# DEVELOPMENT OF A DISTRIBUTED HYDROLOGICAL MODELLING SYSTEM TO ASSIST IN MANAGING THE ECOLOGICAL RESERVE TO THE SABIE RIVER SYSTEM WITHIN THE KRUGER NATIONAL PARK

Andrew Pike • Roland Schulze

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# DEVELOPMENT OF A DISTRIBUTED HYDROLOGICAL MODELLING SYSTEM TO ASSIST IN MANAGING THE ECOLOGICAL RESERVE TO THE SABIE RIVER SYSTEM WITHIN THE KRUGER NATIONAL PARK

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SCHOOL OF BIORESOURCES ENGINEERING AND ENVIRONMENTAL HYDROLOGY
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## List of Abbreviations

| | |
|---|---|
| ***ACRU*** | Agricultural Catchments Research Unit |
| **AGNPS** | AGricultural Non Point Source |
| **ARS** | Agricultural Research Service |
| **ASCII** | American Standard Code for Information Interchange |
| **AWARD** | Association for Water And Rural Development |
| **BBM** | Building Block Methodology |
| **BEEH** | Bioresources Engineering and Environmental Hydrology |
| **CCWR** | Computing Centre for Water Research |
| **CFP** | Chunnett, Fourie and Partners |
| **CMA** | Catchment Management Agency |
| **CREAMS** | Chemicals, Runoff and Erosion from Agricultural Management Systems |
| **CSIR** | Council for Scientific and Industrial Research |
| **DBF** | Data Base Format |
| **DFS** | Desired Future State |
| **DUL** | Drained Upper Limit |
| **DWAF** | Department of Water Affairs and Forestry |
| **EPIC** | Erosion-Productivity ImpaCt generator |
| **GENSCN** | GENeration and analysis of model simulation SCeNarios |
| **GLEAMS** | Groundwater Loading Effects on Agricultural Management Systems |
| **HSPF** | Hydrological Simulation Program - Fortran |
| **HYMO** | HYdrologic MOdel |
| **ICIS** | Integrated Catchment Information System |
| **IFA** | Instream Flow Assessment |
| **IFR** | Instream Flow Requirement |
| **INR** | Institute of Natural Resources |
| **ISCW** | Institute for Soil, Climate and Water |
| **IWR** | Institute for Water Research |
| **KNP** | Kruger National Park |
| **KNPRRP** | Kruger National Park Rivers Research Programme |
| **LANDSAT TM** | LANDSAT Thematic Mapper |
| **MAR** | Mean Annual Runoff |
| **MBB** | Murray, Biesenbach and Badenhorst |
| **MUSLE** | Modified Universal Soil Loss Equation |
| **NLC** | National Land Cover |
| **NWA** | National Water Act |
| **QC** | Quaternary Catchment |
| **ROTO** | Routing Outputs To Outlet |
| **SCS** | Soil Conservation Service |
| **SFRA** | Streamflow Reduction Activity |
| **SWAT** | Soil and Water Assessment Tool |
| **SWRRB** | Simulator for Water Resources in Rural Basins |
| **USDA** | United States Department of Agriculture |
| **USLE** | Universal Soil Loss Equation |
| **WAS** | Water Administration System |
| **WDM** | Watershed Data Management |
| **WRC** | Water Research Commission |
| **WR90** | Surface Water Resources of South Africa 1990 |

# RESEARCH INTO THE DEVELOPMENT OF A DISTRIBUTED HYDROLOGICAL MODELLING SYSTEM TO ASSIST IN MANAGING THE ECOLOGICAL RESERVE TO THE SABIE RIVER SYSTEM WITHIN THE KRUGER NATIONAL PARK

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## SECTION 1 BACKGROUND AND OBJECTIVES

### 1.1 The Kruger National Park Rivers Research Programme (KNPRRP)

#### 1.1.1 Introduction

The Kruger National Park Rivers Research Programme (KNPRRP) developed from an initiative taken during 1987 to begin to define the ecological water requirements of rivers which flow through the Kruger National Park (KNP) on the north eastern border of South Africa and Mozambique. It is a multi-disciplinary, multi-organisational programme which is set against the backdrop of major changes in national water policy and legislation. The Programme, conceived at a workshop convened by the Department of Water Affairs and Forestry (DWAF) in March 1987, was initiated in December 1988, jointly by the then state departments of Water Affairs (now DWAF) and Environment Affairs (now Department of Environmental Affairs and Tourism, DEAT), the Foundation of Research Development (now National Research Foundation), the National Parks Board, the Water Research Commission and various research institutions and provincial nature conservation authorities.

#### 1.1.2 Phases of the KNPRRP

Against this background, what has since become known as Phase I of the KNPRRP commenced in 1987. A large amount of basic and applied research was conducted in the Programme until December 1991. A management review was commissioned at the end of this period. Its major findings were that whilst sound research had been conducted, the Programme was not aligned nor focussed on providing integration with management requirements and thus ran the risk of being ignored by policy makers and water managers. Following the management review, Phase II (1994-1996) was initiated (Dent *et al.*, 1999) and subsequent to that, Phase III (1997-1999).

Phases II and III were designed in accordance with the view that bargaining for water allocation for the environment must be informed by credible science; furthermore, that the complexity of river systems and their dynamic nature in space and time was such that credibility would require complex integrating models. These models would have to be customised and installed. It was envisaged that those who sat at the bargaining table representing environmental interests would require interactive systems so that they could test and explain the likely consequences of options suggested by other interests (Dent *et al.*, 1999).

### 1.1.3 Selection of the Sabie catchment for integrated research

Five of the major international rivers of South Africa rise in the highland to the west of the KNP and flow east down the escarpment into economically poor, heavily populated, overgrazed rural lowlands, through the KNP and into Mozambique. These rivers, which are the lifeblood of the KNP, are highly variable both inter-annually and intra-seasonally and yet sustain approximately 50 per cent of the biodiversity of the park (Dent *et al.*, 1999). Only 4% of the water in the rivers of the park is generated by runoff within the park (Dent *et al.*, 1999). Management of the flow in these rivers by the custodians of the park is therefore an exceptionally difficult challenge. Rapid urbanisation, industrial and agricultural development in the upper reaches of these rivers has increased the demand for water there to the extent that the water resources are often inadequate to meet the existing demands, let alone the river ecosystem health. Of primary concern at present is the allocation of water in an equitable, efficient and ecological sound manner between the natural environment of the rivers and the numerous user sectors within these catchments, e.g. agriculture and industry. Water pollution, associated with changing patterns of land use, also poses a threat to the conservation of the natural environment of the rivers. In this complex socio-economic situation, trade-offs have to be made between conflicting demands for water and between differing water quality requirements.

To facilitate the integration processes between research disciplines and between research and management, a strategic decision was taken to focus Phases II and III in one of the five catchments. The Sabie river catchment was chosen for a variety of reasons. One reason is that in the Sabie alluviation, as a consequence of increased sediment supply and decreased sediment transport capacity, poses a major threat to the biodiversity of the KNP portion of the river in which bedrock significantly determines morphology and available habitat (Rogers and Biggs, 1999).

### 1.1.4 Goals of the KNPRRP

The primary goals of Phase II (1994-1996) were :-

- to inform researchers, system managers and stakeholders about the water quality and quantity requirements to sustain the natural environment of rivers which flow through the KNP; and
- to develop, test and refine methods for predicting the responses of the natural environment of rivers flowing through the KNP and in southern Africa to changing water quality and patterns of supply.

The primary goals of Phase III (1997-1999) are :-

- to achieve a common understanding of the water quality and quantity requirements to sustain the natural environment of rivers which flow through the KNP; and
- to develop, refine and implement methods for predicting and monitoring the responses of the natural environment of rivers flowing through the KNP to fluctuating flow and variable water quality (Dent *et al.*, 1999).

The essential difference between Phase II and Phase III is that the latter seeks to broaden the base of understanding to river forums and other stakeholders and the application of knowledge, understanding and tools to manage river systems. Phase III focussed on a number of core issues, *viz.* continual review, extending decision support and predictive capability, valuation of the natural resources of rivers, extrapolation, capacity building amongst previously disadvantaged communities, honouring international obligations, and the development of a national rivers research programme. A feature of Phase III was the explicit recognition that the processes and concepts developed had to be able to be sufficiently aligned to the operational processes of river management in civil society so that they could maintain "life" after direct funding for the programme ceased. The programme is now in a position to provide a role model for the operational needs of conflict resolution in the social process of water allocation in the region.

## 1.2 The Ecological Reserve

Some of the greatest challenges facing South Africa include the equitable distribution of its limited water resource and ensuring that conflicts over water are addressed and resolved objectively and timeously. These problems are exacerbated by deteriorating water quality which emanates from increased sediment yield resulting from unsuitable land use management in the catchment, as well as enhanced loadings of point and non-point pollutants from increased levels of industry and from agricultural practices. There has, for the past decade, been an increasing awareness of the ecological water requirements in South Africa which has resulted in the allocation of water for the ecological reserve receiving the highest priority immediately after water for basic human needs in the National Water Act of 1998. Thus,

> *"The basic human needs reserve provides for the essential needs of individuals served by the water resource in question and includes water for drinking, for food preparation and for personal hygiene.* ***The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource. The Reserve refers to both the quantity and quality of the water in the resource, and will vary depending on the class of the resource*** (authors' emphasis). *The Minister is required to determine the Reserve for all or part of any significant water resource. If a resource has not yet been classified, a preliminary determination of the Reserve may be made and later superseded by a new one. Once the Reserve is determined for a water resource it is binding in the same way as the class and the resource quality objectives"* (National Water Act, 1998).

The ecological reserve may be determined by a number of different methods which vary in the degree of confidence that can be ascribed to the results, *viz.* the original "Building Block Methodology" - BBM (King and Louw, 1998) and the more recent methodologies known as the "Desktop Estimate", the "Rapid Determination", the "Intermediate Determination" and a "Comprehensive Determination" (Münster and Hughes, in press). The Sabie was among the first rivers in South Africa to have Instream Flow Requirements (IFRs) assigned for the maintenance of the complete river ecosystem via the BBM (Tharme, 1997). The conclusion of this process (while subject to periodic audits) has left the way open for water managers and stakeholders to agree on a catchment management strategy that will not only satisfy both the requirements for basic human consumption and the ecological reserve, but will distribute surplus water in a manner that is equitable and which maximises the benefits of the resource.

One method of consistently and explicitly dealing with the multi-sectoral demands for water is to develop and configure a credible catchment scale hydrological and water quality modelling system which can simulate the various sectoral demands for water and which is also capable of modelling aspects of the quality of water. Ideally, this modelling system should operate on a daily time step in order to integrate the hydrological responses of different land uses with the influence of impoundments in determining the ecological reserve and the consequent impacts thereof.

Once a model has been configured and verified, the resulting outputs may be made available to other research projects and modelling efforts which depend on simulated information as surrogates for "long term" time series data sets. Stakeholders would also have the opportunity of utilising such a model and thus learn about the complexities of natural systems and the modelling thereof. Although all models are an abstraction of reality and depend on the scientific assumptions adopted by the developers, they are a means of obtaining consistent and credible results when installed as operational models. The subjective nature of models makes it essential for developers to supply end users with documentation which should include the assumptions on which the model is based and the operational restrictions of the modelling system.

This project seeks to provide the authorities in the catchment and scientists in the KNP with a credible and verified hydrological modelling system to assist both in managing the ecological reserve and in determining the impact of future changes in land use on the hydrology of the Sabie river system.

## 1.3 Objectives of this Study

The School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of Natal was granted funding by the WRC to undertake an investigation into some of the hydrological aspects of managing the delivery of the ecological reserve to the Sabie river system in Mpumalanga, South Africa. The objectives of this project, as set out in agreement with the WRC, involved the following:

- Refining and reconfiguring the *ACRU* modelling system for the 25 DWAF Quaternary Catchments (QCs) making up the Sabie (16 QCs) and Sand (9 QCs) river systems upstream of the Mozambique border. It was envisaged that the final configuration could be used as an active operational hydrological modelling framework for use in current and future water resource conflict resolution in the Sabie catchment. A description of the configuration and a record of the procedures followed in the process of accomplishing this task is contained in Section 2.2 while a verification study is presented in Section 2.3.
- Provide a modelling infrastructure capable of modelling water quality and thus facilitate the use of this modelling system by water quality modellers. Since the water quality capabilities of *ACRU* do not extend beyond the simulation of sediment yield, phosphorus and *E. coli*, the task of providing the necessary water quality functionality to the user involved an investigation of two different approaches, *viz.* either through the development of links between *ACRU* and other water quality models, or by producing an integrated hybrid model which would have the strengths of the hydrology of the *ACRU* model and have directly imbedded water quality functionality that would be required in the management of southern Africa's water resources in the future. A discussion of the findings of this investigation is included in Section 3.1.
- An effort to involve relevant stakeholders in the Sabie River System in order to convince them of the benefits of a modelling approach to Integrated Catchment Management, thereby securing financial support for the maintenance of the modelling system and for any refinements/additions to the modelling infrastructure identified by stakeholders. Various stakeholder-drivencase studies are presented in Sections 2.5 and 2.6 while Section 3.3 contains a discussion on the experiences and lessons learnt in the course of interacting with stakeholders in this project.
- Endeavour to use the modelling system developed for the Sabie River catchment to involve relevant stakeholders in the Olifants River System to the extent that the stakeholders would financially support the application of the modelling infrastructure in the Olifants River catchment. The developments concerning a configuration of *ACRU* for the Olifants catchment is discussed in Section 4.1. Finally:
- Seek collaboration with the Institute for Water Research (IWR) at Rhodes University, to incorporate the Instream Flow Requirements (IFRs) as operating rules in the modelling infrastructure. This would involve the development of routines to facilitate the releases from impoundments in order to satisfy the Instream Flow Requirements (IFRs) of the catchment. The methodology and results of this work, together with other model enhancements and the development of new utilities, are discussed in Section 3.2 of the report.

## 1.4 Acknowledgements

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- the WRC for funding this research,
- Mr David van der Merwe of the WRC for his chairmanship and advice at various stages of the project,
- members of the Steering Committee of this project for their guidance and contributions in the course of this project,
- staff at the CCWR for their contributions to the links between simulation models and for provision of computing facilities,
- the late Prof Rob Johansen for his many hours of instruction regarding the intricacies of the internal structure and workings of the HSPF model and his advice on the proposed link between the *ACRU* and HSPF models,
- the ISCW for supplying Land Type information for the Sabie catchment,
- the South African Weather Bureau for supplying daily rainfall data to the project,
- the CSIR, Environmentek for supplying land cover information,

- DWAF, for supplying daily streamflow data to the project,
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- Sellick and Associates for permission to use findings on research into the consumptive use of water by different land covers,
- Mr Charles Sellick for his time and advice regarding the implementation of operating rules for impoundments,
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- staff at the KNP for their cooperation in supplying information on the Sabie catchment and providing accommodation during field work in the area,
- colleagues at BEEH for their expert contributions to specific aspects of this project,
- Prof Denis Hughes of the IWR for his instruction in the fields of determining ecological reserves and reservoir operating rules and for his unreserved cooperation in supplying BEEH with regular updates of his IFR and post processing software,
- Prof Charles Breen of the INR and Prof Andre Görgens of Stellenbosch University for their contributions to the round-table discussion held at the INR.

## 1.5 Approach

The findings of this study are presented in the following sections:

- an <u>executive summary</u>, which outlines the objectives of the study, provides a brief description of the methodology followed and concludes with the main findings of the study,
- a <u>scientific report</u>, where the *ACRU* model, the configuration of the Sabie catchment and the verification of results are described, and the use of hydrological models in the assessment of IFR's is discussed,
- an <u>evaluation and discussion report</u>, where various approaches of linking the *ACRU* model to water quality models is discussed, some of the software requirements for model enhancement are described and experiences and problems of stakeholder involvement are presented, and
- <u>conclusions and recommendations</u> for future research and
- <u>appendices</u>, which conclude the report.

## SECTION 2 SCIENTIFIC REPORT

The first objectives of this water resources study was to simulate, in a scientifically objective and transparent manner, and using state-of-the-art modelling techniques, the streamflows under present land use conditions of the Sand and Sabie catchments within the borders of South Africa. This required daily flow sequences to be estimated at predetermined locations within the Sand and Sabie catchments and an assessment to be made on where, within these catchments, streamflow and sediments are generated, in terms of both magnitude and seasonality.

This chapter seeks to introduce hydrological models in general and the *ACRU* model in particular. Thereafter, the discretisation of the Sabie catchment is discussed and an analysis of the performance of the *ACRU* model at Subcatchment 25 is performed through verification study at gauging station X3H004. Finally, two case studies are presented to illustrate some of the problems which can be addressed with the *ACRU* model.

### 2.1 Hydrological Simulation Models

Long term observations of hydrological responses at point, plot, field or catchment scale cannot be made for all feasible combinations of climate, soil and land uses for reasons of logistics, time and cost. In order to mimic such responses, hydrological simulation models are used. Such a model is thus viewed as a tool for transferring knowledge (i.e. observations ⇨ analysis ⇨ information ⇨ prediction) from a selected study area (e.g. a research plot or catchment) to other unmonitored areas (e.g. farm, QC or larger area) where the information is required and hydrological decisions may have to be made.

Many functional and structural conceptualizations of simulation models have been formulated. In broad concept, such a model is a quantitative expression of observation, analysis and prediction of the time variant interactions of various hydrological processes (for example, rainfall, infiltration, evaporation or streamflow). Such models are structured collections of physical laws and empirical observations written in mathematical terminology and combined in such a way as to produce a set of results (the model's outputs, such as runoff, based on a set of known and/or assumed conditions (the model's inputs, such as rainfall, soils or land use). Ultimately, in hydrology, such models are applied as real world decision tools in the planning, design and operation of hydrologically related systems and structures (such as reservoirs or irrigation projects). Because the natural and altered prototypes of hydrological systems are complex ones the models abstract, i.e. they simplify, the behaviour of the catchment prototypes by way of sequential algorithms in the form of equations and pathways which describe the soil-plant-atmosphere-vegetation continuum and the hillslope-channel flow continuum (Schulze, 1998a).

#### 2.1.1 What does a hydrological model do?

In order to undertake such a simulation, an hydrological computer simulation model is used. Such a model requires ***INPUT*** of known, calculable or measurable, factors including information on:

- climate (daily rainfall in different parts of the catchment; temperature, potential evaporation and their variations over the catchment and within seasons)
- soils (spatial variations and distributions of horizon depths; soil water retention constants; drainage characteristics; erodibility indices)
- agricultural land uses (hydrologically relevant above and below ground attributes of, e.g. afforestation, with species distribution and levels of site preparation; commercial crops, with management levels considered; subsistence farming; land cover influences on soil loss)
- other land uses (e.g. hydrological response characteristics of formal urban areas; informal settlements)
- runoff (stormflow generating mechanisms; baseflow depletion rates; flow attenuating characteristics)
- sediment yield production (daily stormflow generating and associated peak discharges; erodibility indices of soils; land cover, land management and topographic indices)
- dams (capacities; surface areas; releases; abstractions; evaporation rates; storage-surface area relationships)

- irrigation practices (crop type and seasonality, with mode of scheduling, areas, source of water, application efficiencies accounted for)
- other abstractions (e.g. amounts; sources of water; seasonality) and
- inter-basin transfers (from where; to where; amounts; seasonal differences) (Pike *et al.*, 1997).

This information is ***UTILISED*** in the model by considering

- the climate, soil, vegetative, hydrological, agricultural and human *subsystems* and
- how they are assumed to *interact* with one another;
- what *thresholds* need to be exceeded for responses to take place
- how the various responses are assumed to *lag* and are *attenuated* at different rates and
- whether there are *feedforwards* and *feedbacks* which allow the system to respond in a forward or reverse direction (Pike *et al.*, 1997).

The model then produces ***OUTPUT*** of the unmeasured variables to be assessed, e.g.

- streamflows (from different parts of the catchment; including stormflow and baseflow on a daily basis; return flows) and low flows
- recharge of water through the soil profile into the subsurface vadoze zone
- reservoir status and
- sediment yield (on an event-by-event basis)

on which risk analyses (month-by-month and annual statistical analysis, including flows under median conditions and for the driest flow in, say, 5 or 10 years; flow variability; low flow analyses), as well as daily flood volume analyses for different recurrence intervals, may be undertaken (Pike *et al.*, 1997). Monthly totals of daily streamflows and monthly totals of sediment yields under present land use conditions were considered in this study.

### 2.1.2 What type of model should be used and why?

The hydrological processes of greatest relevance in any land use are those involving interactions of exchanges of water vapour and heat (condensation, precipitation, runoff, evaporation and transpiration), characteristics of the soil (surface infiltrability, subsurface transmissivity/redistribution of soil water and water holding capacity), of land cover (above-ground attributes related to biomass, physiology and structure, as well as below-ground attributes relating to root structure and distribution) and of topographic features of the landscape such as altitude, slope and aspect (Schulze, 1998b). To model this system realistically, the model's structure needs a sound physical and conceptual basis to enable it to reproduce responses associated with changes in land use on transpiration rates, and/or changes in temperature on evaporation rates, and/or changes in rainfall characteristics or soil properties on runoff generating or soil water redistribution mechanisms. The model should also reproduce the other non-linear process responses (both internal state variables and final model output) with inherent and intuitive accuracy and sensitivity, giving the right answer for the right hydrological reason under a range of climatic, land use and physiographic conditions (Schulze, 1999). Hence, ideally only deterministic models operating in relatively short time steps should be used in such impact studies, as models requiring any form of external calibration, particularly of location-specific exponents or physically non-meaningful parameters, are inherently not usable for land use or climate change-driven hydrological impact studies (Schulze, 1997).

### 2.1.3 The *ACRU* model: A description of attributes

The physical-conceptual[1] structure of the *ACRU* model, developed and widely verified at field, small catchment and operational catchments scales in South Africa (e.g. Schulze, 1995; Kienzle *et al.*, 1997; Taylor *et al.*, 1999), together with the advantage of close proximity of the developers of the model, as

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[1]The *ACRU* model is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly (Schulze, 1995).

well as the Decision Support Systems which have been developed around South African hydrological and climatological databases, make this model a strong contender for use as an installed[2] catchment model for managing land use impacts for Catchment Management Agencies (CMAs) and other Water Authorities.

The *ACRU* simulation model was selected as the agrohydrological model to be applied in the Sabie catchment. *ACRU* is a deterministic, physical-conceptual and integrated modelling system (Schulze, 1995), revolving around a daily time step, two soil layer water budget (Figure 1). It is a multi-purpose model (Figure 2) with options to output, *inter alia*, daily values of streamflow, peak discharge, sediment yield, recharge to groundwater through the soil profile, reservoir status, irrigation supply and demand, irrigation and other return flows as well as seasonal crop yields, at any location within the catchment. Internal state variables (for example, soil moisture or interception) as well as end-product model output (for example, streamflow or sediment yield) have been widely verified under different hydrological regimes in Africa, Europe and the Americas (e.g. Schulze, 1995).

*ACRU* complies with most of the model attribute criteria set out in Section 2.1.2 above. In runoff generating routines account is taken of land use/tillage induced changes in initial infiltration and soil water redistributions as well as of rainfall characteristics. Furthermore, the stormflow and baseflow components of runoff are modelled separately and explicitly. Detailed descriptions of processes and options are given in Schulze (1995). However, one of the shortcomings of the present operational version of the model is its limited water quality functionality, with currently only sediment yields, *E. coli* and phosphorus loadings being simulated.

The model is structured (Figures 1 and 2) to be hydrologically sensitive to catchment land use and changes thereof, including the impacts of commercial and subsistence agriculture, the construction and operation of reservoirs, inter-basin transfers, formal and informal urbanised areas, irrigation practices, river flow abstractions and of afforestation.

## 2.2 Hydrological Configuration of the *ACRU* Model for the Sabie Catchment

To facilitate an analysis of streamflows and sediment yields in response to land use practices the model requires input on location, climate, soils, catchment physiography, land uses, hydrological response parameters, irrigation demand and supply, reservoirs, abstractions and inter-basin transfers on a subcatchment-by-subcatchment basis.

### 2.2.1 Location

The Sabie catchment, as defined for purposes of this study, is in Primary Catchment X and covers an area of 6 260.36 $km^2$. It is located north of Nelspruit in Mpumalanga province in an area which stretches latitudinally from 24°30' to 25°15' S and longitudinally from 30°40' to 32°10' E, while altitudinally the area ranges from 150m in the east to over 1 800 m in the west (Figure 3). As expected, the pattern of mean annual precipitation (MAP) is directly correlated to altitude, with values ranging over nearly a 1000mm from 440mm in the east to 1425mm in the west (Figure 3). The catchment consists of two major river basins, from north to south the

- Sand river basin (1 910.02 $km^2$) made up of QCs X32A to X32J and the
- Sabie river basin (4 350.34 $km^2$) made up of QCs X31A to X31M and below the confluence with the Sand, QCs X33A to X33D.

A dolomitic area runs from north to south through the upper reaches of the Sand and Sabie catchments. Runoff processes associated with karst hydrology were therefore expected to dominate the production of streamflows in subcatchments falling within this area.

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[2]The term "Installed Modelling System" refers to a model which has been configured and verified for a specific catchment. Such a system facilitates the easy evaluation of future scenarios since all the input control and data files required by the model have been checked and are readily available.

