEY OF 1000 HILLS - bush/	CAY	0.70	0.70	0.70	0.60	0.50	0.40	0.40	0.40	0.60	0.65	0.70	0.70
	veld/subsistence crops	LAI-1.00												
		INT	1.50	1.50	1.50	1.50	1.20	1.20	1.20	1.20	1.50	1.50	1.50	1.50
		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
58	INFORMAL RESIDENTIAL, RURAL	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	- pervious portion	LAI	0.90	0.90	0.90	0.59	0.31	0.10	0.10	0.10	0.23	0.45	0.59	0.90
		INT	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
		ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90

D.2 CONTINUED

59 RESIDENTIAL PARKLAND	CAY	0.80	0.80	0.80	0.70	0.50	0.40	0.40	0.40	0.60	0.75	0.80	0.80
	LAI-1.00												
	INT	1.50	1.50	1.50	1.50	1.20	1.20	1.20	1.20	1.50	1.50	1.50	1.50
	ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.80
60 WOODLAND - indigenous/tree-bush savannah	CAY	0.80	0.80	0.80	0.80	0.70	0.70	0.70	0.70	0.75	0.80	0.80	0.80
	LAI-1.00												
	INT	2.50	2.50	2.50	2.00	2.00	2.00	2.00	2.00	2.00	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80
61 MIXED CROPS - MGENI - maize/subsistence	CAY	0.80	0.80	0.60	0.40	0.20	0.20	0.20	0.20	0.20	0.40	0.65	0.80
	LAI-1.00												
	INT	1.30	1.30	1.30	1.30	1.10	0.50	0.50	0.50	0.50	0.50	0.90	1.30
	ROOTA	0.85	0.85	0.85	0.90	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.85
62 CBD / COMMERCIAL - pervious portion	CAY	0.75	0.75	0.75	0.65	0.50	0.40	0.40	0.40	0.50	0.75	0.75	0.75
	LAI-1.00												
	INT	1.50	1.50	1.50	1.50	1.20	1.20	1.20	1.20	1.20	1.50	1.50	1.50
	ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
63 INDUSTRIAL - pervious portion	CAY	0.70	0.70	0.70	0.60	0.40	0.40	0.30	0.30	0.50	0.70	0.70	0.70
	LAI-1												
	INT	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.20	1.40	1.40	1.40
	ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
64 FORMAL RESIDENTIAL, LOW DENSITY - pervious portion	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
	LAI-1												
	INT	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.10	1.20	1.30	1.40
	ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.95	0.95	0.90	0.90	0.80	0.80
65 INFORMAL RESIDENTIAL, URBAN - pervious portion	CAY	0.55	0.55	0.55	0.45	0.20	0.20	0.20	0.20	0.30	0.40	0.50	0.55
	LAI-1												
	INT	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.60	0.70	0.80	0.80	0.80
	ROOTA	0.90	0.90	0.90	0.94	1.00	1.00	1.00	1.00	0.94	0.92	0.90	0.90