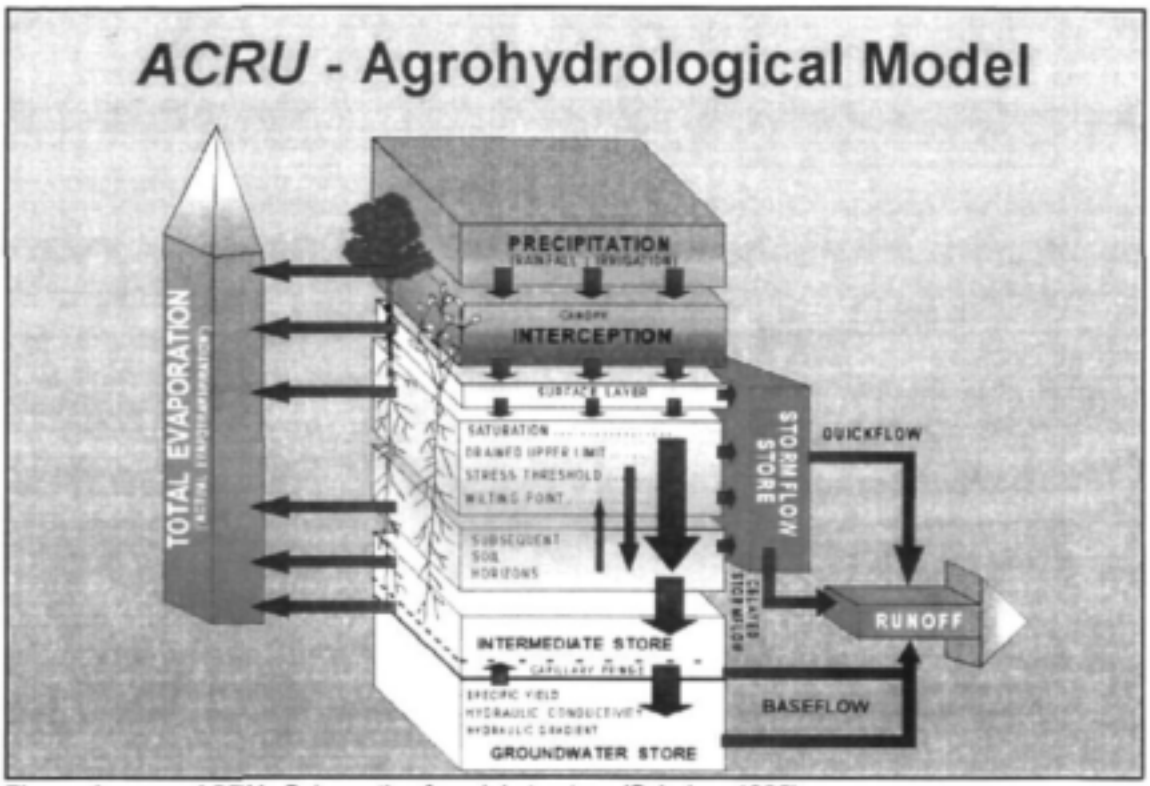


**Figure 1** *ACRU* : Schematic of model structure (Schulze, 1995)

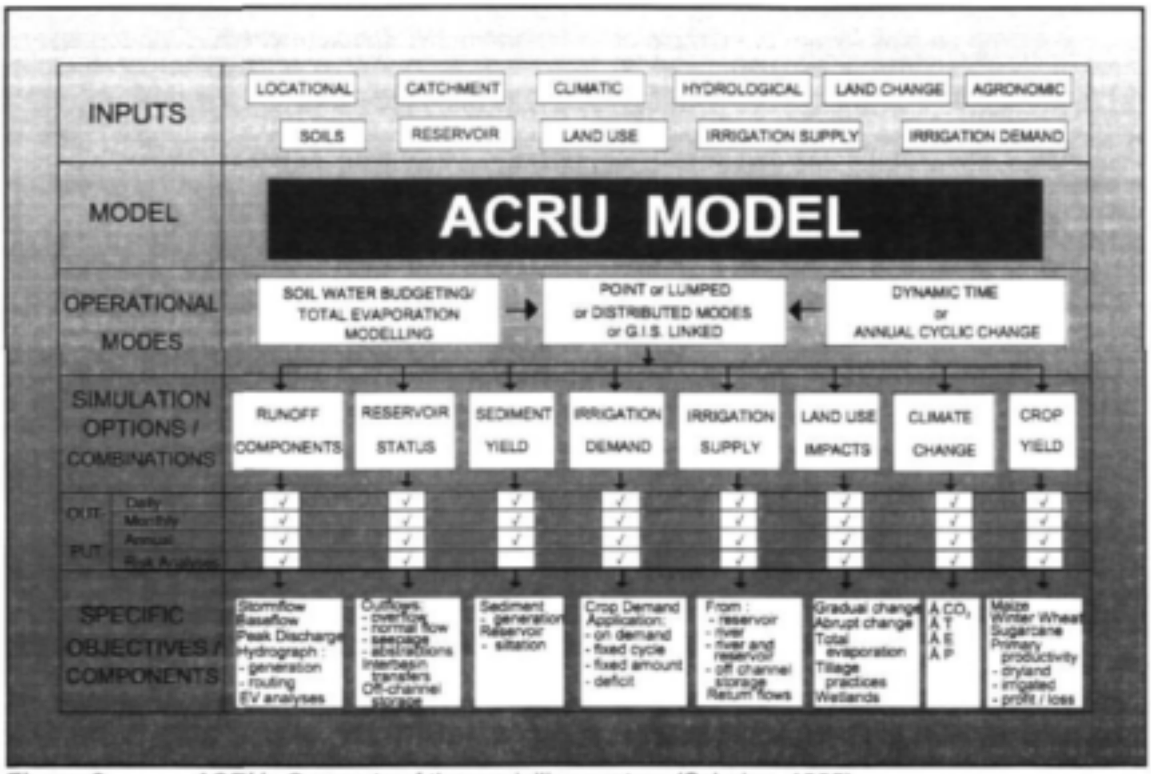


**Figure 2** *ACRU* : Concepts of the modelling system (Schulze, 1995)

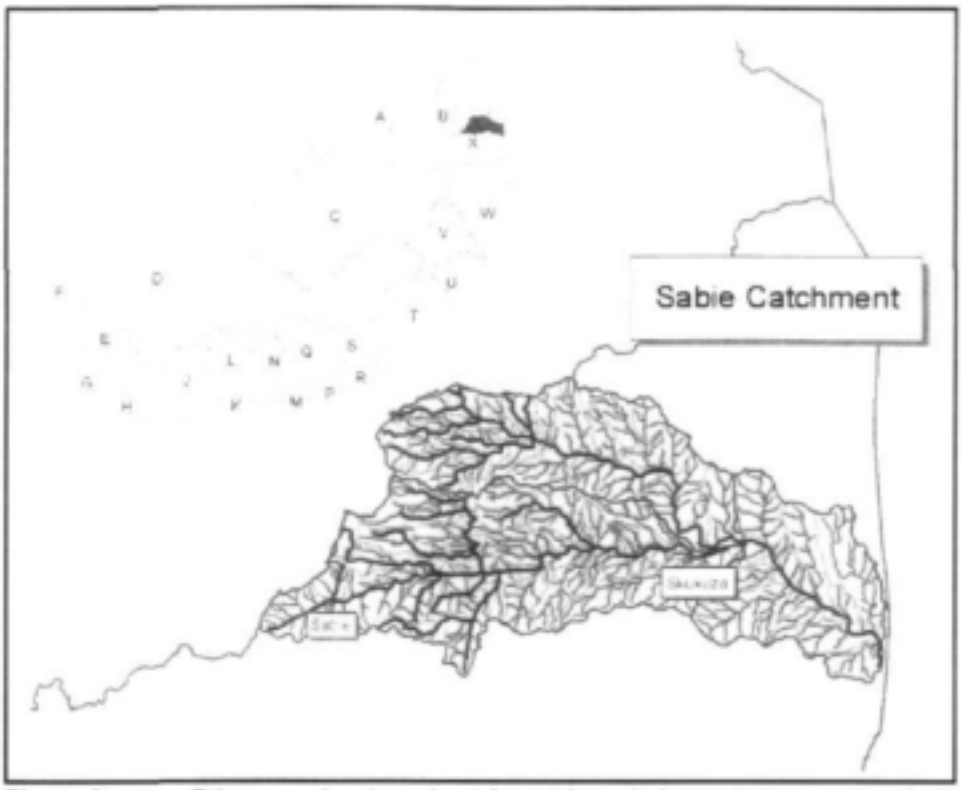


**Figure 3** Primary and major subcatchment boundaries and stream networks in the Sabie catchment

2.2.2 Delimitation of the area into subcatchments

The 25 DWAF QCs making up the study area were selected as the basic spatial units of the Sand and Sabie systems when subdividing them into more homogeneous hydrological regions. Owing to the range of soils, land uses, reservoir locations and climatic variation, the QCs were first subdivided into 17 subcatchments for the Sand and 39 for the Sabie catchments, with each subcatchment having its own unique climate and other inputs. Thereafter, other researchers, water managers and specialists on the hydrological needs of the Sabie system were consulted on their hydrological needs and specialist interests. Prof Jay O'Keeffe, Dr Freek Venter, Ms Sharon Pollard, Mr Alan van Coller and Mr James Mackenzie were then consulted in order to ensure that sites of particular interest to other researchers in the catchment were included in the final model configuration. The requests received from Ms Sharon Pollard, Mr Alan van Coller, Dr Freek Venter and Mr James Mackenzie were incorporated into the final catchment configuration. The eight IFR sites, the location of a new gauging station on the Sabie River and the outlet of the transfer scheme from Injaka Dam to the Sand catchment were also be included in the new configuration.

The final delineation into 130 subcatchments (ranging in area from 0.05 to 266.52 km$^2$) was performed on 1:50 000 topographic maps. This configuration is shown in Figure 4 (a list of the "pseudo" subcatchments corresponding to these subcatchment numbers as used in the *ACRU* simulations is provided in Appendix 4).

A new technique for simulating the water use by different land uses within subcatchments by the *ACRU* model has been developed (Taylor *et al.*, 1999). This involves the creation of "pseudo sub-subcatchments" within the subcatchments. Ideally each pseudo sub-subcatchment should contain a unique major land use. This technique replaces the area-weighted approach whereby the hydrological characteristics of the different land uses of the subcatchment were weighted according to the proportion they occupied. The area-weighting process of averaging water use coefficients, interception losses and root distributions does not account for the non-linearity of hydrological responses between different land

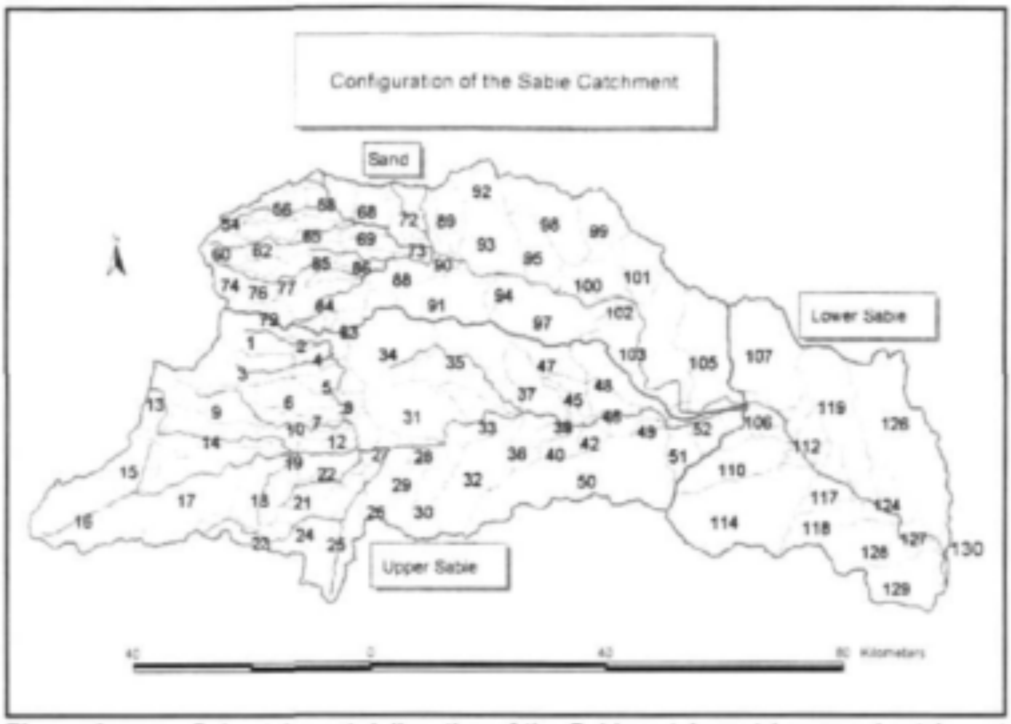


**Figure 4** Subcatchment delineation of the Sabie catchment (some subcatchment numbers have been omitted for sake of clarity)

uses within a defined catchment. A second benefit of this technique occurs in the simulation of hydrological impacts of changing land use scenarios. Previously, the land use information for each subcatchment had to be re-area-weighted for each scenario. Using this technique, only the relative areas of each major land use within the different subcatchments needs to be adjusted for any new scenario.

Subcatchment mean altitude was derived by averaging grid point values of altitude from the 200m Digital Elevation Model (DEM) for South Africa.

### 2.2.3 Rainfall station selection and infilling of missing daily data

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

To account for the regional, seasonal and daily diversity of rainfall, stations with daily rainfall data in and immediately adjacent to the study area were extracted from the Computing Centre for Water Research (CCWR) rainfall database. These stations were analysed by the CalcPPTCor rainfall selection utility (Pike, 1999b), described in Section 2.3.4, which resulted in 25 daily rainfall stations being selected to "drive" the hydrology of the 130 subcatchments (Figure 5). These stations had any missing daily data infilled (patched) for the concurrent period 1 January 1930 to 31 December 1997 using an Inverse Distance Weighting (IDW) technique developed by Meier (1997).

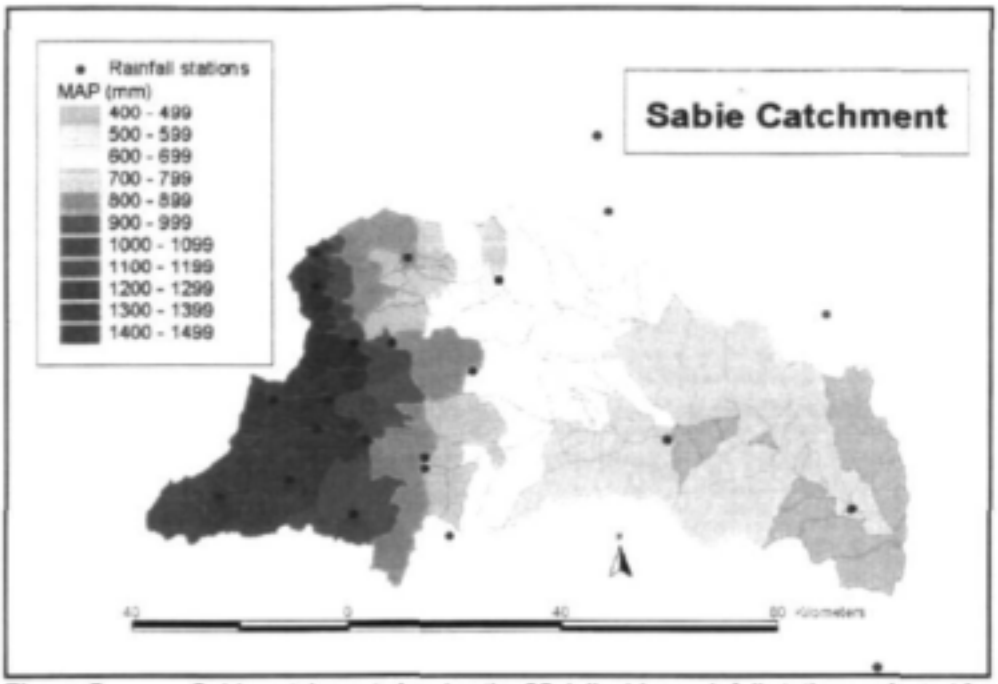


**Figure 5** Sabie catchment showing the 25 daily driver rainfall stations selected for this study and the range in MAP

2.2.4 Temperature and potential evaporation

*ACRU* requires monthly mean values of daily maximum and minimum temperatures in numerous calculations and monthly totals of A-pan equivalent values as its reference for estimating the potential evaporation, $E_r$. Month-by-month subcatchment area-weighted values of monthly means of daily maximum and minimum temperatures and mean totals of A-pan equivalent potential evaporation were determined from 1' x 1' of a degree latitude by longitude gridded values using techniques described in Schulze (1997).

Gridded potential evaporation ($E_r$) values were derived on a regional basis by multiple regression analysis from factors such as maximum temperature, daylength, distance from sea and altitude (Schulze, 1997). These monthly values are then converted by Fourier Analysis to daily values internally within the *ACRU* model. The derived daily values of $E_r$ are then adjusted down by 20% or up by 5% on a day-by-day basis, according to whether or not a threshold rainfall of 5mm was exceeded on that day.

For both temperature and potential evaporation values there are significant spatial variations within the Sand-Sabie catchment on a month-by-month basis. However, the winter months exhibit a smaller difference in $E_r$ throughout the study area than summer months.

2.2.5 Soils

Soils play a crucial role in catchments' hydrological responses by facilitating the infiltration of precipitation, and thereby largely controlling stormflow generation, as well as by acting as a store of water which makes soil water available to plants for transpiration and by redistributing water, both within the soil profile and out of it, by evaporation and transpiration processes and by drainage below the root zone and eventually into the groundwater zone which feeds baseflow (Schulze, 1995).

The GIS coverage of soil Land Types for the Sabie catchment was obtained from the Institute for Soil, Climate and Water (ISCW). In total 38 Land Types, grouped into 9 broad soil mapping units, were identified in the Sand and Sabie catchments. The distributions of the major soil mapping units are shown in Figure 6.

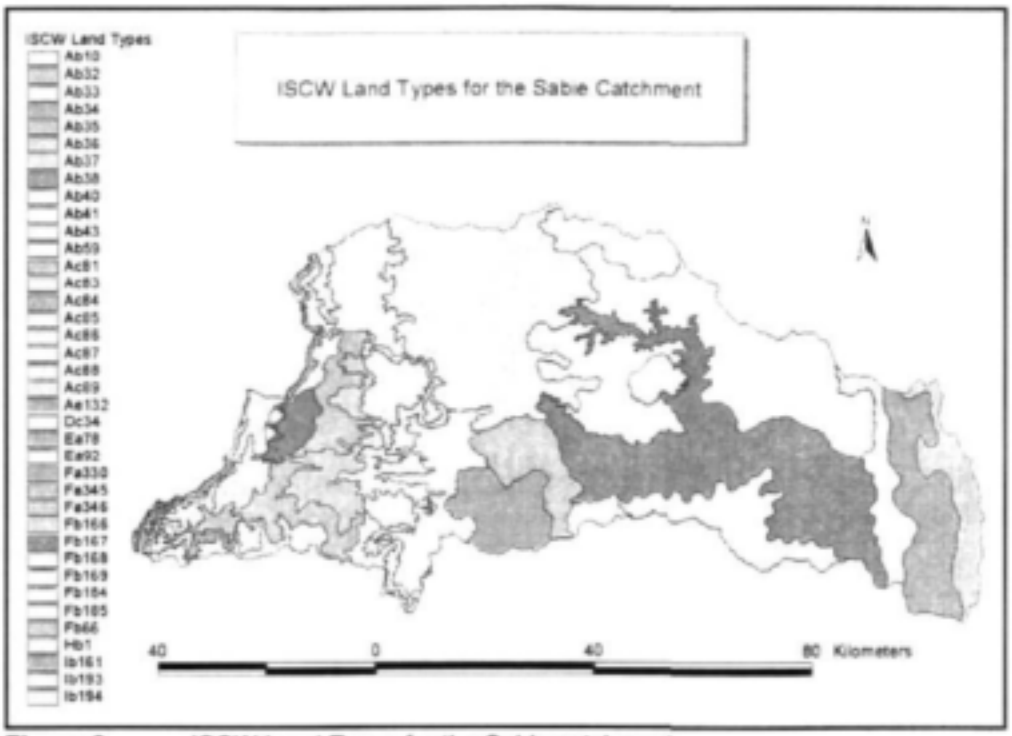


**Figure 6** ISCW Land Types for the Sabie catchment

For each Land Type a vast amount of information on percentages of soil series per terrain unit, soils depths, texture properties and drainage limiting properties was provided by the ISCW. This Land Type information had to be "translated" into the hydrological soils input properties for a two-horizon soil profile, as required by *ACRU*. This translation takes place via a Soils Decisions Support System computer program called AUTOSOILS, developed by Pike and Schulze (1995 and subsequent updates) from information contained in Schulze (1995).

AUTOSOILS output includes values for the thicknesses of the topsoil and subsoil horizons, values of the soil water content at the lower limit (permanent wilting point), drained upper limit (field capacity) and saturation (porosity) for both soil layers, as well as saturated drainage redistribution rates. Values of the above variables were determined for each soil series making up a Land Type and then area-weighted, first according to the proportions of each soil series making up a Land Type and thereafter by the proportions of each Land Type found in a subcatchment. Output from AUTOSOILS also contains runoff related values, derived from Land Type information, of two further variables, *viz.* fractions of adjunct impervious areas within a subcatchment, constituting the areas around channel zones assumed to be permanently wet and from which direct overland flow is hypothesized to occur after a rainfall event, and of disjunct impervious areas such as rock outcrops, from which rainfall running off infiltrates into surrounding areas and influences their water budgets.

The final subcatchment values of soil textures, top- and subsoil horizon thicknesses, retention constants at critical soil water contents, drainage rates and percentages of impervious areas for each of the 130 subcatchments was included in the *ACRU* input "menu" file.

2.2.6 Land cover and land use

Land cover/use input into *ACRU* includes

- an interception loss value, which can change per land use and from month to month during a plant's annual growth cycle, to account for the estimated interception of rainfall by the plant's canopy on a rainday,

- a monthly consumptive water use (or "crop") coefficient (converted internally in the model to daily values by Fourier Analysis), which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference potential evaporation (e.g. A-pan or equivalent), and
- the fraction of plant roots that are active in extracting soil moisture from the topsoil horizon in a given month, this fraction being linked to root growth patterns during a year and periods of senescence brought on, for example, by a lack of soil moisture or by frost.

A further variable which can change seasonally is the coefficient of the initial abstraction ($cl_a$) where, in stormflow generating, the $cl_a$ accounts for depression storage and initial infiltration before stormflow commences. In the *ACRU* model this coefficient takes cognisance of surface roughness (e.g. after ploughing) and the influence of typical rainfall intensities on initial infiltration before stormflow commences. Higher values of $cl_a$ under forests, for example, reflect enhanced infiltration while lower values on veld in summer months are the result of higher rainfall intensities (and consequent lower initial infiltrations) experienced during the thunderstorm season.

In collaboration with the CSIR (Thompson, 1999; personal communication) it was decided to use the National Land Cover (NLC) Database's classification as a basis from which to derive land cover related hydrological variables for the *ACRU* model in South Africa.

From the NLC database 16 land cover classes were identified in the Sabie Catchment, as shown in Figure 7. The class of "Unimproved Grassland" was substituted with the relevant Acocks' Veld Types of North-Eastern Mountain Sourveld, Lowveld Sour Bushveld and Lowveld.

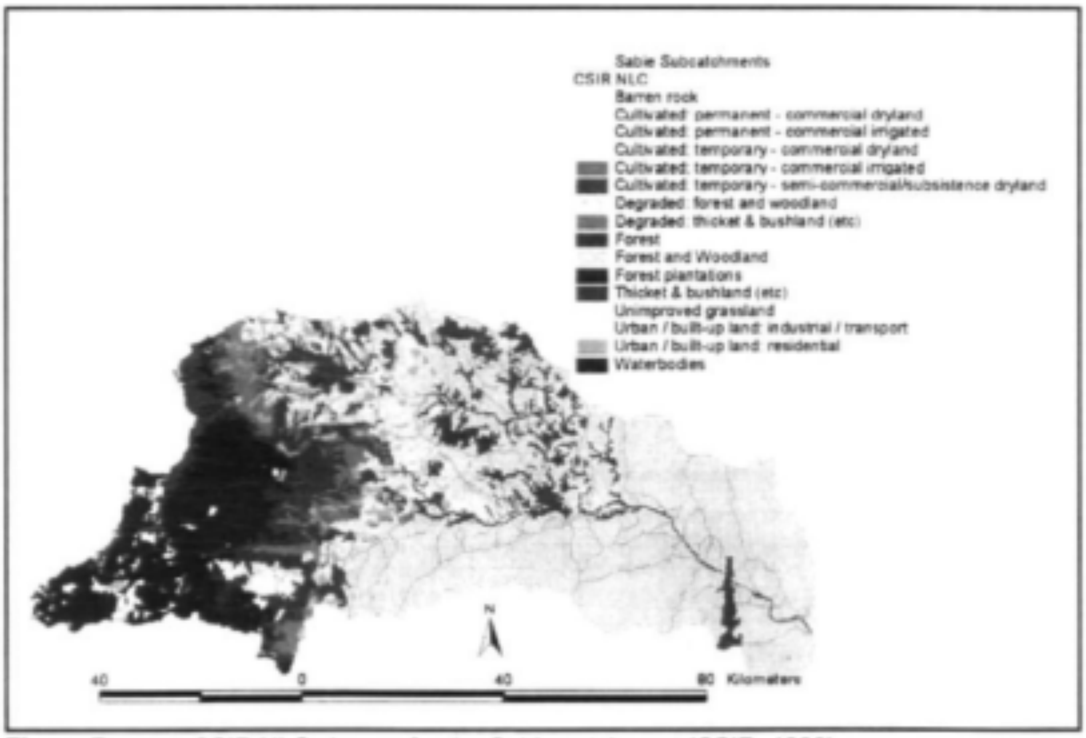


**Figure 7** CSIR NLC classes for the Sabie catchment (CSIR, 1999)

The hydrological variables representing the land cover characteristics of the various classes were assigned to the respective pseudo-subcatchments. None of the values were area-weighted since only one land cover class per pseudo-subcatchment was assumed.

2.2.7 Irrigation

Two main sources of irrigation information were used in this study, *viz.* from Chunnett, Fourie and Partners (CFP, 1990) who published information on the types of irrigation schemes, irrigated crops, and their modes of scheduling, and the information which was collected on a farm-by-farm basis by MBB. The geographic location and areal extent of irrigated areas as defined by MBB (1999) and WRC Report 654/1/97 are presented in Figure 8.

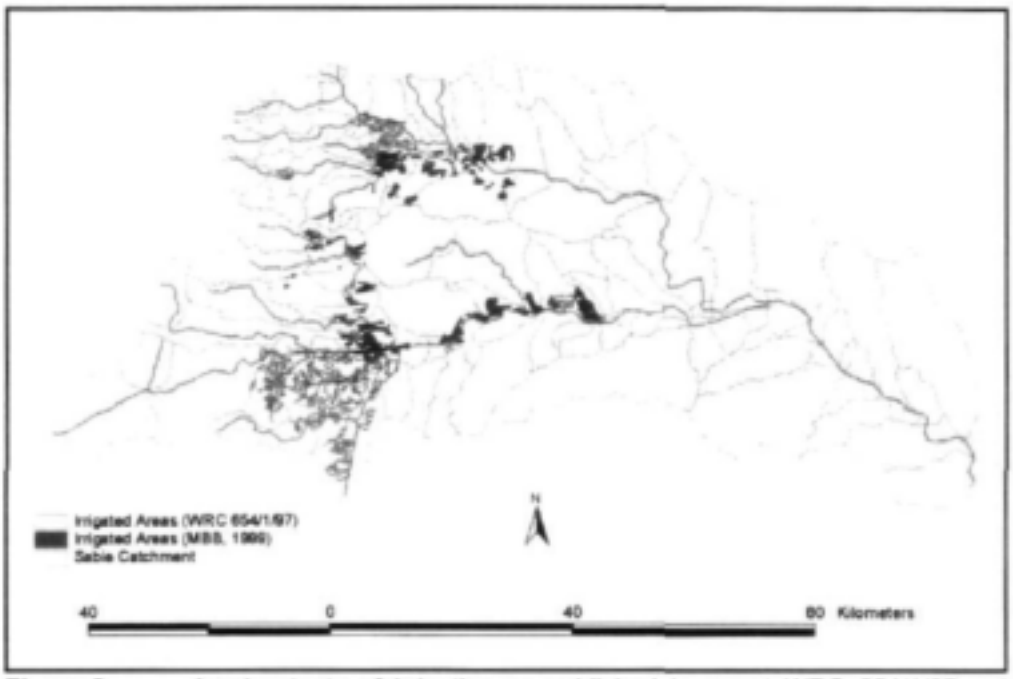


**Figure 8** Areal extents of irrigation as published in report WRC 654/1/97 and collected by MBB, 1999

The latter project was initiated by irrigation farmers in the Sabie catchment to collect information on irrigated areas and pump capacities with possible future water pricing structures in mind. It had been anticipated that this information would be a more accurate guide to present areas under irrigation than the dated information contained in the CFP report. However, information on water abstractions and irrigation scheduling procedures are not available and many of the areas under irrigation in the Sand catchment have been disputed by people with an intimate local knowledge of the area. Consequently it was decided to use the information published by CFP with a view to updating the details once a local stakeholder consensus has been reached regarding the status of present irrigation in the catchment.

It was found that irrigation of perennial, summer and winter crops occurs in 17 of the 130 subcatchments of the study area. The areas under irrigation, the source of water for irrigation, information on irrigated soils, agronomic, irrigation efficiency parameters and the monthly crop water use related input variables were entered into the *ACRU* menu file for the irrigated crops in the Sabie catchment. Where irrigation abstractions were taken from the simulated run-of-river, the supply of irrigation water depended on sufficient streamflows in the river.

Figure 9 shows one of the many conveyance channels in the Sand catchment which transport irrigation water from the Sand River to the irrigated areas.

**Figure 9** A conveyance channel in the Sand catchment

2.2.8 Runoff

In determining daily runoff, the *ACRU* model distinguishes between stormflow and baseflow generation. Variables and parameters used in the generation of runoff include coefficients of initial abstractions, critical soils depths for stormflow generation, impervious areas, saturated drainage rates, baseflow decay rates and stormflow delay factors.

Stormflow from a rainfall event depends on

- the *magnitude* of the rainfall (hence daily rainfall input),
- the *initial abstractions* ($I_a$) before runoff commences (i.e. interception, surface depression storage and initial infiltration - hence inputs on soil properties and seasonally varying evaporative demand, plus a coefficient of initial abstraction, $cl_a$, which also accounts for seasonal rainfall intensity patterns, infiltrability and tillage practices),
- the *wetness of the catchment* (hence the daily multi-soil layer water budget), and
- a *critical soil depth* ($D_{sc}$) considered in stormflow generation (and which is dependent on vegetation, soil and rainfall characteristics),
- the stormflow generated from the catchment's hillslopes after a given rainfall event, not all of which reaches the stream on the same day as the rain fell, because part of it is a delayed lateral flow. A delay factor ($F_{sr}$) has therefore been incorporated in *ACRU* (dependent on catchment slope, area, soil and vegetation characteristics).
- The rain that falls on the permanently wet riparian zone (i.e. adjunct impervious areas) is considered to contribute to same-day and direct stormflow (Schulze, 1995).

The baseflow contribution derives from soil water which has *percolated* out of the base of the subsoil horizon (hence the importance of soil depth and the saturated redistribution fraction) into a baseflow store, from which baseflow amounts are released into the stream at an exponential decay rate ($F_{bf}$).