E.1 LOCATION AND INFORMATION FOR EACH RESERVOIR - EXAMPLES

LATITUDE (DECIMAL	LONGITUDE MINUTES)	AREA (ha)	FLG	CODE	WALL HT (m)	WALL LNTH (m)	AXIS LNTH (m)	BASIN SLOPE (m/m)	DAM SHAPE (1-7)	CAPACITIES (LAS)	(LOW) (*1000m**3)	(AMM)	(ATS)	1:50000 MAP NUMBER
1792.2332	-1772.5833	38.73			5	290.	1000.	.0045	2.	813.3	563.9	1392.50	612.6	292908
1795.2832	-1773.1165	35.00			5	190.	450.	.0196	6.	1029.0	190.0	1220.90	209.9	292908
1794.9500	-1773.7998	34.91			5	170.	800.	.0083	6.	772.7	302.2	1216.80	333.9	292908
1794.8499	-1773.0667	16.71			8	370.	1100.	.0067	4.	410.5	542.7	467.40	875.9	292908
1791.3665	-1770.6831	15.01			<5	200.	500.	.0091	6.	227.7	133.3	406.60	147.3	292908
1796.5667	-1773.8333	10.09			10	70.	400.	.0182	7.	244.9	46.7	242.70	0.0	292908
1797.8665	-1771.2832	8.86			<5	230.	450.	.0119	1.	158.2	103.5	205.00	0.0	292908
1794.3499	-1773.2832	8.21			5	100.	680.	.0118	4.	219.6	56.7	185.70	91.5	292908
1793.4500	-1772.7998	6.00			5	110.	350.	.0250	1.	175.0	64.2	123.60	0.0	292908
1793.0999	-1773.2832	4.73			<5	170.	300.	.0125	1.	59.1	51.0	90.70	0.0	292908
1795.8833	-1773.1499	3.88			5	180.	330.	.0200	2.	119.5	115.5	70.20	125.5	292908
1795.5667	-1774.5000	3.68			5	140.	200.	.0200	6.	49.1	62.2	65.50	68.7	292908
1798.9500	-1772.0667	2.77			7	150.	250.	.0122	2.	39.4	102.1	45.30	110.9	292908
1794.9500	-1774.5667	2.73			5	120.	210.	.0200	6.	38.2	56.0	44.40	61.9	292908
1793.7998	-1773.6165	2.70			<5	180.	200.	.0125	3.	28.1	30.0	43.80	37.4	292908
1796.2332	-1773.7332	2.64			5	120.	200.	.0333	1.	58.6	40.0	42.60	0.0	292908
1795.8665	-1773.3999	2.61			5	180.	140.	.0196	1.	23.9	42.0	41.90	0.0	292908
1795.7832	-1770.8665	2.51			7	120.	280.	.0147	4.	34.4	39.2	39.90	63.3	292908
1790.4500	-1771.7998	1.75			3	70.	150.	.0020	4.	1.7	5.2	24.90	8.5	292908
1794.6165	-1773.7832	1.62			<5	160.	260.	.0100	4.	14.0	20.8	22.60	33.6	292908
1796.2500	-1773.2998	1.60			5	80.	120.	.0385	7.	24.6	8.0	22.20	0.0	292908
1793.5000	-1771.5332	1.56			<5	60.	200.	.0313	1.	32.6	12.0	21.50	0.1	292908
1791.0498	-1772.0498	1.23			<5	110.	140.	.0096	1.	5.5	15.4	15.80	0.0	292908
1798.2666	-1772.2666	1.18			<5	240.	200.	.0119	1.	9.4	48.0	15.00	0.0	292908
1795.8167	-1773.5667	0.86			<5	100.	80.	.0286	2.	9.2	9.3	9.90	10.1	292908
1798.8833	-1773.9165	0.81			<5	90.	160.	.0455	4.	19.7	7.2	9.20	11.6	292908
1798.8999	-1770.4165	0.76			<5	90.	100.	.0208	1.	5.3	9.0	8.40	0.0	292908
1798.9832	-1771.6665	0.76			<5	70.	150.	.0222	4.	8.4	5.2	8.40	8.5	292908
1797.6333	-1771.8333	0.71			<5	50.	50.	.0192	4.	2.3	1.2	7.70	2.0	292908
1795.8167	-1773.6665	0.66			5	110.	100.	.0357	4.	7.9	9.2	7.00	14.8	292908
1797.5000	-1771.5498	0.64			<5	80.	120.	.0227	7.	5.8	4.8	6.80	0.0	292908
1792.4666	-1771.2000	0.56			<5	70.	130.	.0167	4.	4.1	4.5	5.70	7.3	292908
1796.0166	-1773.7666	0.55			<5	100.	80.	.0500	4.	7.3	4.0	5.50	6.5	292908
1798.4666	-1773.1165	0.43			2	50.	50.	.0143	2.	1.4	1.9	4.00	2.1	292908
1792.6499	-1771.7666	0.38			<5	50.	130.	.0167	3.	3.4	5.4	3.40	6.7	292908
1795.2500	-1773.8167	0.34			2	70.	80.	.0556	4.	5.0	1.9	3.00	3.0	292908
1796.3833	-1771.2332	0.31			<5	50.	80.	.0045	1.	0.4	4.0	2.60	0.0	292908