### 2.2.9 Afforestation

In the simulation of forest hydrological responses the *ACRU* model takes cognisance of tree genera (i.e. it distinguishes between water use characteristics of eucalypts, wattle and pines, but not between species within a genera), tree age, site preparation technique and some of the other attributes which change with afforestation, including changes in LAI, canopy interception, wet canopy evaporation rates, initial infiltration, rooting characteristics and plant water stress thresholds. The plant water stress for the three genera is assumed to commence at different fractions of plant available water, *viz.* at 0.9 for pines, 0.5 for wattle and 0.1 for eucalypts (Schulze, 1995). This indicates that pines are a more conservative water consumer than the other genera, by already partially closing stomata at high plant available water.

Assuming established forest rotations to be in place, with some trees young and others of intermediate age or mature or just harvested, a mean tree age of 8 years for pines was input for simulations. From previous studies of afforested catchments (Schulze, 1995; Summerton, 1996), the thicknesses of the subsoil horizons under forest were increased by an area-weighted percentage of a maximum of 0.25 m (for a subcatchment containing 100% afforestation) to account for the deeper rootedness of forest species).

### 2.2.10 Dams

The reservoir water budget in *ACRU* consists of daily *gains* through streamflows, rainfall onto the water surface areas and (where applicable) inter-basin water transfers, and *losses* through surface water evaporation, abstractions by irrigation and for other purposes, overflow, legal flow releases for environmental purposes and downstream riparian users as well as seepage (Schulze, 1995). To effect a dam water budget the individual dams' capacities at full supply, shapes of the dams and surface areas at full supply need to be known. Furthermore, estimates of seepage and legal flow releases, obtained in this study from CFP (1990) or Surface Water Resources of South Africa (WR90), need to be made.

In order to model a reservoir's daily water status with *ACRU* and the influence of dams on downstream water resources and the ecological reserve, information is required on each dam's location, its full supply capacity (FSC), surface area at FSC, storage : surface area relationships (alternatively, for default computations, the spillway width and shape of the dam), legal flow releases (defaulted to be 1/1500 of FSC per day unless otherwise known), seepage (also defaulted to 1/1500 of FSC per day for earth walled dams) , surface water evaporation, dead storage, abstractions and inter-basin transfers into or out of the dam. Information on dams was obtained from the following sources, *viz.*

- the 1993 LANDSAT TM satellite image
- the WR90 Memoirs for South African QCs (Midgley, Pitman and Middleton, 1994)
- 1:50 000 topographic maps and
- the CFP (1990) consulting report.

Smaller internal dams within a subcatchment were combined to form a single reservoir, assumed to be located at the outlet of the relevant subcatchment and having a capacity and surface area of the combined reservoirs with the *ACRU's* 'Internal Dam' routines then switched on for specific computations. In *ACRU* model runs, dead storage was input as 10% and month-by-month reservoir evaporation rates were obtained for this area from the *ACRU* User Manual, with values varying from 0.62 of A-pan equivalent evaporation in winter to 0.72 in autumn months.

### 2.2.11 Domestic and livestock abstractions

Abstractions from rivers for purposes other than irrigation include domestic water consumption and water supply to game and livestock. Annual volumes were either obtained from CFP (1990) and from WR90, or were derived from livestock and human population census figures. Allocations of 10 $l.person^{-1}.day^{-1}$ for humans, and 45 $l.head^{-1}.day^{-1}$ for large livestock and game were input. These annual total consumptions were apportioned between each month while still conserving the total volume.

2.2.12 Inter-basin transfers

There are two water transfer schemes in Subcatchment 35 where 600 000 $m^3.a^{-1}$ and 500 000 $m^{-3}.a^{-1}$ are pumped out of the Sabie catchment area to supply water to Pretoriuskop and KaNgwane respectively. Transfers were converted to monthly values for input into the *ACRU* menu, from which they are converted to daily values within the *ACRU* model.

2.2.13 Sediment yield

The Modified Universal Soil Loss Equation within the ACRU modelling system was used to estimate individual subcatchment sediment yields on an event-by-event basis. This equation requires the following information as input for each subcatchment:

- event-by-event stormflow volume and peak discharge
- weighting parameters for stormflow and peak discharge
- a maximum and minimum soil erodibility factor
- a slope length and steepness factor
- monthly vegetation/ surface cover factors
- a management practice factor and
- the fraction of the event based sediment yield from the subcatchment that reaches the outlet on the day of the event.

The sediment yield option requires that the peak discharge option be invoked. The Schmidt and Schulze (1984) method of calculating catchment lag was selected. In addition to subcatchment area and MAP this method also requires the following information as input:

- average slope (%) of each subcatchment and
- the 2-year return period value of the 30-minute duration rainfall intensity ($\overline{I}_{30}$, $mm.h^{-1}$).

The average subcatchment slopes were calculated from a 200m altitude grid using ARC/INFO GIS routines. Tables K1 and K2 of Appendix K (Pike *et al.*, 1997) contain information on the soil erodibility and cover factors for each subcatchment in the KNPRRP study area while the $\overline{I}_{30}$ values were calculated from information given in the ACRU User Manual (Smithers and Schulze, 1995).

Owing to a lack of sediment data it was not possible to verify the results of the simulation. However, Jewitt and Görgens (2000) reported that the sediment yields simulated for the KNPRRP by Pike *et al.* (1997) (which were based on the same methodology used in this study) were consistent with the estimates by Rooseboom *et al.* (1992) for the region. The lack of sediment routing functionality in *ACRU* has prevented the subcatchment sediment load generated for each event from being aggregated downstream. This limitation has been overcome in the latest version of the model (*ACRU*2000) and the Sabie catchment can be rerun to output aggregated values once *ACRU*2000 is released. It is therefore recommended that the estimates by Pike *et al.* (1997) be utilized in the interim. Two alternative options are available to obtain estimates at the 130 outlets of the most recent configuration. Either a manual aggregation of the estimated sediment yields can be conducted, or a stand alone application may be used to route the estimates to the required outlets.

2.3 Verification of Model Output

In order to assess the degree to which the hydrological models simulate streamflows realistically, a non-calibrated verification study needs to be conducted whereby simulated values are compared against reliable observed data.

### 2.3.1 The basis of verification studies with the *ACRU* model

As a physical-conceptual model, physically realistic and observationally derived variables on climate, soils, land use, irrigation, other water transfers and dams are input in *ACRU*. Structurally and conceptually *ACRU* has, therefore, been designed specifically to simulate scenarios based on land use impacts. *ACRU* is *not* a parameter fitting model in which parameters are externally calibrated until simulated values mimic observed values; rather, it is a deterministically based model structured to give realistic answers for hydrologically valid and correct reasons.

One nevertheless needs to have the assurance that the modelled streamflow values reflect observed values. For this purpose a verification study of the model output was conducted, where the simulated streamflow values from the model were compared to an observed streamflow data record for the same period. For a meaningful verification of modelled streamflows in an operational catchment, the following are required:

- a long observed streamflow record to capture a wide range of climatic conditions and hydrological responses;
- the quality of the streamflow data to be high, this implying that the gauging structure has been well maintained, kept clear of vegetation and that the rating tables have been updated periodically; furthermore, that the structure be capable of recording data accurately over a wide range of flows with no "overtopping" during high flows;
- the determination of the stationarity of flow records in regard to land use changes, over that gauging period;
- good quality model inputs. These should include records from as many raingauges with daily data within and adjacent to the catchment as possible. Figure 10 (Schulze, 1995) shows the minimum rainfall record that is appropriate for different regions in South Africa. These raingauges should also have data which are concurrent with that of the streamflow record. Detailed and accurate information on soils and land use are also required. If the land use inputs only include recent information, the verification may need to be restricted to the time period for which the land use information is considered reasonably representative. This will ensure the stationarity of the streamflow record.

### 2.3.2 Problems encountered in the course of the verification study

On the basis of the points made in 2.3.1, unsuitable gauging stations need to be systematically eliminated in order that the verification be conducted against acceptable streamflow data. Table 1 shows the characteristics of the data collected at the 10 gauging stations in the Sand and Sabie catchments. The location of these stations is shown in Figure 11.

There are many problems associated with the data measured at the various stations in the Sabie catchment. Overtopping of some of the structures occurs during flows exceeding a certain threshold. Examples of this problem are shown in Figures 12, 13 and 14 where the daily streamflows are shown for gauging stations X3H007, X3H008 and X3H015 respectively. The non-stationarity of the record in X3H007 together with the problem of the gauging station overtopping renders these records unsuitable for verification purposes. The problem of overtopping is clearly evident in Figure 13 where the observed streamflows measured at gauging station X3H008 very rarely exceed 10mm and the majority of streamflows greater than 5 mm are either recorded as "overtopped" or zero flows ("0 mm"). The latter situation poses a serious problem to the modeller since the model normally includes zero flows in the verification unless they are specifically flagged as missing ("m") or overtopped ("+").

Despite the problems associated with the streamflow record at X3H015 (see Figure 14 where overtopping of the gauging structure is indicated by green arrows), the verification does reveal an important aspect of the runoff producing processes. During the drought of 1990, the lag between the observed and simulated flows suggests that the Dolomitic areas alluded to in the description of the study area may influence the timing of flows in the Sabie River. It is therefore important for the user to note that *ACRU* does not model karst hydrological responses and this should be taken into account when making use of the simulated output. Although flood routing will improve the simulations on a daily basis, it would have a negligible impact on this monthly verification since the time of concentration (the time it takes for runoff generated at the most remote point in a subcatchment to flow to the outlet) is expected to be less than a month.

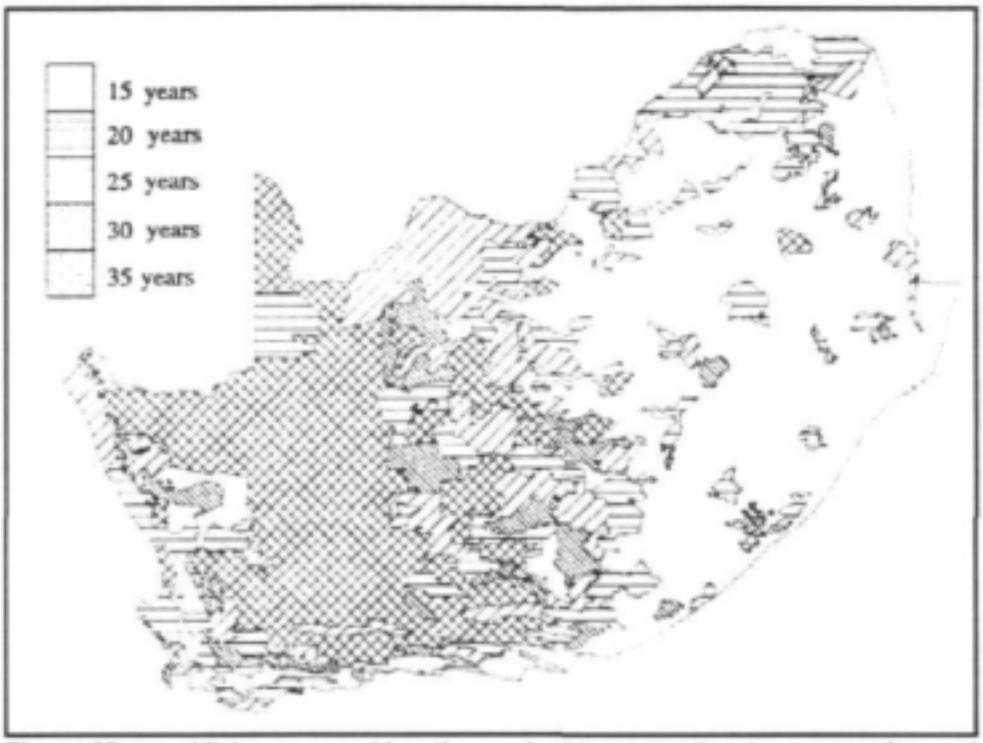


**Figure 10** Minimum record lengths required to ensure that the means of annual rainfall estimates are within 10% of the long term mean 90% of the time (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995)

**Table 1** Monitoring periods of observed daily streamflow records for the 10 gauging stations in the Sand and Sabie catchments

| Catchment | Sub-catchment | Station Identification Code | Contributing Area ($km^2$) | Monitoring Period |
|---|---|---|---|---|
| Sand Catchment | 94 | X3H008 | 1071.98 | 07/09/1967-31/05/1998 |
| Sabie Catchment | 16 | X3H001 | 173.21 | 16/03/1948-30/06/1998 |
| | 15 | X3H002 | 55.87 | 01/02/1964-30/06/1998 |
| | 13 | X3H003 | 46.11 | 17/03/1948-30/06/1998 |
| | 25 | X3H004 | 215.94 | 22/02/1948-30/06/1998 |
| | 22 | X3H006 | 676.59 | 04/09/1958-30/04/1998 |
| | 23 | X3H007 | 60.94 | 13/11/1963-15/09/1991 |
| | 4 | X3H011 | 212.48 | 29/11/1978-31/01/1998 |
| | 125 | X3H015 | 5783.71 | 03/02/1987-31/05/1998 |
| | 44 | X3H021 | 2426.56 | 16/11/1990-30/06/1998 |

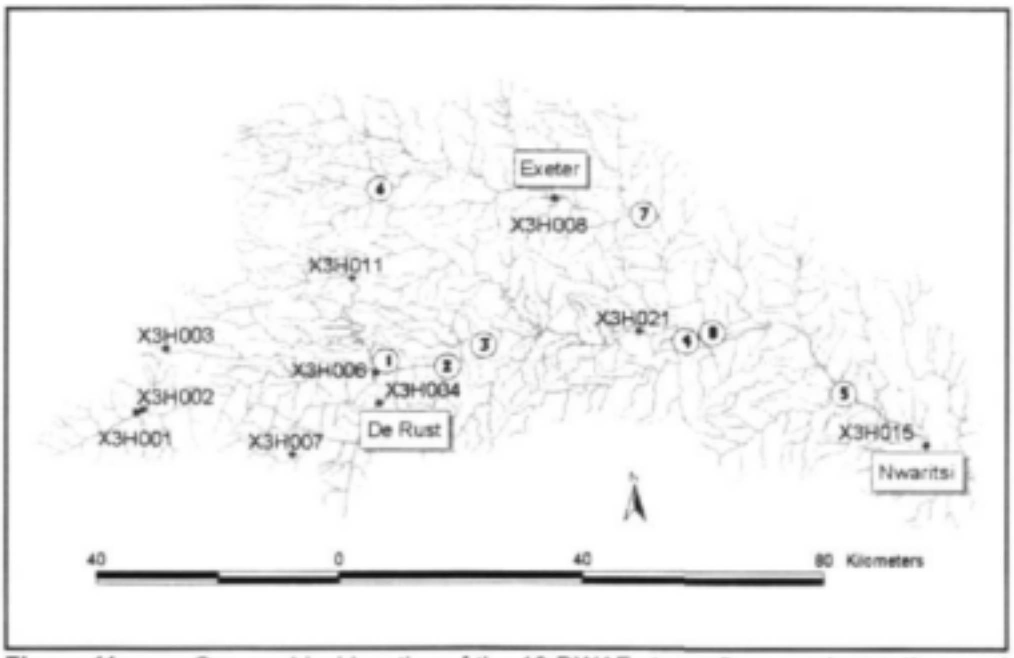


**Figure 11** Geographical location of the 10 DWAF streamflow gauging stations and eight IFR sites in the Sabie catchment

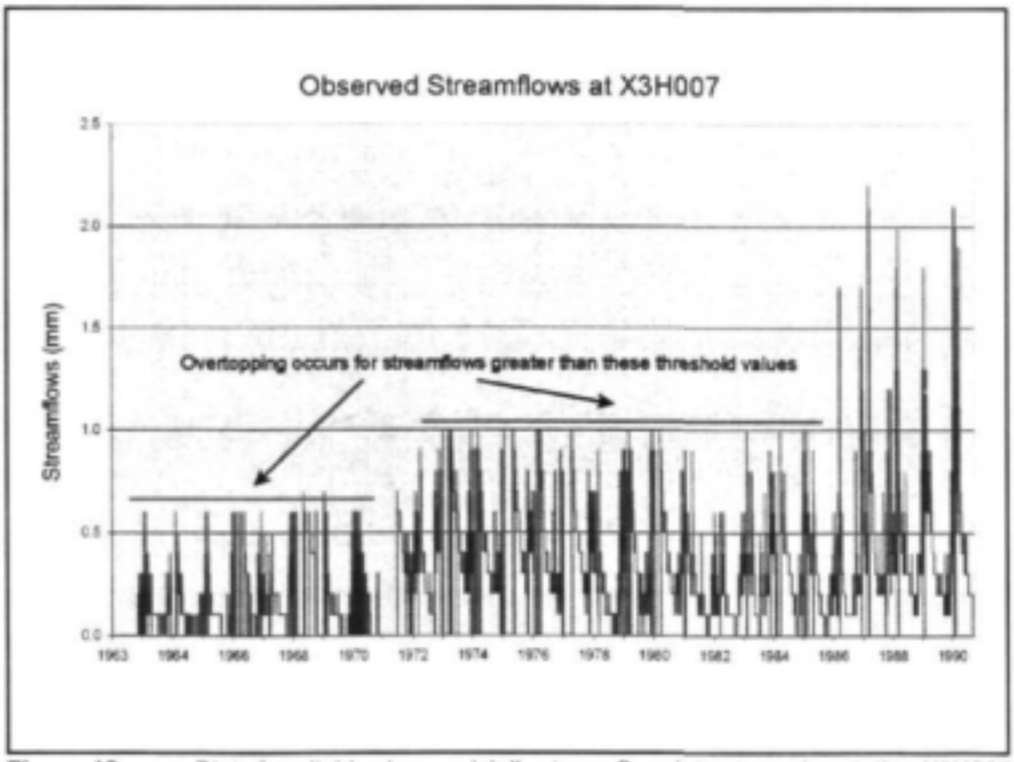


**Figure 12** Plot of available observed daily streamflow data at gauging station X3H007 for the period 13 November 1963-15 September 1991, showing the non-stationarity of the record up to 1986 because of overtopping of the structure

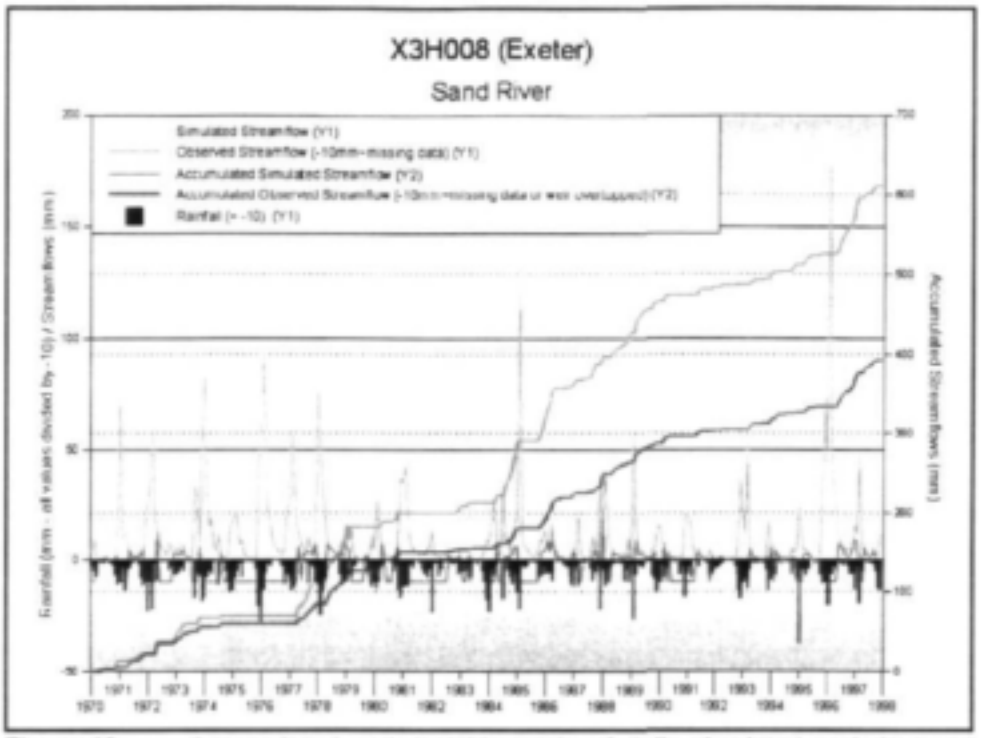


**Figure 13** Accumulated and monthly totals of daily simulated and observed streamflows at gauging station X3H008 for the period 1970 to 1997

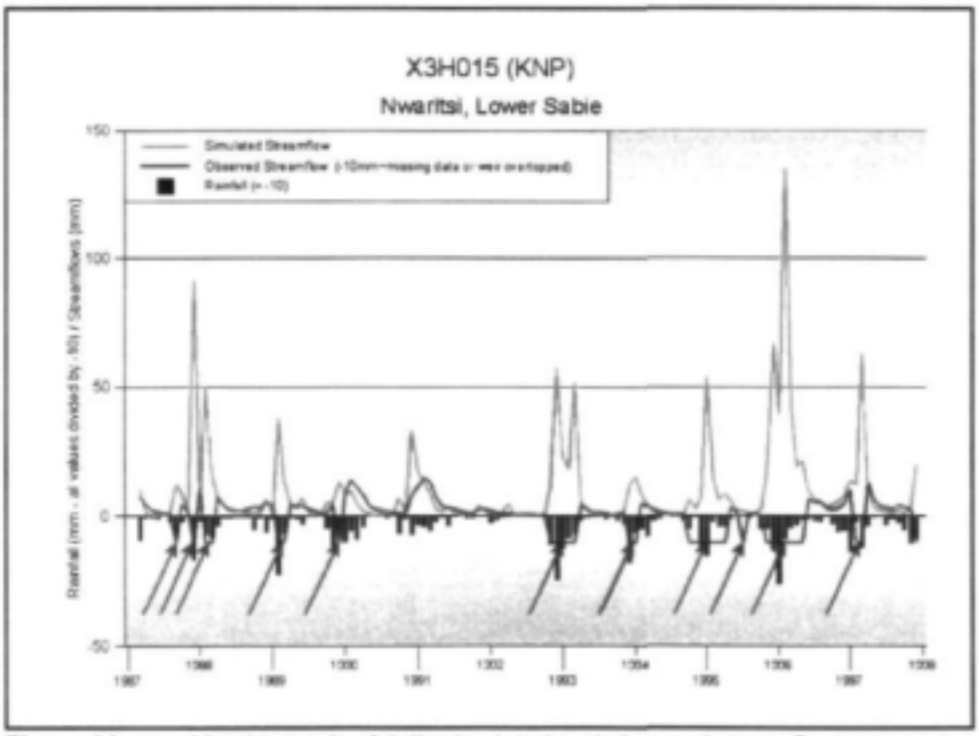


**Figure 14** Monthly totals of daily simulated and observed streamflows at gauging station X3H015 for the period 1987 to 1997 showing the problem of overtopping (indicated by green arrows) and the lag effect of the upstream karst hydrological processes

The above-mentioned problems with the majority of data in the Sabie Catchment resulted in the verification study of output from the *ACRU* model being restricted to gauging stations X3H004 and X3H015 (shaded in Table 1) for periods where the quality of the streamflow data is acceptable. It should, however, be borne in mind that there is only one raingauge in the catchment contributing to simulations conducted at the gauge site of X3H004, an area of 214 km$^2$, and that that raingauge is outside the catchment (cf Figure 5).

This section has highlighted some of the important points to be borne in mind when conducting a verification study in an operational (as opposed to a research) catchment, *viz*.

- The data need to be thoroughly checked before undertaking such a study. A simple regression plot of daily rainfall and observed streamflows will reveal many problems which can occur when the structure is overtopped;
- The number of daily streamflow records with values equal to the upper limit (maximum value) of the data record should be checked. An abnormally high occurrence of these instances could also indicate that overtopped values have not been flagged in the record;
- The streamflow record should be checked for systematic errors which may indicate that the rating table is incorrect or outdated. These data need to be flagged as being unreliable eliminated before a meaningful verification can take place;
- Double mass plots can indicate non-stationarity in the streamflow record. This usually occurs when present land use information is used for the duration of a long term verification study (so-called "hindcasting") without due consideration being given to major changes in land use and/or management practises within a catchment;
- When conducting a monthly verification studies one needs to be aware that if a rain event occurs on the last day or two of the month, the observed runoff will only be reflected in the following month; and finally
- Since rainfall data are discrete and are recorded from 08:00 to 08:00, a rainfall event spanning the 08:00 cutoff could be recorded as two separate events which greatly diminishes its impact on the hydrological response of the system.

2.3.3 Verification of streamflows at gauging station X3H004 and X3H015

Figures 15 and 16 show the double mass plots of monthly totals of daily simulated and observed streamflows at gauging stations X3H004 (1965 to 1997) and X3H015 (1987 to 1997). In the interests of transparency, and to add credibility to the results of this verification study (by ensuring that an independent study will yield identical results to those reported below) the observed data which were excluded from the analyses are presented in Figures 17 and 18. The decision to discard these data points was taken when it became evident that the volume of runoff recorded by the gauging instrument was disproportionate to the amount of rainfall occurring in that month. It is suggested that this problem could be the result of one or more of the following factors:

- either the rainfall or streamflow records include serious observational errors which have not been flagged as unreliable data, or
- an inaccuracy has occurred in process of converting the stage data to runoff data via a rating table, or thirdly
- these "rogue" data points are records of flows which were generated by rainfall events which were not recorded at the raingauges selected for this study.

Months with high flows are well simulated on a monthly totalled basis. The verification also identifies potential problems in the timing the monthly flows, where some of the simulated monthly flows precede the observed flows (e.g. the summers of 1975, 1976 and 1980). However, the timing of some of the other monthly flows seems to be in phase (1972, 1978, 1985 and 1989). The inconsistency of the timing of the flows and the fact that this phenomenon is evident from monthly totals seems to suggest that the problem is of a hydrological nature as opposed to inaccuracies in the data. The *ACRU* model tends to underestimate autumn and winter low flows in the Sabie.