E.2 TOTALS OF RESERVOIR AREAS AND CAPACITIES PER SUBCATCHMENT - EXAMPLES

SUB-CATCHMENT	RESERVOIR AREA(km^2)	CATCHMENT AREA(km^2)	% DAMS	CAPACITY (*1000m**3)
1	1.48	30.006	4.92	5,550.700
2	0.58	41.670	1.39	1,850.300
3	1.25	29.545	4.23	3,616.300
4	0.57	82.533	0.69	1,011.300
5	0.10	83.757	0.12	119.300
6	0.04	25.663	0.17	62.900
7	0.43	30.100	1.42	1,046.000
8	0.20	39.519	0.51	272.300
9	1.07	38.956	2.74	3,543.300
10	1.22	112.904	1.08	2,516.700
11	0.65	65.129	1.00	1,069.400
12	0.32	55.304	0.59	428.900
13	0.59	55.220	1.07	1,145.900
14	0.18	29.255	0.63	257.400
15	0.26	27.645	0.93	364.400
16	0.00	5.951	0.04	1.500
17	0.17	25.669	0.67	263.800
18	0.00	31.757	0.00	0.000

F.1 DYNAMIC INPUT FILE

THIS FILE CONTAINS DATA ENABLING A DYNAMIC DATA INPUT SYSTEM FOR ACRU, ON THE LINES OF THE MENU USED FOR THE INITIAL OPTIONS AND VARIABLES. THE VARIABLES TO BE CHANGED ARE CODED AS FOLLOWS:

	VARIABLE TO BE CHANGED	FORMAT
	Cell Output Options	
1	SUMMRY (print summary of results - 0/1/2/3/4/5/6)	1X,F1.0
2	WRTYLD (crop yield analysis option-0/1)	1X,F1.0
3	RESYLD (reservoir yield analysis option - 0/1)	1X,F1.0
4	IRRIGN (irrigation routine option - 0/1)	1X,F1.0
	Cell Soils Information	
5	PEDDEP (SOILS DEPTH - 1/2/3)	1X,F1.0
6	DEPAHO (DEPTH A-HORIZON - M)	1X,F5.2
7	DEPBHO (DEPTH B-HORIZON - M)	1X,F5.2
	Cell Vegetation Information	
8	CN11 (SCS CURVE NO)	1X,F3.0
9	CONST (SM FRACTION WHERE AE<PE)	1X,F5.2
10	CRLEPO (CRITICAL LEAF WATER POTENTIAL)	1X,F5.2
11	SMDDEP (EFFECTIVE SOIL DEPTH FOR QUICKFLOW RESPONSE)	1X,F6.2
12	CORPAN(I) (CELL PAN CORRECTION FACTORS)	12(1X,F4.2)
13	COIAM(I) (COEF.OF INITIAL ABSTRACTION)	12(1X,F4.2)
14	CAY(I) (CELL CROPPING FACTOR)	12(1X,F4.2)
15	ELAIM(I) (LEAF AREA INDEX)	12(1X,F4.2)
16	ROOTA(I) (PROPORTION ROOTS IN A-HORIZON)	12(1X,F4.2)
17	VEGINT(I) (INTERCEPTION LOSS-MM/RAIN DAY)	12(1X,F4.2)
18	COVER(I) (COVER FACTORS FOR MUSLE)	12(1X,F4.2)
	Cell Sediment Yield Variables In MUSLE	
19	SOIFAC (SOIL ERODABILITY FACTOR IN SCS - K)	1X,2
20	PFACT (SUPPORT PRACTICE FACTOR IN SCS - P)	1X,2
	Cell Irrigation Information	
21	IRRAPL (TYPE IRRIG SIMULATION--ORIGIN-0/1/2/3)	1X,I1
22	SCHED (TYPE OF SCHEDULING - 1/2/3/4)	1X,F1.0
23	EFFIRR (FRACTION IRRIGATION EFFICIENCY)	1X,F4.2
24	CONSTI (FRACTION OF SM WHERE AE<PE)	1X,F4.2
25	PLADEF (PLANNED DEFICIT FOR SCHED=1 - MM)	1X,F5.2
26	AMTIR (AMOUNT TO BE IRRIGATED FOR SCHED=3/4 - MM)	1X,F5.2
27	ICYCLE (NO DAYS IN IRRIGATION CYCLE)	1X,I2
28	CONLOS (FRACTION CONVEYANCE LOSSES)	1X,F4.2
29	FAMLOS (FRACTION FARM LOSSES)	1X,F4.2
30	PPTIRR (PROPORTION CORRECTION OF PPT VALUES FOR SITE)	1X,F6.2
31	UPSTIR (IRRIG UP/DOWNSTREAM OF RESERVOIR)	1X,F1.0
32	HAIRR (I) (AREA IRRIGATED - HA)	12(1X,F4.0)
33	CAYIRR(I) (IRRIGATION CROP FACTORS)	12(1X,F4.2)
34	IRRMON(I) (IRRIG CONTROL OVER MNTHS IRRIG OCCURS)	12(1X,I1)
	Irrigated Soils Information	
35	IRRDEP (SOILS DEPTH - 1/2/3/4)	1X,I1
36	IRTEXT (SOILS TEXTURE - 1/2...10/11)	1X,I2
37	XMXIRR (MAXIMUM ROOTING DEPTH - M)	1X,F6.2
38	FCIR (SMC AT FC)	1X,F4.3
39	WPIR (SMC AT WP)	1X,F4.3
40	POIR (SMC AT POROSITY)	1X,F4.3
	Crop Yield Information	
41	CROP (CROP SELECTION - 1/2)	1X,F1.0
42	PLDATE (CALC/SPECIFY PLANTING DATE - 0/1)	1X,F1.0
43	ISTDAY (DAY OF PLANTING)	1X,I2
44	ISTMO (MONTH OF PLANTING)	1X,I2
45	LENGTH (NO DAYS OF GROWING SEASON)	1X,I3
46	SPRICE (SELLING PRICE - R/TON)	1X,F6.2