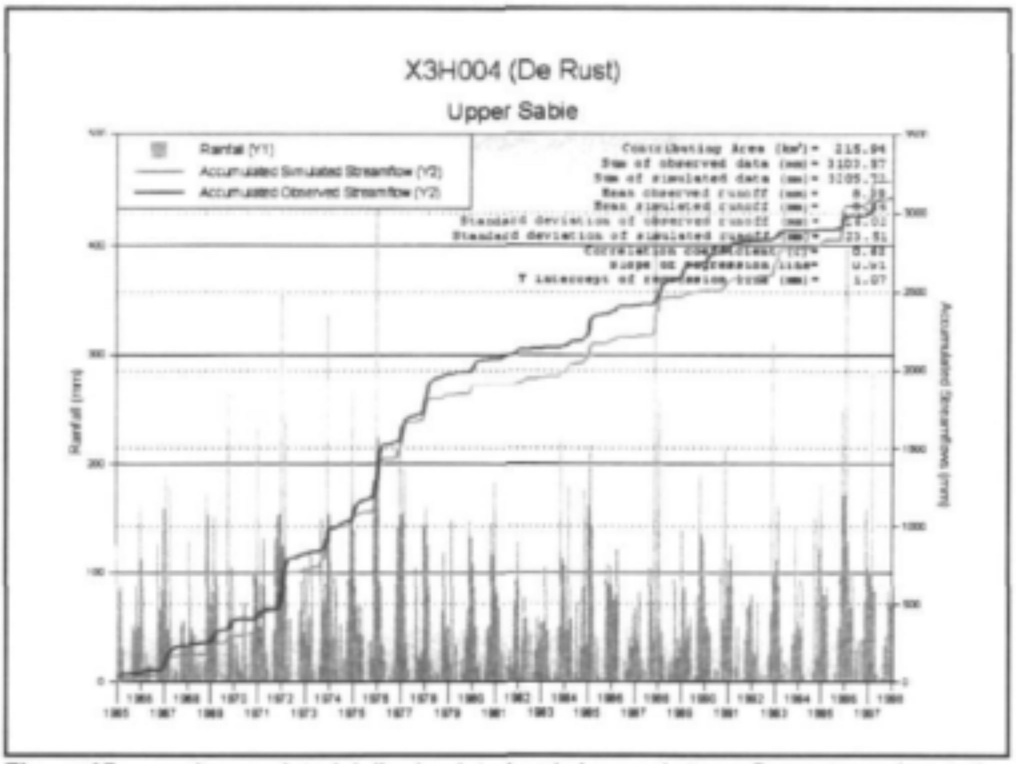


**Figure 15** Accumulated daily simulated and observed streamflows at gauging station X3H004 for the period 1965 to 1997

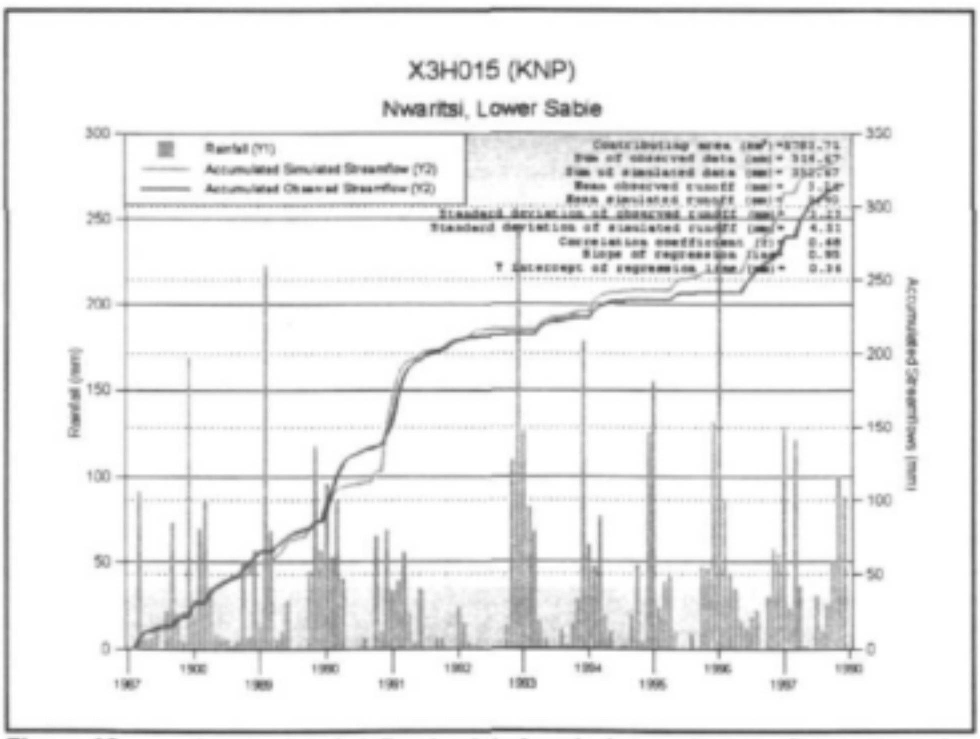


**Figure 16** Accumulated daily simulated and observed streamflows at gauging station X3H015 for the period 1987 to 1997

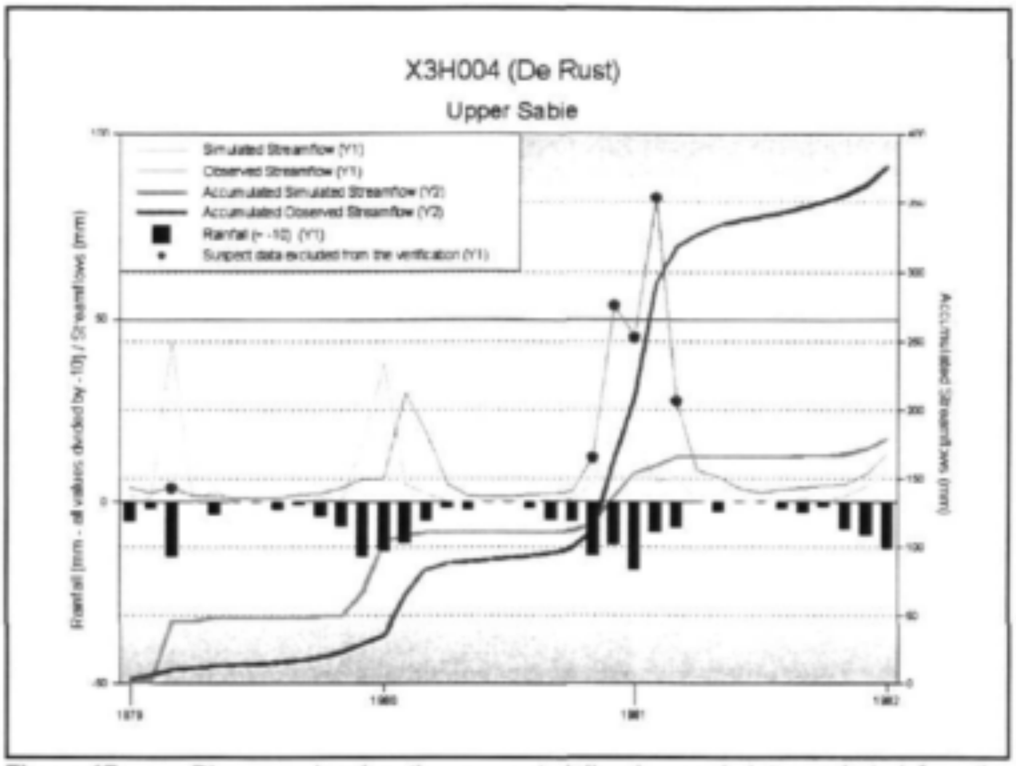


**Figure 17** Diagram showing the suspect daily observed data excluded from the verification at gauging station X3H004 (compare suspect data points with observed rainfall and simulated streamflows)

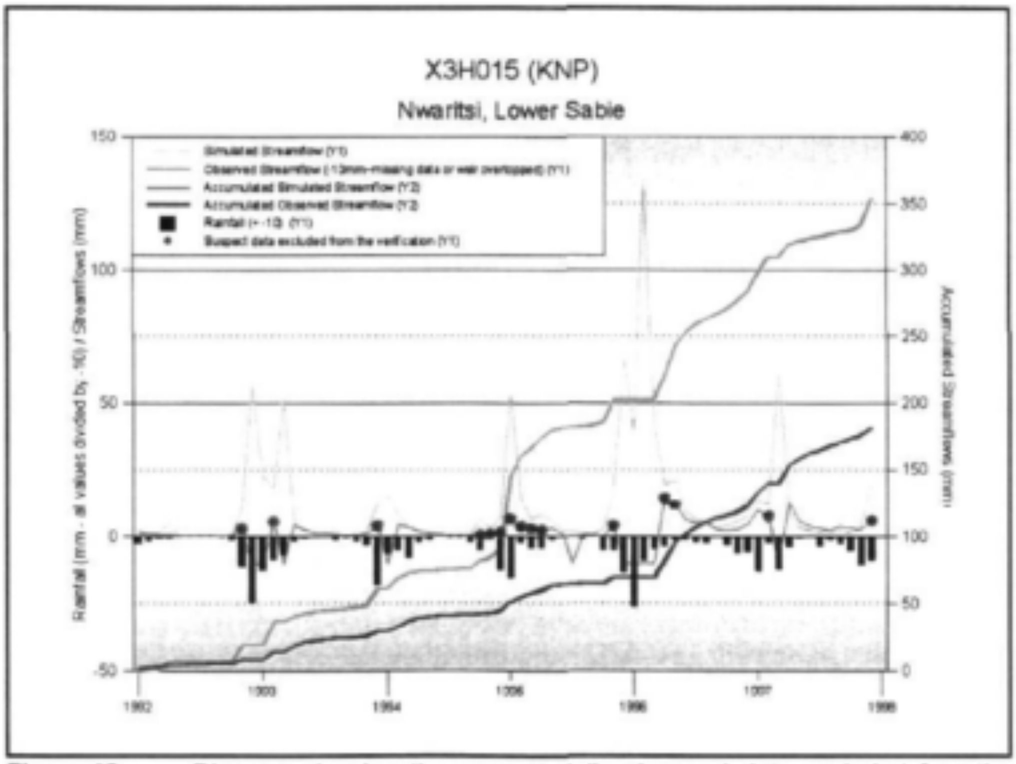


**Figure 18** Diagram showing the suspect daily observed data excluded from the verification at gauging station X3H015 (compare suspect data points with observed rainfall and simulated streamflows)

Despite the inability of ACRU to simulate the karst hydrological processes upstream of X3H015 explicitly, the verification conducted at this gauging station against 11 years of data of acceptable quality serves to show that the model performs adequately at the outlet of this subcatchment which constitutes 92% of the total Sabie Catchment area for this period.

These verifications together with some of the problems encountered in the accurate simulation of low flows and suggestions for future research are discussed in the conclusions and recommendations of this report. Given the problems described with the quality and availability of data in the Sabie and Sand catchments, the opportunity to verify the model against reliable data from this gauging station is a valuable exercise. These results show that at X3H004 and for this period of the streamflow record, the differences between the observed data and the output from the model is within acceptable limits. This verification, together with many others cited for other catchments in the published literature (e.g. Schulze, 1995; Kienzle *et al.*, 1999; Taylor *et al.*, 1999), engender confidence in the conceptual structure of the model, a vital step towards acceptance of the modelling results by the end users and decision makers. This verification is particularly encouraging when one considers that the subcatchments contributing to the streamflows recorded at this gauging station contain irrigated areas in excess of 1 700 ha in summer and 1 450 ha in winter.

## 2.4 Examples of Model Output Useful for Assessing the Ecological Reserve

It is becoming increasingly recognised that the large-scale abstraction of water from river systems cannot continue in an uncontrolled manner without having long-term repercussions with respect to the ecological status of the river and downstream users of water. In order to address this problem, DWAF now requires information on the quantity and patterns of flow that should be allowed to continue downstream of a proposed water resource development.

### 2.4.1 Determination of the quantity component of the ecological reserve

The process of determining the nature of the ecological reserve is referred to as an Instream Flow Assessment (IFA) and is frequently carried out using what has become known as the "Building Block Methodology", BBM (King and Louw, 1998) which is applied during a workshop attended by a range of specialists. The methodology is constantly being refined and developed as it is applied to rivers in different parts of the country, and has been accepted for use when developments are planned and time and data are limited. The application of the BBM results in a recommended flow regime which is expressed in a table of monthly instream flow requirements (IFRs) that are considered to be essential to sustain the river in a desired future condition, or state.

The IFR tables define the low flow (i.e. baseflow) and high flow (flood and freshes) requirements for maintenance situations, i.e. to facilitate the year-by-year ecological maintenance of the river, as well as for drought situations, i.e. to provide for aquatic habitat survival in drought years, and below which flows should never fall (Hughes and Ziervogel, 1998). In addition, some supporting information that describes the duration and other features of the required highflow events, or the manner in which variations are expected to occur between wet, average and dry years, is frequently included. An example of an IFR table for Site 4 on the Sabie River is given in Table 2 (DWAF, 1997).

The IFR table can readily be translated into required monthly release volumes and can be used, in combination with potential water abstractions, to assess the feasibility of various reservoir design options. However, before this information can be used effectively to determine the day-to-day releases that must be made from a reservoir to satisfy the IFA, it must be translated into a set of reservoir operating rules. Those developing the IFR process consider it of the utmost importance that such operating rules should somehow be linked to the prevailing hydroclimatic conditions. This, in turn, would allow the scientists to look beyond the rigid numbers in the IFR table, which take that form because of the requirements of the planners, and the scientists see a more normal-looking daily time series that reflects the IFR and is linked to natural climatic variations (Hughes *et al.*, 1997).

**Table 2** Maintenance and drought IFRs for IFR Site 4 on the Sabie River

| BUILDING BLOCKS | | OCT | NOV | DEC | JAN | FEB | | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAINTENANCE IFR BASEFLOWS | Magnitude ($m^3.s^{-1}$) | 3 | 4 | 5 | 6 | 9 | | 8 | 7 | 6 | 5.2 | 4.5 | 4 | 3.4 |
| | Depth (m) | 0.82 | 0.89 | 0.96 | 1.02 | 1.17 | | 1.12 | 1.07 | 1.02 | 0.97 | 0.93 | 0.89 | 0.85 |
| | Volume (MCM) | 8 | 10.4 | 13.4 | 16.1 | 21.8 | | 21.4 | 18.1 | 16.1 | 13.5 | 12 | 10.7 | 8.8 |
| | FDC % V | 100 | 99 | 99 | 100 | 94 | | 96 | 98 | 98 | 98 | 98 | 98 | 98 |
| | FDC % P | 54 | 69 | 86 | 79 | 74 | | 77 | 76 | 65 | 59 | 55 | 48 | 49 |
| HIGHER FLOWS | Magnitude ($m^3.s^{-1}$) | 6 | 8 | 30 | 12 | 50 | 130 | 12 | 10 | | | | | |
| | Depth (m) | 1.02 | 1.12 | 1.83 | 1.3 | 2.21 | 3.15 | 1.3 | 1.22 | | | | | |
| | Duration (d) | 3 | 3 | 7 | 5 | 10 | 14 | 5 | 5 | | | | | |
| | Return Period (y) | 0.0424 | 0.0424 | 0.0424 | 0.0424 | 0.0424 | 0.0438 | 0.0424 | 0.0424 | | | | | |
| | Volume (MCM) | 0.4 | 0.5 | 7.6 | 1.3 | 17.7 | 7.31 | 0.9 | 0.6 | | | | | |
| | FDC % V | 75 | 75 | 18 | 78 | 25 | 7 | 80 | 90 | | | | | |
| | FDC % P | 17 | 31 | 8 | 45 | 20 | 7 | 60 | 57 | | | | | |
| CAPPING FLOWS | | None Specified | | | | | | | | | | | | |
| DROUGHT IFR BASEFLOWS | Magnitude ($m^3.s^{-1}$) | 2 | 2.5 | 3 | 3.5 | 4 | | 3.7 | 3.3 | 3.1 | 2.8 | 2.5 | 2.3 | 2.1 |
| | Depth (m) | 0.73 | 0.77 | 0.82 | 0.85 | 0.89 | | 0.87 | 0.84 | 0.82 | 0.8 | 0.77 | 0.76 | 0.74 |
| | Volume (MCM) | 5.3 | 6.5 | 8 | 9.4 | 9.7 | | 9.9 | 8.6 | 8.3 | 7.2 | 6.7 | 6.2 | 5.4 |
| | FDC % V | 100 | 100 | 100 | 100 | 100 | | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | FDC % P | 72 | 87 | 92 | 97 | 95 | | 96 | 95 | 93 | 90 | 87 | 81 | 77 |
| HIGHER FLOWS | Magnitude ($m^3.s^{-1}$) | | 5 | 6 | 7 | 8 | | 7 | 6 | | | | | |
| | Depth (m) | | 0.96 | 1.02 | 1.07 | 1.12 | | 1.07 | 1.02 | | | | | |
| | Duration (d) | | 3 | 3 | 3 | 3 | | 3 | 3 | | | | | |
| | Return Period (y) | | 0.0424 | 0.0424 | 0.0424 | 0.0424 | | 0.0424 | 0.0424 | | | | | |
| | Volume (MCM) | | 0.4 | 0.4 | 0.4 | 0.5 | | 0.4 | 0.3 | | | | | |
| | FDC % V | | 97 | 97 | 99 | 96 | | 99 | 100 | | | | | |
| | FDC % P | | 78 | 78 | 65 | 77 | | 81 | 85 | | | | | |

| MAINTENANCE IFR | BASEFLOW | HIGHER FLOWS | TOTAL | DROUGHT IFR | BASEFLOW | HIGHER FLOWS | TOTAL |
|---|---|---|---|---|---|---|---|
| VOLUME (MCM) | 170.3 | 47.5 | 217.8 | VOLUME (MCM) | 91.2 | 2.3 | 93.5 |
| AS % OF MAR | (V) 28.7<br>(P) 41.3 | (V) 8.0<br>(P) 11.5 | (V) 36.7<br>(P) 52.8 | AS % OF MAR | (V) 15.4<br>(P) 22.1 | (V) 0.4<br>(P) 0.6 | (V) 15.8<br>(P) 22.7 |
| MAR (MCM) | (V) 594 | (P) 412 | | | | | |
| MEDIAN (MCM) | (V) 512 | (P) 338 | | | | | |

V=Virgin Land Cover
P=Present Land Use
FDC=Flow Duration Curve
MCM=million $m^3$
MAR=Mean Annual Runoff

### 2.4.2 Assessment of operating rules with the *ACRU* model

The determination of the IFR with the BBM is an interdisciplinary exercise involving ecologists, hydrologists, engineers and policy makers. Adapting the *ACRU* model to mimic the actual IFR process is clearly unfeasible. However, it would be advantageous if *ACRU* could be modified to simulate the effects of different reservoir operating rules based on a particular IFR. The translation of IFRs to reservoir operating rules has been addressed by Hughes and Ziervogel (1998) and Hughes (1999), whereby the daily time-step reservoir balance accounting features of the HYMAS model (Hughes, 1992) are used in the water resource systems model (DAMIFR) to simulate the conditions within the reservoir to determine the actual distribution of available water. The required IFR releases, having been related to the prevailing climate, are provided by the IFR model (Hughes *et al.*, 1997) and used as input as a time series to the DAMIFR model. A set of operating rules is then determined by DAMIFR and these are designed to control the proportion of the daily IFR requirement that is actually released from the reservoir.

Routines have been developed for *ACRU* which provide the "climatic cue" required by reservoir operators in order that releases from the dam reflect the prevailing climate. It was decided that the streamflows at a strategic point in the catchment would be a favourable signal of the climatic conditions and could be used to provide the "trigger" for releases from the reservoir, the assumption being that anthropogenic influences, such as inter-basin transfers and abstractions above the monitoring site, are minimal.

The user provides the model with the appropriate point in the catchment which is to be used as an indicator of hydroclimatic conditions and the percentage of these flows which should ideally be met. This point may be a subcatchment outlet, reservoir or a streamflow gauging station. Simulated streamflows, *overflows, or in the case of a gauging station, observed streamflows are then used at the impoundment* for which operating rules are required to provide the timing of the releases. These releases are effected in one of five ways, *viz.* seepage (in the case of earthen walls), legal ("normal flow") releases, draft from the reservoir, overflow (spillage) or, if the dam is above the dead storage level, via special releases.

The streamflows at the selected point, while acting as an index of the volume of water generated by the catchment in response to the prevailing climate, cannot be used as a measure of the actual volumes required at downstream sites to satisfy the IFRs. At the time of writing (December 2000), the magnitude of IFR releases still need to be determined by the DAMIFR model. This is achieved by supplying *ACRU* with a time series of IFR releases from the DAMIFR stipulating that the DAMIFR flows be used to replace simulated streamflows as input to downstream catchments ( IOBOVR=1). Research is currently being undertaken, with input from the IWR (Hughes, 1999; personal communication), to transfer the remaining DAMIFR functionality into the *ACRU* model in order to determine the actual magnitude and timing of releases to satisfy downstream IFRs.

## 2.5 Stakeholder Case Study 1 : An Assessment of the Impact of Selected Land Use Scenarios on Streamflows of the Sand River

One of the objectives of this study was to engage and interact with relevant stakeholders and other researches with an interest in the Sabie and Sand catchments. Some of these activities, experiences and lessons learnt are summarised in this section and in Section 2.6.

We were approached by researchers from the Association for Water and Rural Development (AWARD), who were involved in a project entitled "Save the Sand Phase 1, Feasibility Study: The Development of a Proposal for a Catchment Plan for the Sand River Catchment", to conduct the hydrological simulations of various land use scenarios in the Sand River catchment. The emphasis of Section 2.5 is to highlight some of the areas of concern which were encountered in the course of interacting with researchers from other disciplines on a common project. The methodology and results of the study are reported in Pollard *et al.* (1998).

The Sand River catchment was originally subdivided into three major zones (Zones A, B and C, as per Figure 12.3 of the report by Pollard *et al.*, 1998). In this case study only Zone A was considered, in which six land use change scenarios, based on a 1996 LANDSAT TM image (CSIR), were analysed (Table 12.8, Pollard *et al.*, 1998).

2.5.1 Methodology : Proposed land use scenarios

AWARD originally requested that scenarios representing every possible combination of removal and replacement of land uses be conducted. After careful consideration, the infeasible scenarios were eliminated and only simulations for the most likely scenarios were conducted. These involved the replacement of varying areas of forestry with realistic combinations of alternative land uses in Zone A. This amounted to eight scenarios in all (Table 3). Further examination of the scenarios suggested that Scenarios 5 and 6 (Table 3) could also be discarded, resulting in six scenarios to be assessed. A summary of these scenarios is presented in Table 3. For these scenario simulations, it was decided to use the then existing 1997 *ACRU* configuration for the Sand catchment (Pike *et al.*, 1997), which was based on a 1993 LANDSAT TM image and furthermore, to only consider the scenarios for Zone A (the area within which commercial forestry occurs) for this feasibility study.

2.5.2 Methodology : Contending with conflicting resolutions and classifications of land use information

The details of the original scenarios had been finalised in a public participation forum prior to a request being issued to BEEH for assistance with the simulations. Since the decision making process had been based on 1996 land use information, and since land use was an issue of potential conflict, it was requested that, if at all possible, the 1996 LANDSAT TM coverage should be used in the simulations. In order to make the best use of the 1996 land use information in the available time, the classes of the 1993 image were preserved and only the proportions of these classes were updated from the 1996 image. This decision was based on the assumption that no new land cover classes would have been introduced into the catchment between 1993 and 1996 and the only changes would have been the proportion of each class.

However, not only were the proportions of land use classes different between the two image, but the classes themselves differed significantly. These differences were due to the fact that the 1996 LANDSAT TM classes were derived for social and conservation based applications while the 1993 image contained more general land cover classes. The two different classifications were finally reconciled by conducting a spatial comparison of the two images and matching the classes where it was assumed that no significant land use changes (in terms of the introduction of new land use classes or the removal of land uses which were present in 1993) would have occurred in the period between the acquisition of the images.

This process of matching, or reconciling, the two LANDSAT TM images with different classification systems was both unsatisfactory in terms of the subjective nature of matching the land uses and the many anomalies which were found. It was also extremely time consuming. This exercise highlighted the urgent need for a standard hydrological classification system of land uses for South Africa.

Further problems were encountered in the process of apportioning the changes in land use to the relevant subcatchments. This proved to be a very difficult exercise since the Sand catchment had been subdivided by AWARD into the three zones without due consideration being given to the subcatchment configuration of Pike *et al.*, 1997. The Zones had been defined in terms of land use and not hydrology, with Zone A representing the afforested area. It was also not desirable to subdivide the existing subcatchments since this would have added subcatchments to the *ACRU* menu, a process which would have complicated the configuration of the menu. This problem was resolved by relaxing the boundaries of Zone A to comply with actual subcatchments.

**Table 3** Summary of scenarios for Zone A (after Pollard *et al.*, 1998)

| | Scenario Description | Forestry (ha) | Unutilized (Conservation) (ha) | Permanent Irrigation (ha) | Annual Irrigation (ha) | Dryland Farming (ha) | Grazing (ha) | Community Conservation (ha) | Harvestable Conservation Areas (ha) | Residential & Garden (ha) | Total Area (excluding water bodies and bare soil) (ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Status Quo | 4 994.00 | 5 270.19 | 0.00 | 0.00 | 0.00 | 1 317.51 | 0.00 | 0.00 | 0.00 | 11 581.70 |
| 2 | Remove 50% Plantation<br>Replace 25 % Permanent Irrigated Agriculture<br>25% Conservation | 2 497.00 | 6 518.69 | 1 248.50 | 0.00 | 0.00 | 1317.51 | 0.00 | 0.00 | 0.00 | 11 581.70 |
| 3 | Remove 50% Plantation<br>Replace 25 % Dryland Agriculture<br>25% Conservation | 2 497.00 | 6 518.69 | 0.00 | 0.00 | 1248.50 | 1 317.51 | 0.00 | 0.00 | 0.00 | 11 581.70 |
| 4 | Remove 50% Plantation<br>Replace 25 % Rangelands (Grazing)<br>25% Conservation | 2 497.00 | 6 518.69 | 0.00 | 0.00 | 0.00 | 2 566.01 | 0.00 | 0.00 | 0.00 | 11 581.70 |
| 5 | Remove 50% Plantation<br>Replace 25 % Annual Irrigated Agriculture<br>25% Conservation | 2 497.00 | 6 518.69 | 0.00 | 1 248.50 | 0.00 | 1 317.51 | 0.00 | 0.00 | 0.00 | 11 581.70 |
| 6 | Remove 50% Plantation<br>Replace 25 % Residential and Garden Plots<br>25% Conservation | 2 497.00 | 6 518.69 | 0.00 | 0.00 | 0.00 | 1 317.51 | 0.00 | 0.00 | 1 248.50 | 11 581.70 |
| 7 | Remove 50% Plantation<br>Replace 25 % Commercial Conservation<br>25% Conservation | 2 497.00 | 5 270.19 | 0.00 | 0.00 | 0.00 | 1 317.51 | 1 248.50 | 1 248.50 | 0.00 | 11 581.70 |
| 8 | Remove 25% Plantation<br>Replace 25% Conservation | 3 745.50 | 6 518.69 | 0.00 | 0.00 | 0.00 | 1 317.51 | 0.00 | 0.00 | 0.00 | 11 581.70 |

### 2.5.3 Evaluation of scenarios

Simulated median monthly and annual streamflows for the six scenarios are presented in Table 4 (Pollard *et al.*, 1998). The results showed that the impacts of the commercial forestry, while significant on a local level, were not as large as had been expected by non-hydrologists on a regional scale (the lack of precision in the conversion between mm/month and $m^3$ ($x10^6$)/month results in the differences in flows for August, September, October and November being indiscernible).

**Table 4** Median monthly and annual streamflows ($x10^6$ $m^3$) at Subcatchment 94 for six land use scenarios

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 Present Land Use | 8.365 | 14.126 | 9.430 | 2.68 | 1.302 | 1.026 | 0.631 | 0.276 | 0.671 | 0.434 | 1.263 | 6.589 | 46.8 |
| Scenario 2 | 8.445 | 14.165 | 9.509 | 2.723 | 1.342 | 1.026 | 0.631 | 0.276 | 0.671 | 0.434 | 1.263 | 6.668 | 47.2 |
| Scenario 3 | 8.483 | 14.244 | 9.588 | 2.723 | 1.342 | 1.065 | 0.671 | 0.276 | 0.671 | 0.434 | 1.263 | 6.708 | 47.4 |
| Scenario 4 | 8.483 | 14.205 | 9.549 | 2.723 | 1.342 | 1.065 | 0.671 | 0.276 | 0.671 | 0.434 | 1.263 | 6.708 | 47.4 |
| Scenario 7 | 8.404 | 14.126 | 9.470 | 2.683 | 1.302 | 1.026 | 0.631 | 0.276 | 0.671 | 0.434 | 1.263 | 6.589 | 46.9 |
| Scenario 8 | 8.365 | 14.126 | 9.430 | 2.68 | 1.300 | 1.026 | 0.631 | 0.276 | 0.671 | 0.434 | 1.263 | 6.589 | 46.8 |
| Baseline ('Pristine') flows | 11.324 | 16.927 | 12.10 | 4.577 | 2.604 | 2.170 | 1.740 | 1.065 | 1.740 | 1.420 | 3.430 | 9.430 | 68.5 |

Explanations for the relatively low hydrological impacts between the different scenarios included the following:

- The changes in land use were affecting the subcatchments in the upper reaches of the catchment, but the analysis of the results was requested for the outlet of the catchment (Subcatchment 94 of Figure 4). This meant that the hydrological contributions of the intermediate subcatchments (297.84 $km^2$ ) offset the impacts of the changes in the afforested subcatchments (96.73 $km^2$).
- The statistical analysis of results was conducted by the Department of Statistical Sciences at the University of Cape Town and since the outlet of subcatchment 73 (Figure 4) was used to assess the relative impacts, neither the afforestation in the south western subcatchments (57.23 $km^2$) nor the hydrological contributions of the other subcatchments comprising the southern tributary (282.26 $km^2$) were considered.
- The removal of afforestation was always accompanied by the replacement of another land use which also consumes water - a factor often overlooked by non-hydrologists. Although the afforestation (in this case 95 per cent pine and only 5 per cent eucalypt) generally uses more water under stress-free conditions than other land uses, it also experiences stress when atmospheric demand exceeds the availability of soil water. This results in a reduced effective water use coefficient for the trees in the dry periods resulting in comparative streamflow reductions which are less than expected.
- The presence of the Casteel (1.6 million $m^3$), Acorn's Hoek (1.1 million $m^3$), Edinburgh (3.3 million $m^3$) and Orinocco (1.9 million $m^3$) impoundments have the effect of reducing any impacts of land use changes made in upstream subcatchments. There are two main reasons for the negation of upstream hydrological impacts of the land use when impoundments are present. Firstly, the impoundments are first filled to full capacity by high flow events before overflow occurs, effectively "resetting" the system and cancelling out impacts upstream land uses would otherwise have had on the yield of the impoundments. This additional storage is then available to supplement the flows in the dry season. The second impact of these reservoirs is manifest in the controlled releases from the impoundments, which again serve to supplement the low flows during the dry season. These effects were especially evident in this study where the hydrological impacts of land use changes in the various subcatchments were assessed in terms of the low flows.

- The impact of abstractions particularly for irrigation purposes, need to be stressed. Abstractions from the Sand River ranging from 200 to 400 $m^3$ per month were simulated for all of subcatchments and abstractions for irrigation were made from the relevant impoundments for Subcatchments 67 (585 ha), 73 (970-1 000 ha) and 86 (580-680 ha) and from the run-of-river flows for Subcatchment 84 (385-425 ha) for all months of the year. These irrigation abstractions can have impacts on the streamflows which are orders of magnitude greater than the additional water use by commercial afforestation. This is due mainly to the fact that abstractions are made even when the commercial forests are under severe stress and that the abstractions come from the small proportion of any rainfall which becomes runoff after balances are made to the soil moisture storage and evapotranspiration has been accounted for.

Simulated baseflows from baseline and present land use conditions and streamflows corresponding to the volumes required to satisfy the maintenance baseflows of the ecological reserves at IFR Sites 6 and 7 are illustrated in Figures 19 and 20 respectively. Pollard *et al.* (1998) concluded that in the case of IFR Site 7, the baseflows resulting from all the scenarios adequately supplied the IFR baseflow requirements while for IFR Site 6 the IFR baseflow requirement is consistently greater that the simulated baseflows generated by *ACRU*. The reason that the IFR baseflows are met for Site 7 but not for Site 6 may be due to the changes in land use occurring in Zone A, which is immediately upstream of Site 6. The reductions in streamflow at Site 6 are therefore an indicator of the local impacts of land use practices while at Site 7, which has a contributing area of 297.84 $km^2$ compared to 96.73 $km^2$ of Site 6 - they are more representative of the diluted regional impacts of the land uses in the catchment.

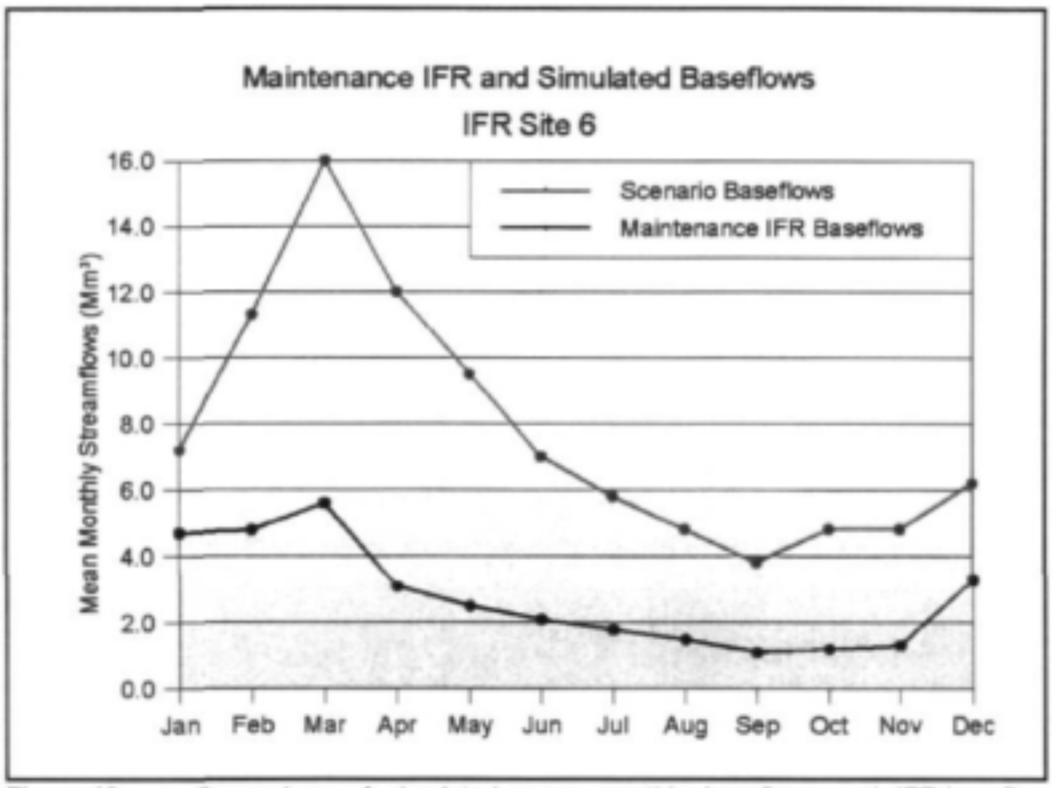


**Figure 19** Comparison of simulated mean monthly baseflows and IFR baseflow requirements requirements at IFR Site 6 (after Pollard *et al.*, 1998)

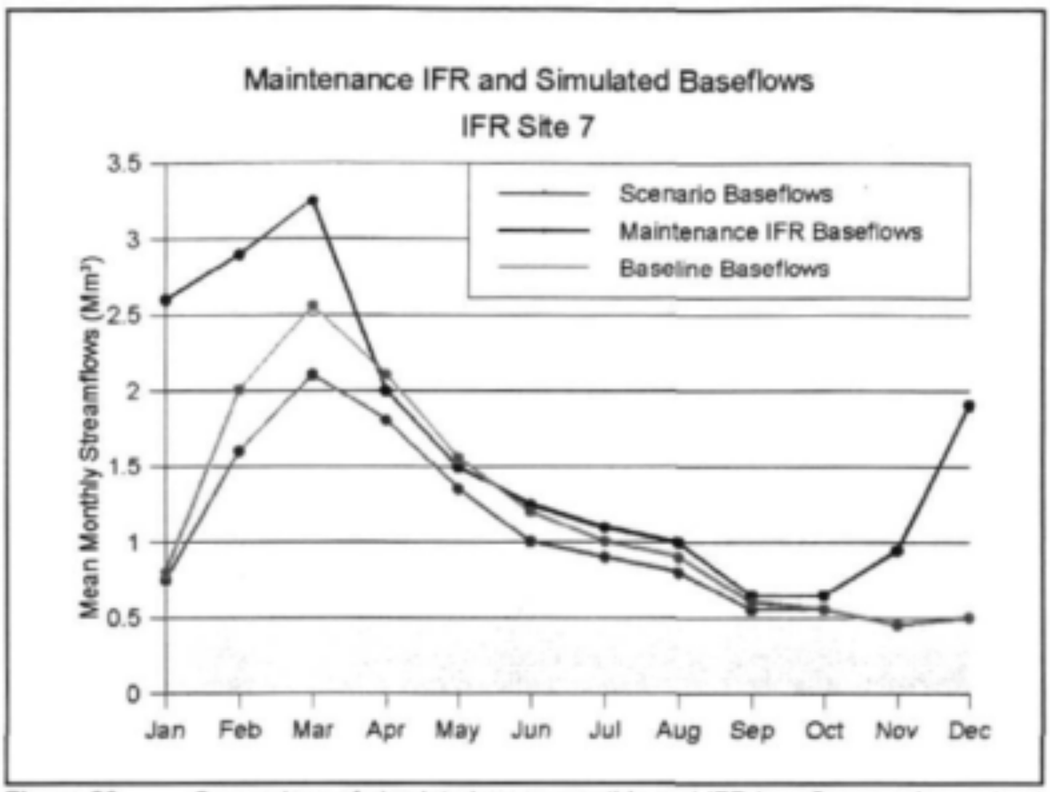


**Figure 20** Comparison of simulated mean monthly and IFR baseflow requirements at IFR Site 7 (after Pollard *et al.*, 1998)

### 2.5.4 Conclusions

In the course of this interdisciplinary, remote modelling exercise, certain misconceptions and false expectations came to the fore. Many of the difficulties encountered were due to a lack of understanding of the process of formulating and conducting scenarios to estimate the impact of land use changes. A lack of knowledge with regards to the physical processes associated with the hydrological responses of different land uses also served to cast doubt on the modelling process. Many researchers with no prior appreciation of hydrological processes and exposure to models moved from a position of amazement and optimism that the model would solve all problems once the advantages of modelling became evident, to a state of scepticism where the impartiality of the modellers and the credibility of the model was questioned in the cases where the outputs did not substantiate the preconceived notions of certain land use impacts of some of the scenarios offered.
Had a physical-conceptual model, where each hydrological process is modelled in a transparent, realistic manner, not been used it is likely that the results could have been discarded.

It also became evident that some researchers without necessary hydrological background held false expectations with regard to the ease of configuring a hydrological model and interpreting the results. Although the inputs to *ACRU* are kept to a minimum and are, for the most part, derived from readily accessible data sources, a model which seeks to represent hydrological processes realistically will place greater demands on inputs that a more "black box" type calibration model. Collecting and checking of data is a time consuming process which pays dividends at a later date when the outputs have to stand up to public scrutiny. The developers of *ACRU* are constantly seeking to improve the model and make more efficient use of readily available information. It is often through the exercise of actually configuring and running the model on complex catchments that the greatest benefits, in terms of future enhancements to the model, are gained. The lessons learned in this project will ensure that future applications of the model, especially in neighbouring catchments or in situations where similar questions need to be addressed, will benefit from the experiences gained.

### 2.6 Stakeholder Case Study 2 : Simulating Local Impacts of Commercial Afforestation on Streamflows of the Sand River

The amount of water used by different land covers under land use practices is currently a contentious issue in South Africa. Commercial forestry and dryland sugarcane are currently under scrutiny by DWAF in terms of their water uses. It is commonly stated that of agricultural land uses these two are responsible for the greatest unit reductions in streamflows. Commercial forestry is the first and thus far, the only land use to have been identified as a "Stream Flow Reduction Activity" (SFRA).

BEEH was commissioned by consulting engineers, Sellick and Associates, on behalf of DWAF, to conduct a study of the impact of commercial afforestation in the Sand catchment. The water use by commercial forestry (assumed to be 95% pine and 5% eucalypt) was compared to that of natural vegetation, which was presented by the Acocks' Veld Types.

#### 2.6.1 Streamflow reduction activities : Background

The concept of SFRAs has become an integral component of South African water law since the adoption of the National Water Act in August 1998. This Act makes provision for the regulation of "land-based activities which reduce stream flow by declaring them to be Stream Flow Reduction Activities" (Part 4 - Introduction), whereby the Minister may "declare any activity (including the cultivation of any particular crop or other vegetation) to be a stream flow reduction activity if that activity is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly" (Section 36, (2), National Water Act, 1998 ).

These SFRAs are identified in terms of factors such as "the extent of stream flow reduction, its duration, *and its impact on any relevant water resource and on other water users" (Part 4 - Introduction).* Furthermore, the Minister may make regulations "prescribing methods for making a volumetric determination of water to be ascribed to a stream flow reduction activity for purposes of water use allocation and the imposition of charges" (Section 26, (1), (m), National Water Act, 1998).

The quantification of the consumptive use of water by a particular land use is a complex process which cannot be accounted for by using a generalised statements on water use (e.g. "riparian wattle uses twice the amount of water as natural veld") or by assigning a quantity of water per day (e.g. "a single eucalypt tree uses 600 litres of water per day"). These broad generalisations ignore the spatial differences (e.g. transpiration inequalities on north and south facing slopes), as well as temporal (annual, seasonal and daily variations in water availability and use) and physical differences (e.g. soil texture and water holding capacity) within and between catchments. The feedbacks between the different land uses in a catchment, the prevailing climatic conditions, the retention and drainage properties of the soil and the hydrological response of the catchment all need to be considered if the estimates of water use by a land use are to be realistic and defendable in the transparent, consultative environment in which water allocation is likely to take place in the future.

The challenge facing hydrologists and water resources managers in South Africa is to provide decision makers with relevant and well tested tools to assist in the objective quantification of the relative consumptive use of water by different crops and vegetation types under a multitude of unique combinations of management practices, climatic regions, soils and growth cycles. Daily time step, physical-conceptual hydrological models lend themselves to applications such as these. This section seeks to explore the application of the *ACRU* agrohydrological model in a case study in the Sand catchment in Mpumalanga.

#### 2.6.2 Objectives

A study was conducted to estimate the relative water use by present commercial afforestation when compared to that of Acocks' Veld Types occurring in the Sand catchment. Hydrological responses from Acocks' Veld Types were assumed to represent baseline land cover conditions. Since streamflow is the integrator of many processes and activities occurring within a catchment and it is streamflow that the Water Act seeks to regulate, the ratios of Mean Annual Runoff (MAR) for the different land uses were analysed for the QCs X32A to X32G (upstream of streamflow gauging station X3H008 at Exeter). The impacts of the eucalypt and pine plantations on streamflows were estimated at both a local sub-Quaternary scale as well as at a regional level. Furthermore, the choice of statistic (mean versus median) proved to be significant and different results were obtained for the ratios of the same land use and vegetation types in different locations given different soils and different climatic inputs.

### 2.6.3 Methodology

The nine DWAF QCs making up the area were selected as the basic spatial units of the Sand system when subdividing them into more homogeneous hydrological regions. Owing to the range of soils, land uses, reservoir locations and climatic variation, the QCs were subdivided into 12 subcatchments, with each subcatchment having its own and thus unique climate and other model inputs. The delineation of subcatchments was performed on 1:50 000 topographic maps. The subcatchments ranged in area from 19.8 to 311.7 km². Figure 21 shows the Acocks' Veld Types and the areas under commercial plantation for the 12 subcatchments of the upper Sand catchment.

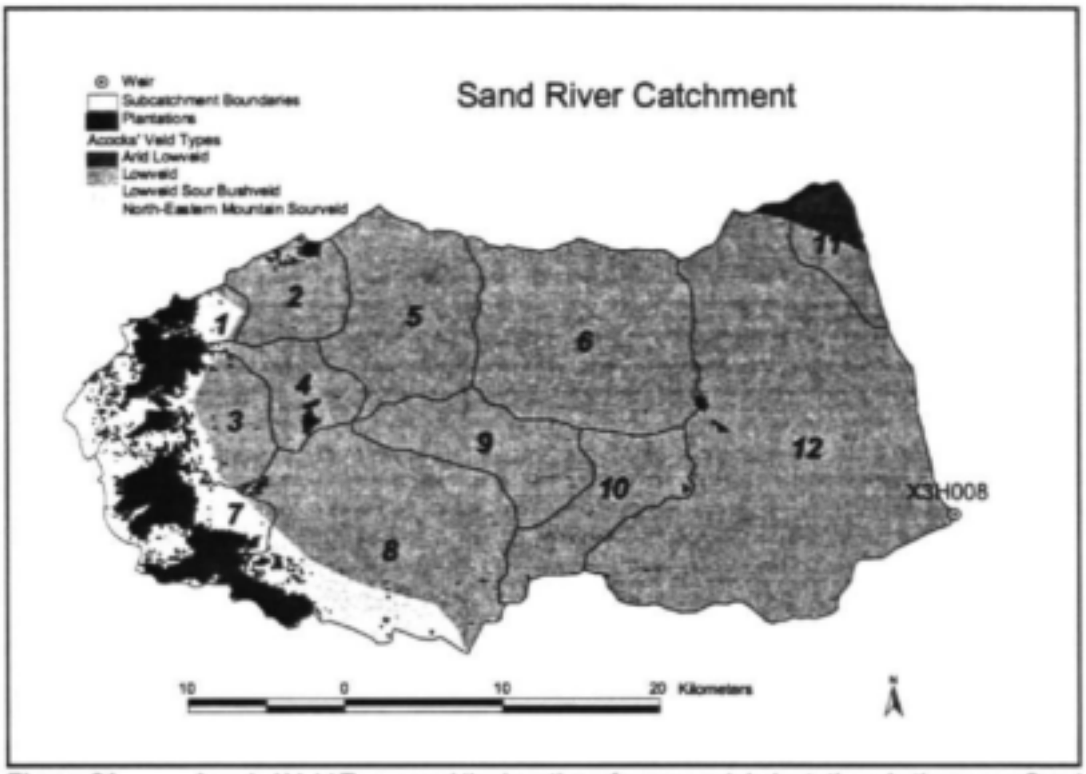


**Figure 21** Acocks' Veld Types and the location of commercial plantations in the upper Sand catchment

The initial objective of the study was defined to be the determination of a water use coefficient that could be used to make comparisons between commercial plantations and baseline conditions in terms of reductions in streamflows. However, it was decided to develop a post processing utility (RATIOS) which could analyse simulated streamflows in order to calculate a water use coefficient for each land use class in each subcatchment. The streamflows were generated using the catchment configuration developed for the "Save the Sand" modelling exercise (Pollard *et al.*, 1998), except that the areas of present commercial plantations were adjusted from the 1996 LANDSAT TM estimate of approximately 5 300 ha to the 7 600 ha used in other studies where the water use by forestry had been estimated.

An example of the output from the utility for Subcatchment 3 is presented in Table 5 and comprises of a series of matrices of water use ratios for each subcatchment. These matrices may be used to

**Table 5** An example of ratios of water use between the different land uses in Subcatchment 3

```
1-Plantation : Eucalypts
2-Plantation : Pines
3-NE Mountain Sourveld
4-Lowveld Sour Bushveld
5-Lowveld
6-Arid Lowveld
7-NODE (Veld in fair hydrological condition)

 Subcatchment 3
             LU in row uses x times MORE water than LU in column
                   1       2       3       4       5       6       7
                 231.9   250.6   314.9   303.0   307.8   310.3   326.7
                 -----------------------------------------------------
  1   231.9|   1.000   1.081   1.358   1.307   1.327
  2   250.6|   0.925   1.000   1.257   1.209   1.228
  3   314.9|   0.736   0.796   1.000   0.962   0.977
  4   303.0|   0.765   0.827   1.039   1.000   1.016
  5   307.8|   0.753   0.814   1.023   0.984   1.000
  6   310.3|
  7   326.7|
      LU in column uses a fraction of x of the water used by the LU in the row
```

compare the water use between any two land uses in any subcatchment. Note that the diagonal ratios (shaded) always equate to 1.00, i.e. eucalypts (columns) will always use 1.00 times the water that eucalypts (rows) use. Eucalypts in two different subcatchments will use different amounts of water.

The different land uses simulated in this study are listed at the top, followed by a matrix of ratios of MAR for each land use. The simulated MAR values are also given for each land use, e.g. 231.9mm for eucalyptus, 250.6mm for pine and 314.9mm for North East Mountain Sourveld.

From this matrix one can deduce that in Subcatchment 1 eucalypts use 1.081 times (or 8.1% more) than the water used by pines and 1.358 times (or 35.8% more) than the water used by North East Mountain Sourveld. Similarly, Lowveld uses 0.814 (or 18.6% less than) of the water used by pines. The following points should be noted:

- These ratios are only for Subcatchment 3 and cannot be generalised to other parts of this catchment or different catchments. The water use by the different land uses is highly dependent on local climatic, soil and hydrological properties of the region. This is the reason why different matrices are given for each different subcatchment.
- Not all the land uses are present in every subcatchment. In the above example, Arid Lowveld does not exist in Subcatchment 3.
- The water use ratios in Table 5 are based on Mean Annual Runoff and the water consumption on a month-by-month basis could vary substantially from these figures. A similar analysis can performed for any month of the year, or for any level of risk, e.g. the driest year in 10.

### 2.6.4 Results

Matrices of either annual or monthly ratios of average, or percentile flows can be calculated with the RATIOS software. The ratios of MAR and median annual runoff for the different land uses in Subcatchments 4, 6 and 10 are presented in Table 6 and discussed in Section 2.6.4.1 while median monthly ratios for February and August are presented in Table 7 and explained in 2.6.4.2 below.

#### 2.6.4.1 Median and mean annual runoff ratios

The differences between the MAR and median annual runoff for pine and Acocks' Lowveld in these subcatchments have been singled out to illustrate two important points. First, whereas the highest MAR ratio is 1.437 (i.e. the MAR from pines in Subcatchment 4 is 1.437 times less than that from Lowveld

**Table 6** MAR and median annual ratios for Subcatchments 4, 6 and 10 (values in brackets denote the corresponding median annual ratio)

1-Plantation : Eucs
2-Plantation : Pine
3-North East Mountain Sourveld
4-Lowveld Sour Bushveld
5-Lowveld
6-Arid Lowveld
7-NODE (Veld in fair hydrological condition)

**Subcatchment 4**

LU in row uses x times MORE water than LU in column

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| | | 114.4 | 129.3 | 190.1 | 182.9 | 185.8 | 187.7 | 197.3 |
| 1 | 114.4 | 1.000 | 1.130 | | 1.599 | 1.624 | | |
| 2 | 129.3 | .885 | 1.000 | | 1.415 | **1.437 (1.874)** | | |
| 3 | 190.1 | | | | | | | |
| 4 | 182.9 | .625 | .707 | | 1.000 | 1.016 | | |
| 5 | 185.8 | .616 | .696 | | .984 | 1.000 | | |
| 6 | 187.7 | | | | | | | |
| 7 | 197.3 | | | | | | | |

LU in column uses a fraction of x of the water used by the LU in the row

**Subcatchment 6**

LU in row uses x times MORE water than LU in column

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| | | 59.5 | 72.6 | 90.0 | 85.2 | 86.7 | 90.4 | 96.8 |
| 1 | 59.5 | | | | | | | |
| 2 | 72.6 | | 1.000 | | | **1.194 (1.620)** | | |
| 3 | 90.0 | | | | | | | |
| 4 | 85.2 | | | | | | | |
| 5 | 86.7 | | .837 | | | 1.000 | | |
| 6 | 90.4 | | | | | | | |
| 7 | 96.8 | | | | | | | |

LU in column uses a fraction of x of the water used by the LU in the row

**Subcatchment 10**

LU in row uses x times MORE water than LU in column

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| | | 22.2 | 28.1 | 39.7 | 36.1 | 37.2 | 38.6 | 43.0 |
| 1 | 22.2 | | | | | | | |
| 2 | 28.1 | | 1.000 | | | **1.324 (2.909)** | | |
| 3 | 39.7 | | | | | | | |
| 4 | 36.1 | | | | | | | |
| 5 | 37.2 | | .755 | | | 1.000 | | |
| 6 | 38.6 | | | | | | | |
| 7 | 43.0 | | | | | | | |

LU in column uses a fraction of x of the water used by the LU in the row

in the same subcatchment) the greatest median annual runoff ratio is 2.909 (i.e. the median annual runoff from pines in Subcatchment 10 is 2.909 times less than that from Lowveld in the same subcatchment). This illustrates that the choice of the statistic that is employed to quantify the consumptive use of water can have a profound influence the outcome of such an exercise.

The second point to note is that not only are there differences in the magnitudes of the ranges of the MAR and median annual runoff ratios, but the physical location of the subcatchments in which these extremes occur are also different. Thus, for example, the highest value of the MAR ratio occurs in Subcatchment 4 (1.437) while the highest median annual runoff ratio occurs in Subcatchment 10 (2.909). These results clearly expose the shortcoming of applying generalised water use coefficients to different

**Table 7** Seasonal median water use ratios for Subcatchment 3

1-Plantation : Eucalypts
2-Plantation : Pine
3-North East Mountain Sourveld
4-Lowveld Sour Bushveld
5-Lowveld
6-Arid Lowveld
7-NODE (Veld in fair hydrological condition)

**Subcatchment 3 (Median monthly ratios for February)**

LU in row uses x times MORE water than LU in column

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| | | 32.3 | 34.2 | 51.3 | 50.1 | 50.5 | 50.2 | 52.7 |
| 1 | 32.3 | 1.000 | 1.059 | 1.588 | 1.551 | **1.563** | | |
| 2 | 34.2 | .944 | 1.000 | 1.500 | 1.465 | **1.477** | | |
| 3 | 51.3 | .630 | .667 | 1.000 | .977 | **.984** | | |
| 4 | 50.1 | .645 | .683 | 1.024 | 1.000 | 1.008 | | |
| 5 | 50.5 | .640 | .677 | 1.016 | .992 | 1.000 | | |
| 6 | 50.2 | | | | | | | |
| 3 | 52.7 | | | | | | | |

**Subcatchment 3 (Median monthly ratios for August)**

LU in row uses x times MORE water than LU in column

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| | | 1.6 | 2.5 | 1.4 | 1.2 | 1.2 | 1.3 | 1.8 |
| 1 | 1.6 | 1.000 | 1.563 | .875 | .750 | **.750** | | |
| 2 | 2.5 | .640 | 1.000 | .560 | .480 | **.480** | | |
| 3 | 1.4 | 1.143 | 1.786 | 1.000 | .857 | **.857** | | |
| 4 | 1.2 | 1.333 | 2.083 | 1.167 | 1.000 | 1.000 | | |
| 5 | 1.2 | 1.333 | 2.083 | 1.167 | 1.000 | 1.000 | | |
| 6 | 1.3 | | | | | | | |
| 7 | 1.8 | | | | | | | |

LU in column uses a fraction of x of the water used by the LU in the row

land use classes without due consideration of the spatial variations in root water uptake and transpiration.

2.6.4.2 Median monthly streamflows for months of high (February) and low (August) flows

An examination of the ratios of median monthly runoff between eucalypts, pines and North East Mountain Sourveld with Lowveld reveals another significant phenomenon that can not be accounted for with a simple annual coefficient. A comparison (cf Table 7) of the wet and dry season ratios shows that the median monthly runoff for eucalypts in February (32.3mm) is 1.563 times less than that for Lowveld (50.5mm). However, the pattern is reversed in the dry season where the median monthly runoff for eucalypts (1.6mm) is greater than that for Lowveld (1.2mm). It is important to note that this phenomenon only occurs when the median monthly flows are considered, since the annual pattern of lower flows in the case of eucalypts (2.9mm), pines (3.5mm) and North East Mountain Sourveld (2.3mm) are higher than the flows for Lowveld (2.1mm).

Although the *ACRU* model accounts for the facts that eucalypts and pines have a higher wet canopy evaporation, deeper root penetration, higher water use coefficients, interception losses per rainday and coefficients of initial abstraction than Lowveld, these factors do not influence the water budget in the dry months since there are very few rainfall events. Furthermore, most vegetation types will experience soil moisture deficits in the drier months which suppresses the transpiration rates of both the plantation and grassland species.

While the absolute differences (in mm) in water use between various values may not be significant, it is worth noting the following two points:

- Careful consideration needs to be given to the selection of the statistic used in quantifying runoff from different land uses. It would be preferable to present the findings of more than one analysis in an investigation such as this.
- Secondly, in some catchments it may be important to consider streamflow reductions on an inter-annual or seasonal basis. This is particularly true in areas where a high demand is placed on the assurance of supply, in which case an analysis of annual flows may not suffice and only should resort to analyses of monthly flows.

### 2.6.5 Conclusions

The purpose of this case study has been to illustrate the need to determine the reductions in streamflows by different land uses by using hydrological models which are:

- spatially sensitive to soils with different retention and drainage characteristics,
- both spatially and temporally sensitive to changes in land use and climatic conditions (in terms of rainfall, temperature, evaporation), and
- are able to simulate seasonal differences in streamflow reductions by different land uses.

This case study has highlighted the need for the SFRAs to reflect these spatial and temporal scale issues and has outlined the dangers associated with assigning a generalised ratio of water use or a consumptive volume to a particular species which is independent of management, locational and seasonal factors (Pike, 1999a).

Shortcomings in the widely held assumption that a greater critical soil thickness for the generation of stormflow be used in the case of forestry as opposed to other land uses has also been highlighted. While the reasons for this assumption may be valid in the wet season, for low flow periods it appears that further investigation into the physical processes which come into play when soil moisture contents are close to or at permanent wilting point is required. A further point to note is that the stands of eucalypt and pine trees were assumed to be of intermediate age and that a rotation of planting to harvesting operations was in place. More realistic simulations of the water use by these species could be achieved by modelling single stands of eucalypts and pines from planting to harvesting using the 'dynamic land use' file within the *ACRU* model. The model would then model the stands throughout their respective rotations rather than on an annual cycle.

A final point with regard to scale issues needs to be made. The original brief of this case study was to assess the impact of the commercial plantations on the streamflows at X3H008. Initially, great concern was expressed when it was shown that the regional impacts were relatively insignificant. Although a land use such as eucalypt plantations may have a great impact on the streamflows on a local scale, e.g. on a hectare-by-hectare or subcatchment by subcatchment basis. Thus these impacts are 'dampened', or attenuated, by the relative areas of these land uses in comparison with the total catchment area and the contributions to the total streamflow of the downstream subcatchments where commercial plantations are absent.

## SECTION 3 EVALUATION AND DISCUSSION REPORT

### 3.1 An Evaluation of Approaches to Enhanced Water Quality Modelling in the Sabie Catchment

The environmental reserve as determined by the BBM is a "static" entity in the sense that does not, nor should it, take into account the hydrological impact of future changes in land use. In order to ensure that proposed land use changes do not infringe on the environmental reserve it is first necessary to determine the water consumption of the various land uses in the catchment. It has been shown in Section 2.6 that the *ACRU* model can be used to assess the impacts of changes in land use on streamflows of a catchment and hence on the environmental reserve. However, since the reserve is defined both in terms of water quantity and water quality, this investigation requires an evaluation of possible solutions to overcome the shortcoming of the lack of water quality functionality within the *ACRU* model.