F.1 CONTINUED

53	PANDAM(I) (CORRECTION FACTOR FOR EVAP OVER DAM)	12(1X,F4.2)
54	PUMPIN(I) (PUMPED INFLOW - 10E6M**3/MONTH)	12(1X,F4.2)
55	DRAFT(I) (DRAFT EXTRACTED - 10E6M**3/MONTH)	12(1X,F4.2)
56	E(J) (A-PAN EVAPORATION)	12(1X,F5.1)
	Sugarcane Yields - Cutting Dates	
57	ICRPDY (DAY OF CUTTING)	1X,I2
58	ICRPMO (MONTH OF CUTTING)	1X,I2
59	ICRPYR (YEAR OF CUTTING)	1X,I2

IYRCH (year of change)
IMOCH (month of change)

IF ANY OF THESE VARIABLES ARE TO BE CHANGED, THE YEAR AND MONTH OF THE CHANGE IS SPECIFIED AND THE CORRESPONDING CODE IS GIVEN A VALUE OF 1. A LINE IS THEN MISSED AND THE NEW VALUES ARE WRITTEN IN THE SEQUENCE GIVEN AND WITH THE CORRECT FORMATS.

F.2 EXAMPLE OF A DYNAMIC INPUT FILE

```
         1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61
          2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 6

         SWRIPDD  CSC     V S  I  ECP ICFPU CIIIX     PI LSBDS    PP   III
I  I     UREREEE CRMOC  ERECOPRSFOLACOAPPHARRRM       LSIEPRAUWQ  AUD  CCC
Y  M     MTSRDPPCOLDRO  LOGOIFRCFNAMYNMTSAYRRTXFWPCDTSNRKMRINSNMR      RRR
R  O     MYYIDABNNEDPICAOIVFAAHISDTCLLITIIMDEICPORADTGIECFDOEDPA       PPP
C  C     RLLGEHHISPEAAAITNEACPERTEILOORIRROEXRIIIOTAMTCVAATREAIF       OMY
H  H     YDDNPOOITOPNMYMATRCTLDRIFRESSRRRRNPTRRRRPEYOHENPRHMPMNTEYOR
-- --    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
61 01 0000000000000000000000000000000000000000000000000000010000000

0.62  0.68  0.70  0.50  0.44  0.41  0.40  0.38  0.39  0.45  0.50  0.53
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         1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61
          2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 6

         SWRIPDD  CSC     V S  I  ECP ICFPU CIIIX     PI LSBDS    PP   III
I  I     UREREEE CRMOC  ERECOPRSFOLACOAPPHARRRM       LSIEPRAUWQ  AUD  CCC
Y  M     MTSRDPPCOLDRO  LOGOIFRCFNAMYNMTSAYRRTXFWPCDTSNRKMRINSNMR      RRR
R  O     MYYIDABNNEDPICAOIVFAAHISDTCLLITIIMDEICPORADTGIECFDOEDPA       PPP
C  C     RLLGEHHISPEAAAITNEACPERTEILOORIRROEXRIIIOTAMTCVAATREAIF       OMY
H  H     YDDNPOOITOPNMYMATRCTLDRIFRESSRRRRNPTRRRRPEYOHENPRHMPMNTEYOR