#### 3.1.1 Importance of water quality to the ecological reserve in the South African context

The National Water Act of 1998 stipulates that the Ecological Reserve is to be determined in terms of both the quantity and quality of water required to protect the aquatic ecosystems in a river system. Thus,

> ***"The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource. The Reserve refers to both the quantity and quality of the water in the resource, and will vary depending on the class of the resource"*** (National Water Act, 1998).

To date, much of the effort in determining the Ecological Reserve has been expended in determining the quantity and, to a lesser degree, the frequency and timing of releases of water from impoundments in order to satisfy downstream aquatic habitat requirements. Future IFR workshops will need to determine IFRs with more consideration been given to upstream erosion and sediment yields, the impacts of upstream agricultural practices (e.g. in terms of nitrates, phosphates, pesticides and salinity) and the biological impacts of river health (e.g. *E. coli* concentrations) than has been the case in the past. The need for a tool capable of modelling both the water quantity and the water quality constituents in a South African context initiated the investigation into adding water quality functionality to the hydrological simulation capabilities of *ACRU*.

#### 3.1.2 Advantages and disadvantages of using the *ACRU* model as a driver model for water quality modelling

The physical-conceptual structure of the *ACRU* model, its extensive verification at field, small catchment and operational catchments scale in South Africa (e.g. Schulze, 1995; Kienzle ***et al.***, 1997; Taylor ***et al.***, 1999), together with the advantage of the close collaboration with the developers of the model, as well as the Decision Support Systems which have been developed around South African hydrological and climatological databases, make this model a strong contender for use as an installed catchment model for Catchment Management Agencies (CMAs) and other Water Authorities. However, one of the shortcomings of the present operational version of the model is its limited water quality functionality (currently, only sediment yields, *E. coli* and phosphorus loadings can be simulated).

#### 3.1.3 Approaches to adding water quality modelling capabilities to *ACRU*

One of the objectives of this project was to investigate the possibility of overcoming this shortcoming by one of two alternatives, *viz.* either through the development of links between the *ACRU* model with other water quality models, or by producing an integrated hybrid model which would maintain the strengths of the hydrological capabilities of the *ACRU* model, but have directly imbedded water quality functionality at a level that would be applicable to the management of southern Africa's water resources in the future.

##### 3.1.3.1 Developing links between *ACRU* and other water quality models

The Hydrological Simulation Program-FORTRAN (HSPF) model was selected as the model to be used in conjunction with *ACRU* to produce a system capable of modelling water quality constituents. Several reasons apply for the choice of the HSPF model over other water quality models:

- There have been previous attempts by researchers of the CCWR and BEEH to build links between the HSPF and *ACRU* models. The experience gained from the past efforts was expected to aid in the refining of these links.
- Given sufficient input information and calibration data, HSPF is capable of modelling runoff, sediment loads, nutrients, pesticides, toxic chemicals and other water quality constituents (Donigian, Bicknell and Imhoff, 1995). It can simulate the continuous, dynamic event, or steady-state behaviour of both hydrological and water quality processes in a catchment, with an integrated linkage of surface, soil and stream processes (Donigian, Bicknell and Imhoff, 1995).
- HSPF uses the Watershed Data Management (WDM) file which is a binary, direct-access file used to store spatial, parametric and time series data in a logical, well-defined structure. It was envisaged that this file format may hold potential for model applications in South Africa.
- Staff at the CCWR are familiar with HSPF and have applied the model in a number of catchments in South Africa.

The following three approaches were investigated in terms of developing links between the *ACRU* and HSPF models, *viz.*

- developing a controller program to link the two models in parallel via the WDM file on a time-step by time-step basis,
- linking the two models in series via the WDM, and
- replacing the water budget of HSPF (PWAT) with the water budget of the *ACRU* model.

These options were evaluated in the light of the objectives of this study and expectations of the KNPRRP (Appendix 4). Particular attention was paid to their respective advantages as well as associated conceptual and practical problems and a great deal of effort was expended in studying the time series management and water quality options in the HSPF model. Each of the options is discussed below.

a) Linking *ACRU* and HSPF via a "Controller" Program

One initial option was that of writing a "commander program" which would control both models on a time step-by-time step basis. This option was not pursued beyond discussions with the Senior Systems Programmer and User Consultants of the CCWR, as this method was deemed to be computationally too complex and inflexible to be a practical solution. However, routines have been added to the *ACRU* model in order that simulated streamflows at sub-daily time steps can now be made available to the HSPF model via a static WDM link.

b) Linking *ACRU* and HSPF via the WDM file

A link was developed which involved feeding the simulated daily streamflows of the *ACRU* model to HSPF via the WDM file. By such a static link each model remains "intact" and no conceptual principles, which differ between the two models, are violated. However, this type of link does not solve the problem that in order to accurately simulate many of the water quality constituents, the relevant routines in the HSPF model require sub-daily streamflows.

The existing static link between the two models was therefore enhanced. The *ACRU* model was modified to output streamflows at any user-defined time step greater than 30 minutes and an integer divisor of 1440 minutes, up to one day. This procedure also requires the flow routing option to be invoked and writes out the sub-daily flow hydrograph at each sub-daily time step. This approach has the potential to go some way towards satisfying the requirements of HSPF in applications where there are no limitations to either of the models, although feedbacks, such as releases from impoundments for downstream users or to satisfy the ecological reserve in periods of low flows, cannot be simulated using this technique.

A further development in terms of the static approach to the link involves a modification to the *ACRU* model whereby all the elements of its water budget are outputed by the model at a daily time step. These variables are then called by the HSPF model which then calculates its own daily water balance. While this approach has the advantage of leaving each model intact, the problems associated with feedbacks are still not resolved.

c) Replacing HSPF's Water Budget (PWAT) with the *ACRU* Water Budget

This approach has been pursued by the CCWR with staff from BEEH offering advice from an *ACRU* model perspective. The daily water budgeting routines (PWAT) of HSPF have been replaced with those of the *ACRU* model. The main advantage of this link is that the Decision Support Systems and South African databases which have been developed for use with the *ACRU* model can be used to simulate streamflows useable within the HSPF model framework.

The computational steps required to repeat the process of substituting water budgets has been comprehensively documented by the CCWR and, given the same model inputs, this hybrid model produces simulated daily streamflows identical to those from the *ACRU* model. However, two main difficulties will need to be addressed if this approach is to be developed further:

- Most of the water quality routines in HSPF require sub-daily streamflows to operate effectively. It is, because of *ACRU's* structural basis as a daily time step model, conceptually not possible to either simply divide the daily streamflow output by a relevant factor in order to convert values into sub-daily amounts (e.g. by 24 to obtain hourly values), nor can sub-daily inputed time series (such as rainfall and temperature) simply be fed through the same daily water budgeting routines of the *ACRU* model in order to generate sub-daily output.
- Secondly, there are fundamental differences in the way that the two models "view" the hydrological "world". These differences become very significant when the models are linked in such an intimate way. Examples of these problems include:
  - the fact that HSPF simulates fluxes for four soil horizons and the water quality routines are reliant on these fluxes while the *ACRU* model uses two soil layers, and
  - that HSPF water budgeting routines simulate an interflow component to runoff while the *ACRU* model produces baseflow and stormflow without an explicit interflow computation.

As the EPA maintenance contractor of HSPF, all official code changes and new releases have been undertaken by AQUA TERRA, a private consulting company in the USA, (in conjunction with the EPA Athens Laboratory and the USGS Office of Surface Water) since the initial release of HSPF in 1980. Any future release of either the *ACRU* or HSPF models would imply that the relevant routines would again need to be migrated across to the HSPF model and any proposed model development may or may not be undertaken at the discretion of AQUA TERRA. Although the HSPF source code is public domain (distributed by the U.S. EPA's Center for Exposure Assessment Modelling -CEAM), any changes made to the code are the responsibility of the individual and not AQUA TERRA. Consequently there would be no guarantee of user support to service this hybrid model unless users are prepared to pay for the service at commercial rates in US dollars.

A further disadvantage of this approach is that the integrated nature of components such as water use by forestry, irrigation and crop yield modelling within the *ACRU* model, a characteristic which is probably one of its greatest strengths, is forfeited. At present there is no generic facility within HSPF to model crop yield or irrigation abstractions explicitly, although the next release may include some irrigation routines (currently irrigation may be accounted for by using the conditional special actions although this option requires a great deal of expertise as it can become extremely complicated and does not offer a generic, integrated solution).

Even if these problems could be successfully addressed, such a hybrid *ACRU*/HSPF model would only be applicable for areas where the application of the "Stanford Watershed Model" is appropriate (Donigian and Huber, 1991). Furthermore, the data needs of the HSPF model are extensive (Donigian and Huber, 1991; Devries and Hromadka, 1992; De Vos, 1995) and the hybrid model would require climatic data at a sub-daily resolution to simulate water quality successfully. Previous applications of the HSPF model in South Africa have shown that there are insufficient sub-daily data to simulate water quality adequately (Jewitt and Görgens, 2000).

3.1.3.2 Integrating water quality functionality into *ACRU* using SWAT model routines

The second approach which was investigated was that of adding (i.e. imbedding) water quality routines to the *ACRU* model from models based on a similar conceptual and structural philosophy to that of *ACRU*. After evaluating numerous water quality models (e.g. GLEAMS, EPIC, AGNPS, AnnAGNPS, ANSWERS, WEPP and SWMM) the Soil and Water Assessment Tool (SWAT) model (Arnold *et al.*, 1996) was considered to be the one most similar to the *ACRU* model in both its developmental history and its conceptual approach to modelling streamflows. The SWAT model is the latest generation non-point source model to evolve out of the USDA Agricultural Research Service (ARS) modelling teams. It is the culmination of research first initiated in the mid-1970s and which produced a suite of models which include CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems), EPIC (Erosion-Productivity Impact Calculator), AGNPS (Agricultural Nonpoint Source), SWRRB (Simulator for Water Resources in Rural Basins) and ROTO (Routing Outputs to Outlet). Specific models that contributed significantly to the development of the SWAT model were CREAMS, GLEAMS and EPIC (Arnold *et al.*, 1996).

The objective in the development of the SWAT model was to predict the impact of management on water, sediment and agricultural chemical yields in large ungauged basins. SWAT is a public domain model actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas. The functionality of the SWAT model, in terms of the major components, is presented in Table 8.

**Table 8** Major components of the SWAT model

| Major Components | Details |
|---|---|
| Hydrology | Surface Runoff (volume and peak runoff rate) |
| | Evapotranspiration (potential evaporation as well as soil and plant evaporation separately) |
| | Percolation |
| | Lateral Subsurface Flow |
| | Groundwater Flow |
| | Snow Melt |
| | Transmission Losses |
| | Farm Dams |
| Sedimentation | Sediment Yield |
| | Soil Temperature |
| Nutrients | Nitrate Loss in Surface Runoff |
| | Nitrate Leaching |
| | Organic N Transport by Sediment |
| | Denitrification |
| | Mineralization |
| | Immobilization |
| | Rainfall |
| | Crop Uptake |
| Phosphorus | Soluble P Loss in Surface Runoff |
| | P Transport by Sediment |
| | Mineralization |
| | Immobilization |

| Major Components | Details |
|---|---|
| Pesticides | |
| Soil Temperature | |
| Crop Growth | Potential Growth |
| | Crop Yield |
| | Growth Constraints (water, temperature and nutrient stress) |
| Agricultural Management | Tillage |
| | Irrigation |
| | Fertilization |
| | Pesticide Applications |
| | Grazing |
| | Growing Degree Day Scheduling |
| | Biomass and Harvest Index Override |
| Channel Flood Routing | Transmission Losses |
| | Evaporation Losses |
| Channel Sediment Routing | |
| Sediment Routing in Impoundments | |
| Nutrient and Pesticide Routing in Impoundments | Nitrate Routing |
| | Organic N Routing |
| | P Routing |
| | Pesticide Routing |
| Water Quality in Impoundments | Toxic Balance |
| | Soil-Liquid Partitioning |
| | Phosphorus Mass Balance in Lake |
| | Relationship Between Total Phosphorus and Trophic Status |
| Water Management | Irrigation Water Transfers |
| | Water Use Withdrawals |
| | Simulation of Impoundment |
| | Simulation of Hydrological Response Units |

The Introduction from the SWAT manual is included as Appendix 1 as background to the model. From Appendix 1 it is evident that many of the approaches to modelling hydrological processes within the SWAT model are very similar to those employed in the *ACRU* model, *viz.*

- SWAT is physical-conceptually based and does not use external calibration to optimise parameter values,
- the model uses readily available inputs,
- it is a daily time step model,
- it uses equations based on the SCS concept to estimate runoff volumes and peak discharge rates,
- the soil water budgeting uses a similar threshold based approach as that in *ACRU*,
- it also simulates soil water fluxes for two soil layers,
- unsaturated drainage and capillary action are both simulated,
- the model partitions evaporation from soil surfaces and plants separately using Ritchie (1972)-like routines, as does the *ACRU* model,

- the model can estimate the effects of $CO_2$ changes,
- event based sediment yield, as in *ACRU*, is estimated by means of the Modified Universal Soil Loss Equation (MUSLE), and
- sediment routing in impoundments is identical to that used in the *ACRU* model.

The similarities in structure between the two models gave rise to the idea of adapting some of the water quality capabilities of the SWAT model into the *ACRU* model. As a consequence it was decided to investigate the feasibility of building the SWAT routines pertaining to the routing of sediments in channels into the *ACRU* model. Background information to the sediment routing routines in the SWAT model are included in Appendix 2.

The greatest difficulty to be overcome was to gain clarity on the units used in some of the equations in SWAT, as Imperial units are still used in places. However, the user support from the team of developers is excellent and requests were usually answered within 24 hours. The ease in which these routines were adapted for use in the *ACRU* model and the assurance of user support and up-to-date documentation (the manuals were being revised and updated and are available on-line at the time of writing this report) provide further opportunities for including other water quality routines in the *ACRU* model. The main concern with this approach, when compared to the others discussed above, shifts from one of conceptual compatibility of the water quality routines and the *ACRU* model, to the problem of limitations in observed water quality data in South Africa, since water quality models place very high input data demands on the user.

#### 3.1.4 Summary

It should be noted that many of the current shortcomings of the *ACRU* model Version 3.00 have been addressed in the latest version of the model (*ACRU2000*). These changes include the processing of subcatchments on a time-step by time-step basis as opposed to the subcatchment by subcatchment method employed in previous versions. This will facilitate the easy transfer of water between any subcatchments and will eliminate the so-called feedback problems encountered before.

A further development in *ACRU2000* has been the explicit simulation of the river channel as a separate subcatchment. This will ensure that operations involving channel hydraulics and routing of water quality constituents can be added without any restructuring of the model. Since the *ACRU2000* model has been designed to overcome former limitations of *ACRU* and to facilitate the strengths of other models to be incorporated with relative ease, it is envisaged that the addition of routines to simulate operations such as reservoir releases and water quality constituents will be accommodated with far less difficulty than was previously the case.

It is the opinion of the researchers involved in this project and their colleagues that the option which shows the greatest promise is that of improving the water quality functionality within the *ACRU* modelling system. This could be done by drawing on the strengths of water quality modules from HSPF and SWAT to produce an integrated model which will circumvent the complications of conflicting data formats and modelling philosophies. To this end work is currently progressing well through a collaboration with the University of Florida.

## 3.2 An Evaluation and Discussion of Other Software Requirements for Model Enhancement

In this section the enhancements made to the *ACRU* model and some of the "stand alone" utilities which were developed during this project are reviewed. These developments improve the functionality of *ACRU* and increase the ease with which users can prepare the information required by the model.

### 3.2.1 Addition of the WDM file as an output option from *ACRU*

Routines have been added to Release 28 of Version 3 of the *ACRU* model to offer the user the option to write its daily output to a WDM file (cf Section 3.1.3.1). Since the WDM is the file format used by the HSPF model, this option brings the concept of a "seamless" serial link between the two models one step closer to reality. Staff from the CCWR also collaborated with researchers of BEEH to enable the user to use the GENERATION and analysis of model simulation SCENARIOS (GENSCN) software to manage modelling projects. GENSCN provides an interactive framework for analysis, is based on the WDM format, is built around an established and adaptable watershed model (usually HSPF) and was developed to create simulation scenarios, analyse results of the scenarios, and compare scenarios.

However, several disadvantages to using this software were also encountered. These include the following:

- Since GENSCN is based on the WDM file, either output from *ACRU* needs to be converted into this format or *ACRU* needs to be modified in order to produce WDM output files. These options have been built into *ACRU*, but the execution speed of the model is adversely affected by at least an order of magnitude when the latter WDM option is invoked. This problem was addressed by staff of the CCWR and researchers of BEEH and seems to be irreconcilable with the present structure of the model. It is due to the combination of the fact that the *ACRU* model writes its daily output at monthly intervals and that WDM has a complex internal structure. The system of direct access pointers within the WDM file means that the overheads (in terms of processor time) involved in configuring a WDM are much greater than the time it takes to populate or interrogate the file. With the WDM being accessed frequently (e.g. on a monthly basis in the case of the *ACRU* model), it becomes a computationally very inefficient way of storing simulation results at run time. This problem has been addressed by developing stand-alone post processor software to convert output from *ACRU* to WDM and may be overcome in *ACRU2000* if JAVA interfaces (DLLs) can be developed to access the WDM.
- The WDM is not transferable between computing platforms such as UNIX and Windows. Such an operation involves exporting the WDM to ASCII before moving to the other operating system and then importing the ASCII to WDM format. This is a major disadvantage when it comes to complex catchment configuration such as that of the Sabie with the total number of hydrological response units numbering in excess of 500 subcatchments. A more advantageous option would be a format such as dBASE file format (.dbf files or something similar) which are platform independent and may be accessed by software such as ACCESS, PARADOX, ORACLE, QUATTRO PRO, EXCEL and ArcView.
- Although the GENSCN software is still under development and it therefore remains to be seen what the final graphical functionality will include, the present version neither offers all the functionality required by modellers using the *ACRU* system nor does it include the features available in the graphical and statistical software developed at the Institute for Water Research (IWR) at Rhodes University. It is unlikely that an "off the shelf" project management software package which has been written explicitly for a specific model will service all the needs required by modellers using alternate modelling systems. It seems that a preferable option would be to further develop and customise the postprocessing software developed at the IWR or the Integrated Catchment Information System (ICIS) developed by the CCWR. Ongoing discussions have been held with Hughes (1999, personal communication) of the IWR on future developments of their software. It is of great benefit if model developers and users can have some influence on the structure and features of project management or post processing software.

### 3.2.2 Operating rules for impoundments

An IFR workshop for the Sabie River (including the Sand and Marite Rivers) was held in 1996 and the final report became available in August 1997. A total of eight IFR sites were identified in the Sabie catchment (Figure 11). Each site has a corresponding desired future state (DFS) encapsulating the streamflow aspects of the ecological reserve in terms of baseflows and higher flows under maintenance and drought conditions. In catchments where impoundments occur, these flow regimes should be attained by applying appropriate operating rules at the reservoir. In situations where no impoundments are present, the IFRs are met by applying controls on abstractions and transfers from the river.

The development of a methodology to determine operating rules to satisfy IFRs in South African is a very recent development (Hughes *et al.*, 1997; Hughes and Ziervogel, 1998 and Hughes, 1999). These methodologies are of paramount importance to hydrological modellers who will be called on to assess the impacts of different operating rule scenarios. Consequently, several meetings were held with Hughes

(1999, personal communication) and Sellick (1999, personal communication) to discuss the definition of these operating rules and their implementation.

From these meetings it was ascertained that there has been a shift in the management of impoundments from a system whereby water restrictions were put in place fairly early in a drought situation to a risk-based system based on probabilities of the system running out of water. The more recent trend is to operate the impoundment in such a way as to give the users access to the stored water until the impoundment is almost dry. The rules are determined so as to use the stored water as efficiently as possible by operating the impoundment to agreed levels of probability of failure. This approach avoids the situation where users are subject to frequent water restrictions while the storage levels in the impoundments never fall below a predetermined lower limit.

Although the IFR workshop for the Sabie River has been held at the time of finalising this report (March, 2000), the IFRs are still in the process of being translated into operating rules for Injaka Dam. Some of the problems facing the operators of impoundments include the following:

- a situation where releases to satisfy the IFRs at particular sites result in IFRs at other sites being violated,
- quantifying the magnitude and timing of releases to satisfy the high and low flow release (freshet) requirements during drought and maintenance periods of a site a great distance from the impoundment since the attenuating effects and the storage in pools need to be accounted for,
- the risk involved in releasing water to satisfy freshet requirements only to have a major runoff event soon thereafter, and
- the differences in streamflow estimates between those used in the IFR workshop and those simulated with Water Resources 90 (WR90).

A further problem highlighted at these meetings involved the role of simulation models in the day-to-day operation of impoundments. Since simulation models require historical data, they cannot provide the climatic cues required to trigger releases or restrictions of flows. For this reason the impoundments will be operated using the Water Administration System (WAS) model to provide cues to release water, the PROCAN model to simulate the attenuation of flows through the system and the YIELD model to simulate the system yield. In order to use daily hydrological simulation models to control the operation of impoundments, both the accuracy of rainfall forecasts needs to be improved and true "real-time" functionality needs to be developed within these models. Until then, these operations will be based on observed flows at gauged sites.

It was also noted that while the IFRs in the Sabie catchment may be met by the efficient operation of Injaka Dam, the only way to satisfy the IFRs in the Sand catchment will be through restrictions on abstractions for irrigation. The rationale for this is that while the water use by commercial forestry may be significant on local scales, irrigation abstractions will dominate the overall yield of the catchment.

At the meetings it was agreed that the best way to simulate the impacts of operating rules of impoundments on downstream water resources would be to add the appropriate routines to the *ACRU* model rather than attempting to link with the daily reservoir simulation model developed at the IWR. The main reason for this decision was once again the complication of the feedbacks which occur when making releases of stored water for the benefit of the environment or downstream users. The key to both the timing and magnitude of IFR releases from impoundments appears to be the climatic or hydrological cue supplied by flows occurring either at the inlet of the reservoir or at some other strategic point in the catchment. To this end routines have been added to the *ACRU* model to ensure that in situations when the storage in a dam is greater than the dead storage level, the flows at a specified point in the catchment will be matched or exceeded by seepage (in the case of earthen structures), normal flow releases, overflows and special IFR releases. While this addition to the model does not ensure that the IFRs at downstream river reaches are met, this development will ensure that the timing of these releases is correct. A collaborative research project between the IWR and BEEH in 2000 and 2001 will further investigate the quantification of the magnitude of these releases with the *ACRU* model. Furthermore, since Flow Duration Frequency analyses form the core of the methodology to determine IFRs, software has been developed to perform such an analysis on streamflows simulated with the *ACRU* model.

A final point that was made clear in these meetings is that while BEEH may develop software to analyse simulated streamflows for comparison with predetermined IFRs and to conduct impact assessments of different IFR scenarios, it would not be the function of BEEH to develop the capabilities to *determine* these IFRs within the *ACRU* modelling framework. Specialised software for this purpose is either already available or, in the case of operating rules, is under development by the IWR.

### 3.2.3 Progress on the AUTOSOILS soils decision support system

The AUTOSOILS program developed in BEEH to translate the soils information supplied by the ISCW into soils attributes required by the *ACRU* model was modified to write output into a format compatible with ArcView GIS. The information produced by AUTOSOILS is appended to the Land Types shape file resulting in a powerful hydrological database of soils parameters which can then be used to automate the creation of a menu file for *ACRU*. A further development has been the option to analyse the ISCW information down to the hillslope scale of a Terrain Unit. This option results in the potential for determining the *ACRU* soil water retention and drainage characteristics for every Terrain Unit in South Africa.

In the course of this project, many years of negotiation with the ISCW culminated in an agreement whereby the AUTOSOILS utility was installed at the ISCW and was used to analyse all the Land Types of southern Africa. In return, DWAF and BEEH were given copies of the output of the analysis. It is hoped that this cooperation will be strengthened in the future and that collaboration between the ISCW and BEEH in the delineation of Terrain Units will bear fruit in a subsequent WRC funded project at BEEH.

### 3.2.4 Development of CalcPPTCor

CalcPPTCor is a utility which assists the user in selecting the most representative rainfall station for a particular catchment and automatically calculates the month-by-month precipitation adjustment factors required for each subcatchment by *ACRU*. This adjustment is in the form of a multiplicative correction factor, which varies month-by-month, applied to each daily rainfall amount from the driver station for a specific subcatchment to obtain representative daily rainfall values for each of the subcatchments. The program uses the BEEH gridded median monthly rainfall surfaces and a file of customisable options and assigns a suitability index, and ranking of the rainfall stations which qualify for selection as driver stations, as well as displaying them. The user defined criteria for selection include proximity to the subcatchment, length of record, most recent date of operation, and representativeness on a monthly basis.

An example of the output from CalcPPTCor for Subcatchment 9 is shown in Table 9.

## 3.3 Stakeholder Involvement: Experiences and Problems

In dealing with individuals with non-hydrological backgrounds it has become evident in this project that the process of collaboration and interaction between researchers from different fields is one in which a great deal of time needs to be invested and one where considerable patience needs to be exercised. A collaboration process cannot be successful, for example, under the following circumstances:

- The motives and integrity of the collaborating parties may be in question. This can occur when the ideal working relationship, which is based on the assumption that each party has the best interests of the other at heart, is not met (i.e. it should not just be a case of "what is in it for me").
- Secondly, the hydrological competency and scientific ability of the collaborating parties may be in doubt. Such doubts will lead to the suspicion that ones own reputation and credibility will be compromised if incorrect conclusions are drawn from your results by the collaborators. This does not imply that research across and between different disciplines will invariably fail, but the assumption of "maximum intelligence but minimal knowledge" on the part of collaborating parties needs to be applied.

**Table 9** Output from the CalcPPTCor rainfall station selection program for Subcatchment 9

```
File containing the CCWR station details: CCWR.ackn.daily
TEMPLATE name of files containing the gridded median monthly values for RSA: m_rain.12
TEMPLATE name of files containing the subcatchment median monthly information: gmrf112st.ascii
File containing subcatchment lat and longs (ddmm): subcatchment_lat_long.dat
File containing subcatchment altitude values (m): subcatchment_alt.dat
File containing subcatchment MAPs (mm): subcatchment_map.dat

The DRY season extendes from March to August.  (During this season the rainfall station is not penalised for
CORPPT values which are outside of the range of 0.70 - 1.30)
Rainfall stations with more than 3 months with CORPPT values out of the range of 0.70 - 1.30 during the WET SEASON have not been included in this printout
Threshhold distance (km) from centroid to limit rainfall stations in output :60 km
All stations in this output have a record length of 20.0 years or more (edit your menu file to change this value)
All stations have an end year of 1990 or later (edit your menu file to change this value)

Central meridian used in distance calculations: 31.0 degrees
Geographic coordinated outputted in Degrees Decimals
```

| Subcatchment 9 STATION DETAILS | 24.71 LAT | 30.92 LONG | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Record Span | # Yrs Actual | # Yrs Good | Subc.●Stat.● Alt Alt (m) (m) | Subc.●Stat.● MAP MAP (mm) (mm) | Dist.● (km) (Merid.= 31 Deg) | # mths out of range in WET Season | Suitability INDEX (%) | RANK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Monthly Precipitation Correction Factors | | | | | | | | | | | | | | | | | | | | |
| 2 0594635 W | 24.58 | 30.87 | 1.06 | .98 | 1.06 | 1.14 | .95 | .70 | .87 | 1.00 | 1.18 | 1.01 | 1.18 | 1.00 | 1928-1997 | 70 | 50 | 1046.●1320.● | 1313.●1348.● | 13.9 | 0 | 53.7 | 2 |
| 3 0594828 W | 24.83 | 31.00 | .95 | 1.18 | .89 | .97 | 1.02 | .92 | 1.30 | 1.15 | .92 | .95 | .96 | 1.00 | 1963-1998 | 36 | 31 | 1046.● 910.● | 1313.●1340.● | 17.0 | 0 | 44.4 | |
| 11 0555579 W | 25.15 | 30.83 | .98 | 1.09 | 1.11 | 1.27 | 1.30 | .70 | .82 | 1.30 | .93 | 1.02 | .92 | 1.13 | 1933-1998 | 66 | 49 | 1046.●1380.● | 1313.●1224.● | 50.6 | 0 | 35.9 | |
| 12 0555461 W | 25.18 | 30.77 | .93 | 1.13 | 1.03 | 1.08 | .96 | .92 | .87 | 1.15 | .84 | .81 | .81 | .97 | 1912-1998 | 87 | 8 | 1046.●1360.● | 1313.●1339.● | 55.6 | 0 | 12.7 | |
| 14 0594764 W | 24.73 | 30.93 | .89 | .87 | .84 | .85 | .92 | .84 | .70 | .70 | .77 | .89 | .88 | .85 | 1940-1998 | 59 | 42 | 1046.● 930.● | 1313.●1476.● | 4.1 | 1 | 63.2 | 1 |
| 15 0594806 W | 24.93 | 30.95 | 1.19 | 1.25 | 1.13 | 1.19 | 1.09 | 1.01 | .95 | 1.15 | 1.09 | 1.15 | 1.09 | 1.17 | 1935-1998 | 64 | 54 | 1046.● 980.● | 1313.●1136.● | 26.1 | 1 | 38.0 | |
| 16 0594779 W | 24.98 | 30.93 | .93 | .99 | .93 | .94 | 1.01 | .70 | .70 | .95 | .77 | .87 | .83 | .95 | 1943-1998 | 56 | 33 | 1046.● 940.● | 1313.●1433.● | 31.4 | 1 | 29.5 | |
| 18 0555483 W | 25.05 | 30.78 | 1.09 | 1.24 | 1.10 | 1.20 | 1.14 | .83 | .95 | 1.05 | .95 | .95 | .96 | 1.10 | 1957-1998 | 42 | 14 | 1046.●1150.● | 1313.●1189.● | 41.0 | 1 | 19.3 | |
| 19 0555455 W | 25.10 | 30.75 | 1.10 | 1.25 | 1.07 | 1.11 | 1.14 | .70 | 1.14 | 1.03 | .92 | .91 | .88 | 1.07 | 1931-1998 | 68 | 54 | 1046.●1027.● | 1313.●1194.● | 47.4 | 1 | 45.1 | |
| 22 0555878 W | 25.13 | 31.00 | 1.16 | 1.30 | 1.28 | 1.30 | 1.12 | 1.10 | 1.01 | 1.08 | .87 | 1.09 | .98 | 1.16 | 1929-1993 | 65 | 53 | 1046.●1050.● | 1313.●1145.● | 48.7 | 1 | 47.3 | 4 |
| 26 0555280 W | 25.17 | 30.67 | 1.05 | 1.23 | 1.16 | 1.17 | 1.09 | 1.21 | 1.24 | 1.30 | .90 | .84 | .85 | 1.00 | 1961-1994 | 34 | 15 | 1046.●1608.● | 1313.●1230.● | 57.5 | 1 | 20.7 | |
| 28 0555673 W | 25.23 | 30.88 | 1.10 | 1.30 | 1.29 | 1.27 | 1.30 | .89 | .89 | 1.20 | .94 | .93 | .94 | 1.17 | 1937-1998 | 62 | 56 | 1046.●1060.● | 1313.●1133.● | 59.2 | 1 | 45.8 | 5 |
| 32 0594760 W | 24.67 | 30.93 | .81 | .84 | .91 | .79 | .71 | .70 | 1.06 | .79 | .74 | .78 | .88 | .82 | 1949-1998 | 50 | 32 | 1046.● 993.● | 1313.●1544.● | 4.1 | 2 | 49.6 | 3 |
| 33 0594696 W | 24.60 | 30.90 | 1.04 | 1.06 | 1.07 | 1.04 | 1.11 | .70 | 1.09 | 1.30 | 1.29 | .98 | 1.20 | 1.07 | 1935-1998 | 64 | 51 | 1046.● 860.● | 1313.●1230.● | 11.2 | 2 | 37.6 | |
| 34 0594590 W | 24.83 | 30.83 | 1.03 | .99 | 1.10 | 1.29 | 1.06 | .70 | .95 | 1.30 | 1.20 | 1.11 | 1.06 | 1.23 | 1926-1998 | 73 | 57 | 1046.●1310.● | 1313.●1209.● | 17.0 | 2 | 27.6 | |
| 35 0594802 W | 24.87 | 30.95 | .95 | .86 | .86 | .94 | .83 | .70 | .70 | .88 | .77 | .72 | .82 | .88 | 1950-1998 | 49 | 36 | 1046.● 960.● | 1313.●1542.● | 18.8 | 2 | 24.4 | |
| 37 0595025 W | 24.88 | 31.00 | 1.20 | 1.26 | 1.12 | 1.19 | 1.12 | 1.27 | 1.15 | 1.30 | 1.13 | 1.17 | 1.12 | 1.19 | 1972-1998 | 27 | 9 | 1046.● 835.● | 1313.●1130.● | 22.0 | 2 | 6.4 | |
| 40 0594626 W | 24.93 | 30.85 | .86 | .91 | .83 | .97 | .76 | .70 | .70 | .73 | .75 | .78 | .81 | .94 | 1906-1992 | 87 | 13 | 1046.●1463.● | 1313.●1515.● | 26.7 | 2 | 13.2 | |
| 42 0594626 W | 24.93 | 30.85 | .86 | .91 | .83 | .97 | .76 | .70 | .70 | .73 | .75 | .78 | .81 | .94 | 1949-1998 | 50 | 19 | 1046.●1463.● | 1313.●1515.● | 26.7 | 2 | 13.9 | |
| 43 0594539 W | 24.98 | 30.82 | .88 | .88 | .74 | .93 | .84 | .70 | .70 | .79 | .72 | .80 | .83 | .89 | 1914-1992 | 79 | 61 | 1046.●1250.● | 1313.●1529.● | 33.0 | 2 | 23.1 | |
| 44 0555662 W | 25.03 | 30.88 | .92 | 1.03 | .84 | .92 | .88 | 1.13 | .70 | .70 | .70 | .78 | .86 | .88 | 1952-1998 | 47 | 29 | 1046.●1020.● | 1313.●1467.● | 37.1 | 2 | 28.3 | |
| 45 0555664 W | 25.07 | 30.88 | 1.06 | 1.24 | 1.30 | 1.04 | .70 | .70 | .94 | .70 | .77 | .97 | .98 | .99 | 1960-1998 | 39 | 23 | 1046.● 900.● | 1313.●1250.● | 40.8 | 2 | 21.9 | |
| 50 0555792 W | 25.20 | 30.95 | 1.21 | 1.30 | 1.28 | 1.30 | .97 | .89 | .89 | 1.20 | .90 | 1.00 | .93 | 1.04 | 1953-1994 | 42 | 31 | 1046.●1080.● | 1313.●1139.● | 55.5 | 2 | 27.7 | |
| 55 0594715 W | 24.92 | 30.90 | .83 | .99 | .78 | .91 | .86 | .70 | .70 | .70 | .72 | .73 | .83 | .79 | 1949-1994 | 46 | 31 | 1046.●1070.● | 1313.●1582.● | 24.1 | 3 | 27.3 | |
| 56 0595030 W | 25.00 | 31.02 | 1.21 | 1.30 | 1.12 | 1.28 | 1.23 | 1.08 | .77 | .95 | .78 | 1.00 | 1.09 | 1.04 | 1965-1998 | 34 | 20 | 1046.● 960.● | 1313.●1170.● | 34.7 | 3 | 18.6 | |
| 58 0555486 W | 25.10 | 30.78 | 1.27 | 1.30 | 1.30 | 1.30 | 1.30 | 1.01 | 1.24 | 1.20 | 1.09 | 1.10 | 1.10 | 1.29 | 1973-1998 | 26 | 17 | 1046.●1060.● | 1313.●1017.● | 66.3 | 3 | 20.4 | |

- Thirdly, problems arise when there is limited opportunity to invest the time in informing the collaborating parties and keeping all the groups up-to-date with the latest developments in the project. In the initial stages of a project, most parties are usually in agreement as to what is expected of themselves and others. However, it is only later that the ramifications of lists of requests, bordering on demands, by collaborators become evident. This is often due to the fact that the different parties are usually committed to other projects in addition to the collaborative research and that the amount of time they can afford to dedicate to the project at hand is limited. Progress on this project was considerably delayed when, for example, details of the land use scenarios on hydrological responses were changed without informing the hydrological modellers.

These types of problems are encountered in the process of working remotely (in this case between Pietermaritzburg, Cape Town and the Wits Rural Facility situated in a remote part of the Sand catchment with very poor communication transmission lines).

### 3.3.1 Unrealistic expectations

Several situations in the "Save the Sand" project were encountered where unrealistic expectations by collaborators needed to be dealt with. Initially it was expected that all permutations of the different scenarios listed in Table 3 would be simulated in spite of the fact that some were identical in terms of the hydrological impacts and others were physically unfeasible. This would have entailed modelling scenarios which represented the removal and substitution of every combination of land use in the three zones. This request emanates from ignorance in the process of devising and conducting hydrological impact studies and constitutes a typical case of "lets model every conceivable permutation simply because it is possible". The various parties were finally persuaded that since this project was only in a first phase of a feasibility study, the six (previously eight) scenarios described in Table 3 above would suffice. It was felt that in the time available, the potential of using a physical-conceptual daily model such as *ACRU* could be illustrated with these scenarios and that a more complete set of simulations could follow at a later date.

### 3.3.2 Preconceptions and misunderstandings

Some of the questions posed and comments made by collaborators in the course of this project made it obvious that either the methodology and results of the simulations were misunderstood or that the preconceived notions of the relative impacts of the changes in land use were not confirmed by the hydrological simulations. It soon became clear that many of the members of the "Save the Sand" steering committee had expected that commercial afforestation would account for a far greater consumptive use of water and that the removal of 25 or 50 per cent of this afforestation would yield considerably more streamflow than was simulated (cf Section 2.5 for a discussion of the results).

The results of the "Save the Sand" case study were based on the assumptions made in generating the scenarios and the configuration of the catchment. One of the sources of frustration from a modelling perspective was that the land use from the 1996 LANDSAT TM image had to be matched with the 1993 image since the scenarios were based on the 1996 information, but the *ACRU* menu file had been configured using the 1993 information. Secondly, the scenarios were formulated for three zones with little or no consideration having been given to the hydrological catchment configuration. This resulted in the proposed changes being apportioned to the different subcatchments constituting the relevant zone. This particular problem will undoubtedly be encountered more frequently in the future since CMAs and other water authorities will need to make decisions on a catchment scale, while many of the stakeholders operate according to their specific scales of concern which are independent of catchment boundaries (e.g. farm-by-farm, magisterial or enumerator districts).

### 3.3.3 Future collaborative links

A request has been received from AWARD to conduct further hydrological simulations both of the status quo and of future land use scenarios in the Sand River catchment. AWARD have made recommendations to DWAF regarding strong collaborative links between themselves and BEEH. A further meeting was held in 1999 to discuss possible cooperation in the context of the WRC project entitled "Development of an Installed Hydrological Modelling System". Although there is a fair degree of overlap between the broad objectives of the two projects there are several issues which will need clarification, e.g. the scale at which the AWARD project intends to work is far more detailed than that required by this project, which implies that a spatial scaling down of simulated results may be necessary. However, efforts will be made to accommodate the needs of the stakeholders of the Sand catchment.

## SECTION 4 CONCLUSIONS AND RECOMMENDATIONS

### 4.1 Conclusions and Benefits of this Research

The objectives of this project were:

- first, to refine, re-configure where necessary and verify a dynamic, land use sensitive, spatially distributed hydrological model for the Sabie River System in South Africa and, (bearing in mind limitations in the accuracy of input data and the assumptions on which the model is based) to provide historical sequences of daily time series of streamflow and sediment yield at any point of interest/conflict to other modellers involved in the KNPRRP and to relevant stakeholders in the catchments;
- secondly, to establish an active operational hydrological modelling framework for use in current and future water resource conflict resolution in the Sabie catchment;
- thirdly, to provide a modelling infrastructure capable of modelling water quality and thus facilitate the use of this modelling system by water quality modellers;
- fourthly, to endeavour to involve relevant stakeholders in the Sabie River System to the extent that at the completion of the first phase (18 months) of the project, sufficient interest would have been generated to secure financial support by the stakeholders for the maintenance of the modelling system and for any refinements/additions to the modelling infrastructure identified by stakeholders;
- fifthly, to endeavour to use the modelling system developed for the Sabie River catchment to involve relevant stakeholders in the Olifants River System to the extent that the stakeholders would financially support the application of the modelling infrastructure in the Olifants River catchment; and
- sixthly, to seek collaboration with the IWR at Rhodes University, to incorporate the IFRs as operating rules in the modelling infrastructure.

The **first two objectives** have been met with the establishment a modelling framework comprising the following:

- 130 subcatchments which take IFR sites, abstraction and transfer sites, areas of irrigation, geomorphological and aquatic sampling sites and land cover into consideration,
- a patched and representative set of 26 rainfall stations which have been assigned to the respective subcatchments,
- observed streamflow records for all the gauging stations in the catchment,
- present land cover derived from the recently released National Land Cover database,
- detailed soils information from the ISCW Land Type database, and
- irrigation information for the relevant subcatchments. The MBB coverage of the extent of irrigated areas is also available, but still requires ground truthing and accompanying information on crop types and irrigation schedules.

However it should be noted that the present version of *ACRU* does not account for losses to evaporation and disconnected water tables, and cannot explicitly simulate the effects of Karst processes.

Mention has been made of the fact that, unlike simulated streamflows, event-by-event estimations of sediment yield are only available at a pseudo-subcatchment scale. However, reliable estimations are available at each of the 56 subcatchment outlets used in the 1997 study by Pike *et al.* Should the need for estimations of sediment yields at a finer scale arise, this deficiency can be addressed once a public version of *ACRU*2000 becomes available.

The benefit of this modelling framework is that it is dynamic in that it can be updated on a regular basis as more accurate information pertaining to activities such as abstractions and irrigation becomes available. Since the catchment has been discretised and configured for the *ACRU* model, the framework is readily available for future research and to managers. Effort can now be expended in updating and refining the system and in answering the many difficult questions that will be posed in the coming era of representative, bargaining-based water allocations and licensing. The simulation results may be written to standard *ACRU* format files or to a WDM file. It is expected that the modelling system will be transferred to a dedicated computer at the KNP in the near future.

In regard to the **third objective**, various options regarding water quality modelling in the Sabie have been investigated and the findings have been discussed at length in the document. It is the contention of the authors that when it comes to altering the internal structure of complex hydrological models the most preferable option would be to gain the support of the developers of the model, so that the changes can be accommodated in future releases of the model. It would also be advantageous to have the support of the developers to give advice and guidance when needed.

The static link between models seems to be the most simple to implement since it leaves both models intact and they can both operate within the modelling context in with they were developed. The disadvantage of this approach is that it cannot provide for the situation where feedbacks between the models are necessary. This approach also presents some problems in the case where the output from one model needs to be manipulated before it can be used by the other. The most flexible and convenient approach would seem to be an internal link between models whereby a decision is taken to further develop one or other of the models and the routines or algorithms are transferred between the models. However, this option can only be successful if the two models share presuppositions that are scientifically compatible and adhere to the same assumptions regarding scale and error limits.

The goal of the **fourth objective** was essentially to secure financial support for the maintenance of, and additions to the modelling system. Although this goal was not achieved explicitly, it is believed that the Scientific Services division of the KNP has acquired a powerful computer from the CCWR which will accommodate, among many other applications and databases, the modelling system resulting from this project. This configuration will therefore be readily available for future refinements or simulations by, or on behalf of, stakeholders in the catchment. However, it should be noted that the developers of the model recommend very strongly that operators of the model need to be suitably qualified and experienced in using the model (having received some form of formal training in configuring and running the model and analysing the results) before they can expect to receive support from the *ACRU* User Consultant or an endorsement of their findings by the developers.. Development of the *ACRU* model is ongoing under current WRC and other externally funded projects. This research has historically been user driven although other relevant "by-products" of unrelated projects are also considered for incorporation into the model. In this way *ACRU* users can benefit from these refinements and additional functionality if they ensure that the most recent public version of the model is used in simulations.

With reference to the **penultimate objective**, DWAF commissioned BKS Consulting Engineers to undertake an independent investigation into the feasibility of installing the *ACRU* modelling system in the Olifants catchment. Researchers of BEEH offered initial training with the model. The consultants have meanwhile completed an assessment of the *ACRU* model as an appropriate tool for water resources management in South Africa and, together with BEEH, are currently configuring the *ACRU* model in the Olifants.

In terms of satisfying the ecological reserve, it is believed that a physically based conceptual hydrological model can be an invaluable asset in assisting authorities such as the future CMAs in decisions regarding the allocation of water rights and land use permits. However, in the future scenario of a "bottom up" approach to allocations and catchment management as envisaged by the National Water Act (1998), it will not be the outputs of a hydrological model alone that determine the outcome of conflicts over water resources. Rather, by providing the decision makers and affected parties in a catchment with opportunities to evaluate the future consequences of their current decisions, it is hoped that physical-conceptual hydrological models will play a prominent role in ensuring that the scarce water resources in southern Africa are managed in an equitable and sustainable manner. If this modelling system can contribute towards this goal, it is believed that the funding supplied by the WRC and the effort expended by the researchers and members of the steering committee in the course of this project will have been justified.

Many valuable lessons were learnt by both sides in the course of this exercise. These included, on the part of the non-hydrologists, a realisation of the importance to include all members of the proposed research team in the planning of the different scenarios to ensure that all scenarios are both hydrologically relevant and logistically feasible, an appreciation of the complexities involved in configuring a hydrological model, and a better understanding of some of the preconceptions that abound concerning the water consumption by different land uses (including an improved understanding of some of the factors affecting water consumption between different species).

The exercise of interacting with colleagues who, while being specialists in their own disciplines, are not trained in the field of hydrology and have had little or no exposure with simulation models, was a new experience for the modelling team. It soon became apparent that the adage "expect maximum intelligence but minimum knowledge" applies in interdisciplinary research of this nature. Many of the difficulties and frustrations encountered were not due to ineptitude or a lack of integrity among the different partners, but to a lack of appreciation of the level of complexity and effort required in evaluating some of the scenarios, or to preconceptions which hindered the acceptance of final results.

Finally, in regard to the **sixth and last objective**, one of the most valuable "products" of this project has been the spirit in which collaboration has been carried out between BEEH and the IWR. A great deal of expertise and experience in the fields of hydrological modelling and the determination of ecological water requirements resides at the IWR and it is encouraging to report that there was no hesitation in sharing expertise and resources when colleagues at Rhodes were approached by BEEH for advice. It is sincerely hoped that this relationship will be strengthened as continuing research into the aspect of Reservoir Operating Rules is conducted in other WRC funded research projects.

## 4.2 Technology Transfer

The following workshops were attended and presentations were made in the course of this project.

- A KNPRRP workshop to discuss Integrated River and Catchment Management in the Lowveld was attended over the period of 9-12 March, 1998 during which opportunities arose to explain the modelling approach to water resource management.
- The methodology adopted for the simulation of the "Save the Sand" scenarios and some of the results of the simulations were presented at the final meeting of the "Save the Sand" steering committee held at Skukuza on 24 June 1998. While the hydrological study only accounted for a part of the entire project, both in terms of budget and time allocated at the meeting, many of the other facets of the project were dependent on the availability of water under present and future catchment conditions. Some of the difficulties encountered in communicating the reasons for the magnitude of the hydrological impacts of the changes in land use have already been discussed under the heading of "Problems Encountered".
- A paper entitled "Questions facing hydrological modellers as we approach the second millennium - some experiences from the KNPRRP" was presented at the National Rivers Initiative organized by the South African Society of Aquatic Sciences in Pietermaritzburg from 29 June to 1 July 1998. There were also several opportunities in the workshop sessions to discuss the results of the Sand scenarios and to debate the hydrological impacts of changes in land use and the effect of impoundments on the hydrological response of catchments.
- The Mpumalanga Indaba held in Nelspruit on 9 and 10 April 1999 to discuss SFRAs was attended. Once again the need for estimates of water use by major land covers in different geographic regions and under various management scenarios was highlighted as an essential requirement for the successful implementation of the new licensing system of SFRAs as required by the new Water Act.
- A paper titled "Estimation of water use by present commercial afforestation in the Sand catchment, Mpumalanga" was presented at the 9th South African National Hydrological Symposium held at the University of the Western Cape on 29 and 30 November 1999.

Finally, a meeting was arranged at CSIR Environmentek, Pretoria with Mr Mark Thompson, where the NLC Database was discussed as possibly becoming the future standard for hydrological modelling with the *ACRU* model in South Africa. Although a similar classification system to that utilised in the *ACRU* model has been used, the disadvantage is that there is currently no hydrological interpretation of the different land cover classes. An informal agreement was reached whereby the CSIR release the NLC database to BEEH in return for hydrological parameters describing the water use coefficients, rooting distributions and interception estimates for each land cover class. This interpretation will be conducted for all the land cover classes and the resulting information will be available in future applications of the model.

## 4.3 Recommendations for Future Research

The following 10 recommendations for future research are proposed:

- Standardised national soils and land use databases
  Physical-conceptual models require reliable and current land use and soils information in order to simulate catchment based processes accurately. The Land Type data base of the ISCW and the NLC CSIR Environmentek database are sources of valuable information from which many inputs to hydrological models may be derived. Through agreements with the relevant organisations, BEEH have made good progress in the process of deriving appropriate soil inputs from the Land Type database and are in the process of assigning hydrological parameters to the NLC land use classes. However, these databases contain information which was recorded at a finer scale than is currently been utilised. It is believed that, from a hydrological modelling perspective, further research into the process of interrogating and translating the respective databases is necessary before the full potential of these national resources can be realised. It is further recommended that the NLC database be adopted as the standard land use database for use by hydrological modellers and future CMAs*.
- Availability of reliable, long term, daily climate and hydrological data records
  Many of the problems inherent in the present version of the *ACRU* model (such as feedbacks, river channel hydraulics and the potential to route sediments in river reaches) have already been addressed in the *ACRU2000* release of the model. However, one problem encountered by both water quantity and quality modellers in southern Africa that may become worse in years to come is that of data availability. This problem becomes even more acute when one considers the increasing demand for models to produce accurate simulations for the evaluation of different scenarios, or the generation of long term synthetic streamflow records for ungauged catchments or in South Africa. In this light, an appeal is made to protect the existing and increase the future levels of funding allocated to measure, check and store hydrologically related data.
- Model validation and verification of simulations
  One of the primary motivations for developing hydrological models is to provide simulated estimates at locations in a catchment where observed data are either unreliable or not available. In developing new routines for simulation models, great care should be taken to ensure that all algorithms are derived from, and validated against reliable, representative data sets. Furthermore, before applying the model in areas where observations are not available, sufficient evidence needs to be present for the applicability of the algorithms and their validity in the prevailing climatic and physiographic conditions present at the simulation site to be beyond doubt. The process of engendering confidence in the model is essential before parties in conflict situations, or stakeholders, can be expected to embrace the recommendations resulting from a simulation-based catchment study.

  Therefore, wherever suitable quality data are available, simulations should be preceded by a verification study in which observed data and simulated estimates are compared by means of statistical analyses and double mass plots on a daily or monthly basis. This exercise should preferably be carried out within the catchment under scrutiny, or alternatively in a neighbouring catchment which is subject to a similar climatic regime and does not differ too significantly in terms of soils and land use from the catchment in question. Such a study should reveal the level of confidence which can be attributed to the modelled results*.
- Project management, analysis and visualisation software
  Many misunderstandings on the part of researchers from other disciplines and other stakeholders can be avoided if the results of modelling exercises are presented in a way in which technical jargon is avoided and yet simultaneously an appreciation of the complexity of the hydrological system is gained. It is believed that the effort spent in developing a generic suite of project management software will be well rewarded. Ideally this software should combine the many good ideas contained in the spatially referenced GENSCN and ICIS packages and the graphical software developed by the IWR.

- Data interfaces
  If the WDM is to be used as a possible data format by CMAs who will also be running the *ACRU2000* model in the future, JAVA DLLs will need to be developed in order to give the user the option of outputing results to the WDM (staff at the CCWR are in the process of addressing this issue). The standard output formats of *ACRU2000* is ASCII and DBF and Hughes (1999, personal communication) is optimistic that the DBF format can be offered as an input option to the IWR graphical software.
- Routines to model operating rules and IFRs
  At the time of writing, the procedure by which releases are made from impoundment to satisfy the ecological reserve is still an area undergoing much research in South Africa. Future collaboration will be sought with the relevant researchers in order to continue the process of quantifying the volumes of water to be released and determining the timing and attenuation of the releases in order to satisfy IFRs at downstream sites. The findings of this research should then be built into the *ACRU* model for future operational simulations where IFR releases are of concern*.
- Surrogates for complex inputs required to model water quality
  Water quality models, owing to their more extensive data requirements, are likely to be affected more detrimentally than water quantity models with the decline of hydrological observations. It may become necessary to investigate the use of surrogates for some of the more complex inputs required by these models. This approach has been adopted in the development of routines for simulation of phosphorus and *E. coli* in the *ACRU* model and the simulations in the Mgeni catchment in KwaZulu-Natal have shown great promise (Kienzle *et al.*, 1997). It is contended that such an approach could be extended to the simulation of other constituents of water quality and also in the derivation of channel characteristics for hydraulic operations such as flood and water quality routing, although these applications would require a real time version of the model (the current version of *ACRU* is a "historic" model in the sense that it requires input files of prerecorded daily data). Collaboration in this regard with the University of Florida, USA, is already underway at no cost to the WRC*.
- Model installation and user training
  It is recommended that, once the transfer of the modelling system to the KNP computing system is complete, a standard *ACRU* course be offered to the likely users of the model or its output. Attendees will receive theoretical and practical instruction in the various aspects of the modelling system and have the opportunity to become familiarised with the Sabie configuration. It is further suggested that the modelling system be updated to run under the *ACRU*2000 system once it becomes available for public use.
- Guidelines for cooperation with stakeholders
  One of the most pressing issues facing modellers today is the question of conveying the essence of complex scenarios to managers and decision makers who are not necessarily familiar with the terminology and methodologies employed by scientists and engineers - the so-called task of "Technology Transfer". The challenge is to accomplish this in such a way as to engender confidence in the results whilst at the same time ensuring that ones audience appreciates the limitations of the computer models and the problems associated with the representativity and accuracy of data from which results are derived. Furthermore, experience has shown that, while it would be preferable to know something of the relevant problems at the outset of a modelling exercise, all too often the stakeholders do not know what the questions are which need answering. Hopefully, as the modelling fraternity interacts to a greater extent with the catchment management authorities and stakeholders, the misconceptions and suspicions which exist will begin to decline.

  In the interim it is suggested that a set of guidelines be developed for cooperation between researchers and stakeholders. It is recommended that guidance be given on such subjects as including the relevant research organisation form the outset of a proposed study, ensuring that the stakeholders know what the crucial questions and issues are prior to completing the planning phase of a project and ensuring that proper liability clauses are included in final reports.

- <u>Climate forecasts for operational hydrology</u>
  The final recommendation of this project is to develop techniques to ensemble 1, 3, 7, 14 day and 1 and 3 month climate forecasts for operational hydrology. The procedures to determine these forecasts should be automatically undateable and spatially self correcting. These forecasts would be invaluable in the management of operational catchments where the operating rules of impoundments need to be balanced against the variability of the local climate to meet the requirements of downstream water users.

(* denotes aspects of new projects within BEEH and other organisations (e.g. CSIR) that are already being funded by the WRC and other agencies)

## APPENDICES

### Appendix 1 Overview of the SWAT Model

(This is an adaptation of the introduction from the SWAT Manual (Arnold *et al.*, 1996) - A list of notations used Appendices 1 and 2 are provided in Appendix 3)

#### Introduction

Large area water resources development and management require an understanding of basic hydrological processes and simulation capabilities at the catchment scale. The USDA-Agricultural Research Service (ARS) defines large areas as catchments of thousands or tens of thousands of square kilometres. Current concerns that are motivating the development of large area hydrological modelling include climate change, management of water supplies in arid regions, large scale flooding and offsite impacts of land management. Recent advances in computer hardware and software including increased speed and storage, advanced software debugging tools and GIS/spatial analysis software have allowed large area simulation to become feasible. The objective of this overview is to briefly describe the history, an overview of model operation and a description of model components of a catchment scale model called SWAT (Soil and Water Assessment Tool).

SWAT is the continuation of a long-term effort of nonpoint source pollution modelling with the (ARS). In the early to mid-1970's, in response to the Clean Water Act, ARS assembled a team of interdisciplinary scientists from across the USA to develop a process-based, nonpoint source simulation model. From that effort, a model called CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) was developed (Knisel, 1980). CREAMS is a field scale model developed to simulate the impact of land management on water, sediment, nutrients and pesticides leaving the edge of a field. *By the early and mid-1980s, several models were being developed with origins from the* original CREAMS model. GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) by Leonard *et al.* (1987) concentrated on pesticide and nutrient groundwater loadings. A model called EPIC (Erosion-Productivity Impact Calculator) by Williams *et al.* (1985) was originally developed to simulate the impact of erosion on crop productivity and has now evolved into a comprehensive agricultural management, field scale, nonpoint source loading model.