-- --    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
62 01 0000000000000000000000000000000000000000000000000000010000000

0.54  0.59  0.61  0.43  0.38  0.36  0.35  0.43  0.44  0.50  0.56  0.59
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         1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61
          2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 6

         SWRIPDD  CSC     V S  I  ECP ICFPU CIIIX     PI LSBDS    PP   III
I  I     UREREEE CRMOC  ERECOPRSFOLACOAPPHARRRM       LSIEPRAUWQ  AUD  CCC
Y  M     MTSRDPPCOLDRO  LOGOIFRCFNAMYNMTSAYRRTXFWPCDTSNRKMRINSNMR      RRR
R  O     MYYIDABNNEDPICAOIVFAAHISDTCLLITIIMDEICPORADTGIECFDOEDPA       PPP
C  C     RLLGEHHISPEAAAITNEACPERTEILOORIRROEXRIIIOTAMTCVAATREAIF       OMY
H  H     YDDNPOOITOPNMYMATRCTLDRIFRESSRRRRNPTRRRRPEYOHENPRHMPMNTEYOR
-- --    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
63 01 0000000000000000000000000000000000000000000000000000010000000

0.61  0.66  0.68  0.48  0.43  0.40  0.39  0.41  0.42  0.48  0.53  0.57
```

G. LAND TYPE INFORMATION - EXAMPLE

CATCHMENT NAME: u23xxxx

FOR COMPREHENSIVE INFORMATION ON SOILS WITHIN EACH OF THE LAND TYPES SEE CLTEX OUTPUT

LAND TYPE	(%)
C6	100.00

TERRAIN UNIT SOILS INFORMATION AND HYDROLOGICAL PROPERTIES

TERRAIN UNIT	%	SLOPE(%)	SLOPE LENGTH(M)	ROCK(%)	EROSION(%)	STREAMBEDS(%)	MARSH(%)
1	0.00	0.	0.	0.0	0.0	0.0	0.0
2	0.00	0.	0.	0.0	0.0	0.0	0.0
3	24.75	8.	325.	0.0	0.0	0.0	0.0
4	34.65	4.	300.	0.0	0.0	0.0	0.0
5	39.60	4.	275.	0.0	2.0	20.0	0.0

TERRAIN UNIT	DEPAHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO2	ABRESP	BFRESP
1	0.0	0.0	.000	.000	.000	.000	.000	.000	0.00	0.00
2	0.0	0.0	.000	.000	.000	.000	.000	.000	0.00	0.00
3	234.6	333.2	.135	.148	.236	.253	.424	.422	0.39	0.32
4	240.9	457.9	.130	.204	.218	.282	.408	.422	0.36	0.28
5	307.1	568.4	.130	.167	.226	.271	.408	.411	0.47	0.42

CATCHMENT SOILS INFORMATION AND HYDROLOGICAL PROPERTIES

SLOPE(%)	SLOPE LENGTH(M)	ROCK(%)	EROSION(%)	STREAMBEDS(%)	MARSH(%)
5.	293.	0.0	0.8	7.9	0.0

DEPAHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO2	ABRESP	BFRESP
263.1	466.2	.130	.174	.223	.268	.408	.413	0.41	0.34