Other efforts were initiated which involved modifying CREAMS to simulate complex catchments with varying soils, land use and management. One effort was the AGNPS (Agricultural Nonpoint Source) by Young *et al.* (1987) model. AGNPS is a spatially detailed, single event (storm) model that subdivides complex catchments into grid cells. A model called SWRRB (Simulator for Water Resources in Rural Basins) (Williams *et al.*, 1985; Arnold *et al.*, 1990) was developed to simulate nonpoint source loadings from catchments. SWRRB is a continuous time (daily time step model) that allows a catchment to be subdivided into a maximum of ten subcatchments.

To create SWRBB, the CREAMS daily rainfall hydrology model was modified for application to large, complex, rural catchments. The major changes involved were that:

1. the model was expanded to allow simultaneous computations on several subcatchments to predict the catchment water yield,
2. a return flow component was added,
3. a reservoir storage component was added for use in determining the effects of farm dams and reservoirs on water and sediment yield,
4. a climate simulation model (rainfall, solar radiation and temperature) was added to provide for longer-term simulations and more representative climate inputs, both temporally and spatially,
5. a better method was developed for predicting the peak runoff rate,
6. a crop growth model was added to account for annual variation in growth,
7. a simple flood routing component was added,
8. components were added to simulate sediment movement through farm dams, reservoirs, streams and valleys, and
9. transmission losses were calculated.

Since the late 1980s, most of the SWRRB model development has been focussed on problems involving water quality. Example additions include the GLEAMS (Leonard *et al.*, 1987) pesticide fate component, optional SCS technology for estimating peak runoff rates, and newly developed sediment yield equations.

These and other less significant developments extended SWRRB's capabilities to deal with a wide variety of catchment management problems.

Also in the late 1980's, the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico. SWRRB was utilised for smaller catchments within the catchment (up to a few hundred km$^2$), but it was necessary to simulate streamflow from much larger catchments (several 1 000 km$^2$). This required the catchment to be divided into several hundred subcatchments. SWRRB was limited to ten subcatchments and also had a simplistic routing structure with outputs routed from the subcatchment outlets directly to the catchment outlet. This problem led to the development of a model called ROTO (Routing Outputs to Outlet) by Arnold *et al.* (1995). ROTO was developed to take output from multiple SWRRB runs and route the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB subcatchment limitation by "linking" multiple SWRRB runs together. Although this approach was effective, the input and output of multiple SWRRB output files was cumbersome and required considerable computer storage. Limitations also occurred because all SWRRB runs had to be made independently, and then input to ROTO for the channel and reservoir routing. Thus, the SWAT model was developed by merging SWRRB and ROTO into one catchment scale model. SWAT allows a catchment to be divided into hundreds or thousands of grid cells or subcatchments. SWAT is a continuous time model (daily time step) that is required to look at long-term impacts of management (i.e. reservoir sedimentation over 50-100 years) and also timing of agricultural practices within a year (i.e. crop rotations, planting and harvest dates, irrigation, fertilizer and pesticide application rates and timing).

**Model Operation**

SWAT is a continuous time model that operates on a daily time step. The objective in model development was to predict the impact of management on water, sediment and agricultural chemical yields in large ungauged catchments. To satisfy the objective, the model

1. is physically based (calibration is not possible on ungauged catchments);
2. uses readily available inputs;
3. is computationally efficient to operate on large catchments in a reasonable time, and
4. is continuous time and capable of simulating long periods for computing the effects of management changes.

SWAT uses a command structure for routing runoff and chemicals through a catchment similar to the structure of HYMO (Williams and Hann, 1973). Commands are included for routing flows through streams and reservoirs, adding flows and inputting measured data or point sources. Using a routing command language, the model can simulate a catchment subdivided into grid cells or subcatchments. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows. Also, output data from other simulation models can be input to SWAT.

Using the transfer command, water can be transferred from any reach or reservoir to any other reach or reservoir within the catchment. The user can specify the fraction of flow to divert, the minimum flow remaining in the channel or reservoir, or a daily amount to divert. The user can also apply water directly to a subcatchment for irrigation. Although the model operates on a daily time step and is efficient enough to run for many years, it is intended as a long term yield model and is not capable of detailed, single-event, flood routing.

**Model Components**

**1. Subcatchment Components**

The subcatchment components of SWAT can be placed into eight major divisions - hydrology, climate, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management.

a) **Hydrology**

i) ***Surface Runoff.*** Surface runoff from daily rainfall is predicted using a procedure similar to that in the CREAMS runoff model, Option 1 (Knisel, 1980; Williams and Nicks, 1982). Like the CREAMS model, runoff volume is estimated with a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). The curve number varies non-linearly from the 1 (dry) condition at wilting point to the 3 (wet) conditions at field capacity and approaches 100 at saturation. The SWAT model also includes a provision for estimating runoff from frozen soil.

Peak runoff rate predictions are based on a modification of the Rational Formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the catchment time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The catchment time of concentration is estimated using Manning's Formula considering both overland and channel flow.

ii) ***Percolation.*** The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when Drained Upper Limit (DUL) of a soil layer is exceeded if the layer below is not saturated. The downward flow rate is governed by the saturated conductivity of the soil layer. Upward flow may occur when a lower layer exceeds DUL. Movement from a lower layer to an adjoining upper layer is regulated by the soil water to DUL ratios of the two layers. Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer.

iii) ***Lateral Subsurface Flow.*** Lateral subsurface flow in the soil profile (0-2 m) is calculated simultaneously with percolation. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content. It also allows for flow upward to an adjacent layer or to the surface.

iv) ***Groundwater Flow.*** Groundwater flow contribution to total streamflow is simulated by creating a shallow aquifer storage (Arnold *et al.*, 1993). Percolate from the bottom of the root zone is recharge to the shallow aquifer. A recession constant, derived from daily streamflow records, is used to lag flow from the aquifer to the stream. Other components include evaporation, pumping withdrawals and seepage to the deep aquifer.

v) ***Evapotranspiration.*** The model offers three options for estimating potential ET– Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972) and Penman-Monteith (Monteith, 1965). The Penman-Monteith method requires solar radiation, air temperature, wind speed and relative humidity as input. If wind speed, relative humidity and solar radiation data are not available (daily values can be generated from average monthly values), the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases.

The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential ET and leaf area index (area of plant leaves relative to the soil surface area). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET and leaf area index.

vi) ***Snow Melt.*** The SWAT snow melt component is similar to that of the CREAMS model (Knisel, 1980). If snow is present, it is melted on days when the maximum temperature exceeds 0°C, using a linear function of temperature. Melted snow is treated the same as rainfall for estimating runoff and percolation, but rainfall energy is set to 0.0 and peak runoff rate is estimated assuming uniformly distributed rainfall for a 24 h duration.

vii) ***Transmission Losses***. Many semiarid catchments have alluvial channels that abstract large volumes of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes as the flood wave travels downstream. SWAT uses Lane's method described in Chapter 19 of the SCS Hydrology Handbook (USDA, 1983) to estimate transmission losses. Channel losses are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur.

viii) ***Farm Dams***. Farm dams are small structures that occur within a subcatchment. Dam storage is simulated as a function of dam capacity, daily inflows and outflows, seepage and evaporation. Dams are assumed to have only emergency spillways. Required inputs are capacity and surface area. Surface area below capacity is estimated as a non-linear function of storage.

### b) Climate

The climate variables necessary for driving SWAT are precipitation, air temperature, solar radiation, wind speed and relative humidity. If daily precipitation and maximum/minimum temperature data are available, they can be input directly to SWAT. If not, the climate generator can simulate daily rainfall and temperature. Solar radiation, wind speed and relative humidity are always simulated. One set of climate variables may be simulated for the entire catchment, or different climate may be simulated for each subcatchment.

i) ***Precipitation***. The SWAT precipitation model developed by Nicks (1974) is a first-order Markov chain model. Thus, input to the model must include monthly probabilities of receiving precipitation if the previous day was dry and if the previous day was wet. Given the wet-dry state, the model determines stochastically if precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating from a skewed normal daily precipitation distribution. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature.

ii) ***Temperature and Solar Radiation***. Daily maximum and minimum air temperature and solar radiation are generated from a normal distribution corrected for wet-dry probability state. The correction factor is used to provide more deviation in temperatures and radiation when climate changes and for rainy days. Conversely, deviations are smaller on dry days. The correction factors are calculated to insure that long-term standard deviations of daily variables are maintained.

iii) ***Wind Speed and Relative Humidity***. Daily wind speed is simulated using a modified exponential equation given the mean monthly wind speed as input. The relative humidity model simulates daily average relative humidity from the monthly average by using a triangular distribution. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects.

### c) Sedimentation

i) ***Sediment Yield***. Sediment yield is estimated for each subcatchment with the Modified Universal Soil Loss Equation, MUSLE (Williams, 1975). The hydrology model supplies estimates of runoff volume and peak runoff rate. The crop management factor is evaluated as a function of above-ground biomass, crop residue on the surface and the minimum C factor for the crop. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978).

ii) ***Soil Temperature***. Daily average soil temperature is simulated at the centre of each soil layer for use in hydrology and residue decay. The temperature of the soil surface is estimated using daily maximum and minimum air temperature and snow, plant and residue cover for the day of interest plus the four days immediately preceding. Soil temperature is simulated for each layer using a function of damping depth, surface temperature and mean annual air temperature. Damping depth is dependent upon bulk density and soil water.

**d) Crop Growth Model**

A single model is used in SWAT for simulating all crops. Energy interception is estimated as a function of solar radiation and the crop's leaf area index. The potential increase in biomass for a day is estimated as the product of intercepted energy and a crop parameter for converting energy to biomass. The leaf area index is simulated with equations dependent upon heat units. Crop yield is estimated using the harvest index concept. Harvest index increases as a non-linear function of heat units from zero at planting to the optimal value at maturity. The harvest index may be reduced by water stress during critical crop stages (usually between 30 and 90% of maturity).

**e) Nutrients**

i) ***Nitrogen***. Amounts of $N0_3$-N contained in runoff, lateral flow and percolation are estimated as the products of the volume of water and the average concentration. Leaching and lateral subsurface flow in lower layers are treated with the same approach used in the upper layer, except that surface runoff is not considered. A loading function developed by McElroy *et al.* (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield and the enrichment ratio. Also, crop use of N is estimated using a supply and demand approach.

ii) ***Phosphorus***. The SWAT approach to estimating soluble P loss in surface runoff is based on the concept of partitioning pesticides into the solution and sediment phases as described by Leonard and Wauchope in Knisel (1980). Because P is mostly associated with the sediment phase, the soluble P runoff is predicted using labile P concentration in the top soil layer, runoff volume and a partitioning factor. Sediment transport of P is simulated with a loading function as described in organic N transport. Crop use of P is also estimated with the supply and demand approach.

**f) Pesticides**

GLEAMS (Leonard *et al.*, 1987) technology for simulating pesticide transport by runoff, percolate, soil evaporation and sediment was added to SWAT. Pesticides may be applied at any time and rate to plant foliage or below the soil surface at any depth. The plant leaf-area-index (LAI) determines what fraction of foliar applied pesticide reaches the soil surface. Also, a fraction of the application rate (called application efficiency) is lost to the atmosphere. Each pesticide has a unique set of parameters including solubility, half life in soil and on foliage, wash off fraction, organic carbon adsorption coefficient and cost. Pesticide on plant foliage and in the soil degrade exponentially according to the appropriate half lives. Pesticide transported by water and sediment is calculated for each runoff event and pesticide leaching is estimated for each soil layer when percolation occurs.

**g) Agricultural Management**

SWAT allows for unlimited years of crop rotations and up to three crops per year. The user can also input irrigation, nutrient and pesticide application dates and amounts.

i) ***Tillage and Residue***. The SWAT tillage component was designed to partition the above-ground biomass at harvest. Part of the biomass is removed as yield, part is incorporated into the soil and the remainder is left on the soil surface as residue. The model has no process interactions with incorporated residue. Also, tillage does not effect soil properties.

ii) ***Irrigation***. The user has the option to simulate dryland or irrigated agriculture. If irrigation is selected, he must also specify the runoff ratio (volume of water leaving the field/volume applied) and a plant water stress level to trigger irrigation. The plant water stress factor ranges from 0 to 1.0 (1 means no stress and 0 means no growth). When the user-specified stress level is reached, enough water is applied to fill the root zone to DUL.

## 2. Routing Components

### a) Channel Flood Routing

Channel routing uses a variable storage coefficient method developed by Williams (1969). Channel inputs include the reach length, channel slope, bankfull width and depth, channel side slope, flood plain slope and Manning's n for channel and flood plain. Flow rate and average velocity are calculated using Manning's equation and travel time is computed by dividing channel length by velocity. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions and return flow.

### b) Channel Sediment Routing

The sediment routing model consists of two components operating simultaneously (deposition and degradation). The deposition component is based on fall velocity and the degradation component is based on Bagnold's stream power concept (Williams, 1980). Deposition in the channel and flood plain from the subcatchment to the catchment outlet is based on sediment particle fall velocity. Fall velocity is calculated as a function of particle diameter squared using Stokes Law. The depth of fall through a routing reach is the product of fall velocity and reach travel time. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time and flow depth. Stream power is used to predict degradation in the routing reaches. Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) modified Bagnold's equation to place more weight on high values of stream power--stream power raised to 1.5. Available stream power is used to re-entrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted by the USLE soil erodibility and cover factors of the channel and flood plain.

### c) Channel Nutrient and Pesticide Routing

Currently no transformations or degradation of nutrients or pesticides are simulated in channels. Soluble chemicals are considered conservative, while chemicals adsorbed to the sediment are allowed to be deposited with the sediment.

## 3. Reservoir Routing

### a) Reservoir Water Balance and Routing

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions and return flow. There are currently three methods to estimate outflow. The first method simply reads in measured outflow and allows the model to simulate the other components of the water balance. The second method is for small uncontrolled reservoirs and outflow occurs at a specified release rate when volume exceeds the principle storage. Volume exceeding the emergency spillway is released within one day. For larger managed reservoirs, a monthly target volume approach is used.

### b) Reservoir Sediment Routing

Inflow sediment yield to dams and reservoirs (P/R) is computed with MUSLE. The outflow from P/R is calculated as the product of outflow volume and sediment concentration. Outflow P/R concentration is estimated using a simple continuity equation based on volumes and concentrations of inflow, outflow and dam storage. Initial dam concentration is input and between storm concentration decreases as a function of time and median particle size of inflow sediment.

### c) Reservoir Nutrients and Pesticides

A simple model for phosphorus mass balance was taken from Thomann and Mueller (1987). The model assumes:

i) completely mixed lake;
ii) phosphorus limited; and
iii) total phosphorus can be a measure of trophic status.

The first assumption ignores lake stratification and intensification of phytoplankton in the epilimnon. The second assumption is generally valid when non-point sources dominate and the third assumption implies that a relationship exists between total phosphorus and biomass. The phosphorus mass balance equation includes the concentration in the lake, inflow, outflow and an overall loss rate.

The lake toxic (pesticide) balance model is taken from Chapra (1989) and assumes well mixed conditions. The system is partitioned into a well mixed surface water layer underlain by a well mixed sediment layer. The toxic is partitioned into dissolved and particulate in both the water and sediment layers. The major processes simulated by the model are loading, outflow, reactions, volatilisation, settling, diffusion, resuspension and burial.

## Appendix 2 Channel Sediment Routing

The sediment routing model consists of two components operating simultaneously (deposition and degradation). The deposition component is based on fall velocity and the degradation component is based on Bagnold's stream power concept (Williams, 1980). Deposition in the channel and flood plain from the subcatchment to the catchment outlet is based on sediment particle fall velocity. Fall velocity is calculated as a function of particle diameter squared using Stokes Law. The depth of fall through a routing reach is the product of fall velocity and reach travel time. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time and flow depth. Stream power is used to predict degradation in the routing reaches. Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) modified Bagnold's equation to place more weight on high values of stream power--stream power raised to 1.5. Available stream power is used to re-entrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted by the USLE soil erodibility and cover factors of the channel and flood plain.

With a temperature of 22°C and a sediment density of 1.2 t.m$^{-3}$, Stokes' Law for fall velocity becomes:

$$V_f = 411\ (d^2) \qquad \textbf{(1)}$$

where $V_f$ is the fall velocity in m.h$^{-1}$ and $d$ is the sediment particle diameter. The depth ($y_f$) that sediment of particle size $d$ will fall during time, $TT$, is

$$y_f = (V_f)\ (TT) \qquad \textbf{(2)}$$

The sediment delivery ratio ($DR$) through the reach is estimated with the equations:

$$DR = \frac{1 - 0.5\ y_f}{d_q} \qquad y_f \le d_q \qquad \textbf{(3)}$$

$$DR = \frac{0.5\ (d_q)}{y_f} \qquad y_f > d_q \qquad \textbf{(4)}$$

where $d_q$ is the depth of flow.

Finally, deposition is calculated with the equation:

$$DEP = SED_{IN}\ (1 - DR) \qquad \textbf{(5)}$$

Stream power is used to predict degradation in the routing reaches. Williams (1980) used Bagnold's (1977) definition of stream power to develop a method for determining degradation in channels. Bagnold defined stream power, $SP$, with the equation:

$$SP = ã\ q\ S_w \qquad \textbf{(6)}$$

where $\tilde{a}_w$ is the density of the water, $q$ is the flow rate and $S_W$ is the water surface slope. By applying stream power to bed load predictions (Bagnold, 1977) and estimating model parameters (Williams, 1980), the equation for sediment re-entrained, $DEG_R$, is

$$DEG_R = \acute{a}_{sp}\ \tilde{a}_w^{1.5}\ (dur)\ (w)\ (d_q\ S_W\ V_c)^{1.5} \qquad \textbf{(7)}$$

where $\acute{a}_{sp}$ is a parameter dependent on maximum stream power for the reach and $V_c$ is the velocity in the channel.

The parameter $\acute{a}_{sp}$ can be estimated with the equation:

$$\acute{a}_{sp} = (\tilde{a}_w q\ S_c)_{mx}^{-0.5} \qquad \textbf{(8)}$$

where $S_c$ is the slope of the channel and the subscript *mx* refers to the maximum flow expected in the reach for extreme events. The value of $q$ is assumed to equal some maximum rainfall intensity ($250 mm.hr^{-1}$) and $\acute{a}_{sp}$ becomes:

$$\acute{a}_{sp} = (69.44\ \tilde{a}_w\ DA\ S_c)^{-0.5} \qquad \textbf{(9)}$$

where $DA$ is the drainage area into the reach in $km^2$.

All of the stream power is used for re-entrainment of loose and deposited material until all of the material has been removed. When this occurs, degradation of the bed material, $DEG_B$, begins and is calculated by:

$$DEG_B = K.C.DEG_R \qquad \textbf{(10)}$$

where $K$ and $C$ are MUSLE (Williams and Berndt, 1977) factors for the stream channel. Total degradation, $DEG$, is the sum of the re-entrainment and bed degradation components. This amount is also allowed to be redeposited before reaching the catchment outlet.

$$DEG = (DEG_R + DEG_B)\ (1 - DR) \qquad \textbf{(11)}$$

Finally, the amount of sediment reaching the catchment outlet, $SED_{out}$, is:

$$SED_{out} = SED_{in} - DEP + DEG \qquad \textbf{(12)}$$

where $SED_{in}$ is the sediment entering the reach.

## Appendix 3 Notations used in the documentation of the SWAT model

| | | |
|---|---|---|
| $\acute{a}_{sp}$ | = | parameter dependent on maximum stream power for the reach (dimensionless) |
| $\tilde{a}_{w}$ | = | density of water ($t.m^{-3}$) |
| $C$ | = | crop management factor (dimensionless) |
| $d$ | = | sediment particle diameter (mm) |
| $DA$ | = | drainage area into the reach ($km^2$) |
| $DEG$ | = | total degradation (t) |
| $DEG_B$ | = | degradation of the bed material (t) |
| $DEG_R$ | = | re-entrained sediment (t) |
| $DEP$ | = | sediment deposition (t) |
| $d_o$ | = | depth of flow (m) |
| $DR$ | = | sediment delivery ratio (subcatchment sediment yield divided by gross sheet erosion) (dimensionless) |
| $K$ | = | soil erodibility factor (dimensionless) |
| $mx$ | = | maximum flow expected in the reach for extreme events ($m^3.s^{-1}$) |
| $q$ | = | flow rate ($m^3.s^{-1}$) |
| $S_c$ | = | slope of the channel ($m.m^{-1}$) |
| $SED_{in}$ | = | sediment entering the reach (t) |
| $SED_{out}$ | = | sediment reaching the catchment outlet (t) |
| $SP$ | = | stream power (dimensionless) |
| $S_W$ | = | water surface slope ($m.m^{-1}$) |
| $TT$ | = | travel time (h) |
| $V_f$ | = | fall velocity ($m.h^{-1}$) |
| $V_c$ | = | average channel velocity ($m.s^{-1}$) |
| $y_f$ | = | depth that sediment of particle size d will fall during time $TT$ (m) |

**Appendix 4 Table of pseudo-subcatchment numbers corresponding to the subcatchments shown in Figure 4**

| Upper Sabie River Catchment | | | |
|---|---|---|---|
| Subcatchment ID Number (1-26) | Equivalent ACRU ID number | Subcatchment ID Number (27-53) | Equivalent ACRU ID number |
| 1 | 5 | 27 | 166 |
| 2 | 8 | 28 | 170 |
| 3 | 14 | 29 | 176 |
| 4 | 20 | 30 | 180 |
| 5 | 25 | 31 | 186 |
| 6 | 29 | 32 | 193 |
| 7 | 33 | 33 | 200 |
| 8 | 38 | 34 | 207 |
| 9 | 45 | 35 | 216 |
| 10 | 48 | 36 | 221 |
| 11 | 52 | 37 | 228 |
| 12 | 58 | 38 | 232 |
| 13 | 64 | 39 | 235 |
| 14 | 71 | 40 | 239 |
| 15 | 78 | 41 | 245 |
| 16 | 86 | 42 | 248 |
| 17 | 96 | 43 | 251 |
| 18 | 103 | 44 | 254 |
| 19 | 106 | 45 | 259 |
| 20 | 110 | 46 | 262 |
| 21 | 115 | 47 | 266 |
| 22 | 122 | 48 | 272 |
| 23 | 129 | 49 | 277 |
| 24 | 136 | 50 | 280 |
| 25 | 149 | 51 | 284 |
| 26 | 157 | 52 | 287 |
| | | 53 | 290 |

| Sand River Catchment | | | |
|---|---|---|---|
| Subcatchment ID Number (54-79) | Equivalent ACRU ID number | Subcatchment ID Number (80-105) | Equivalent ACRU ID number |
| 54 | 297 | 80 | 447 |
| 55 | 303 | 81 | 452 |
| 56 | 310 | 82 | 457 |
| 57 | 315 | 83 | 461 |
| 58 | 321 | 84 | 468 |
| 59 | 327 | 85 | 474 |
| 60 | 334 | 86 | 480 |
| 61 | 338 | 87 | 485 |
| 62 | 344 | 88 | 492 |
| 63 | 349 | 89 | 500 |
| 64 | 356 | 90 | 507 |
| 65 | 362 | 91 | 515 |
| 66 | 366 | 92 | 521 |
| 67 | 372 | 93 | 529 |
| 68 | 377 | 94 | 534 |
| 69 | 382 | 95 | 540 |
| 70 | 387 | 96 | 544 |
| 71 | 392 | 97 | 549 |
| 72 | 399 | 98 | 555 |
| 73 | 407 | 99 | 559 |
| 74 | 412 | 100 | 562 |
| 75 | 417 | 101 | 565 |
| 76 | 423 | 102 | 569 |
| 77 | 431 | 103 | 573 |
| 78 | 437 | 104 | 576 |
| 79 | 441 | 105 | 580 |

| Lower Sabie River Catchment | | | |
|---|---|---|---|
| Subcatchment ID Number (106-117) | Equivalent ACRU ID number | Subcatchment ID Number (118-130) | Equivalent ACRU ID number |
| 106 | 584 | 118 | 616 |
| 107 | 586 | 119 | 620 |
| 108 | 589 | 120 | 623 |
| 109 | 592 | 121 | 626 |
| 110 | 594 | 122 | 630 |
| 111 | 597 | 123 | 633 |
| 112 | 600 | 124 | 636 |
| 113 | 602 | 125 | 639 |
| 114 | 604 | 126 | 642 |
| 115 | 607 | 127 | 645 |
| 116 | 610 | 128 | 648 |
| 117 | 613 | 129 | 652 |
| | | 130 | 655 |

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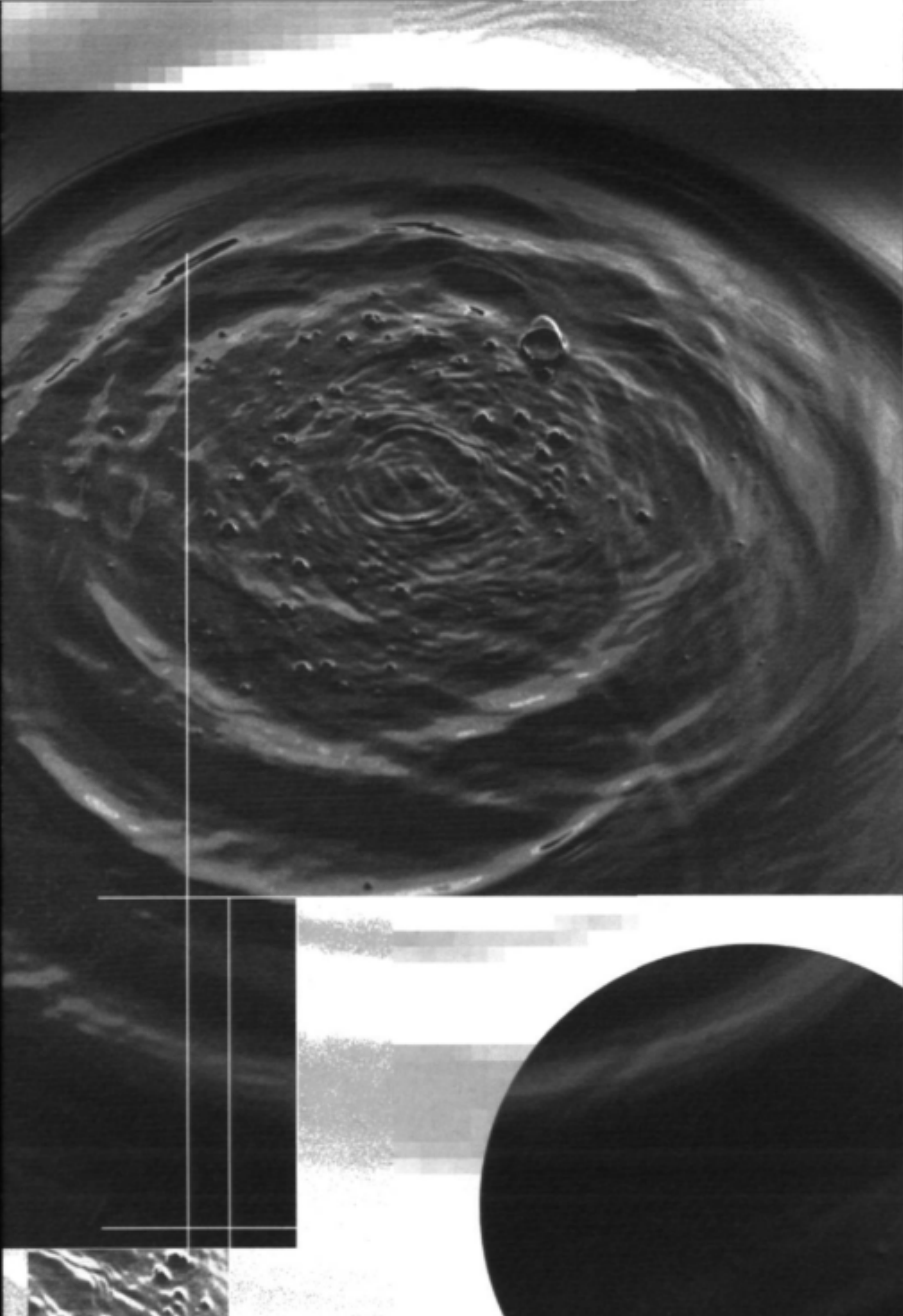

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