DEVELOPMENT OF PROVISIONAL GUIDELINES FOR THE TREATMENT OF SCALE AND RESOLUTION IN ASSESSING STREAMFLOW REDUCTION IMPACTS OF ALIEN PLANT INFESTATIONS AND COMMERCIAL AFFORESTATION IN WATER RESOURCES MODELLING STUDIES

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature   Date

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ABSTRACT

Experiments conducted on afforested catchments in South Africa have shown that alien trees can cause substantial reductions in catchment runoff (Scott et al, 2000).

In recognition of the impact which alien trees can have on the country's water resources, commercial afforestation was declared a stream flow reduction activity (SFRA) in terms of the National Water Act (NWA) (No. 36 of 1998), and the Department of Water affairs and forestry launched the Working for Water Programme (WfW) in 1995 with the recovery of water resources lost to Invasive alien plants (IAPs) as one of the Programme's objectives. These initiatives have intensified the need to quantify SFR; for example, for licensing purposes to satisfy the requirements of the NWA and for predicting the effects of IAP clearing by WfW projects. Of interest to water resources practitioners, is the impact of SFR on mean annual runoff (MAR), on low flows and on water resource system, or reservoir, yield.

In South Africa two basic methods of streamflow reduction (SFR) estimation have been developed for commercial afforestation and IAPs. These are

- free-standing empirical relationships in the form of the CSIR SFR curves, used in conjunction with the monthly, calibration-based, Pitman model.
- component modules in the physically-based, land-use sensitive ACRU rainfall-runoff catchment model, run at a daily time step with relatively fine subcatchment delineation.

There has been a strong need for an evaluative comparison of the impacts of SFR estimated via these two methods. This study aimed to meet this need by using both methods to estimate SFR for a number of commercial afforestation and IAP scenarios in three study systems, the Berg, Sabie and Mhlatuze, representing different bioclimatic conditions in South Africa, and running the SFR sequences from the two estimation methods through the Water Resources Yield Model to determine the impact of the SFR on yield. The analysis differentiated between upland and riparian SFR, and between SFR produced by different tree classes.

Study conclusions included the following points:

- Both the ACRU and SHELL models are capable of achieving a reasonable average seasonal correspondence of high and low flows with the observed averages, though the actual averages produced by the two models can differ substantially.

- In general, ACRU simulates less SFR than SHELL, and gains in SFR after afforestation or invasion by IAPs may be simulated by ACRU during dry periods. The selection of crop factors for different plant species has a strong influence on the relative water use of the species modelled in ACRU.
- The impacts on yield of SFR due to IAPS and afforestation tends to be greater than the impact on MAR, and impacts tend to be more severe for small subcatchments than for the total catchment. A simulated reduction in MAR can result in a simulated increase in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow gains, and vice versa.

Research recommendations centred on improving the availability of reliable field measurements of parameters and processes required for the effective modelling of SFR.

Based on the results of the study, guidelines were formulated for SFR modelling, focussing on the choice of SFR estimation method and the treatment of various parameters and considerations which influence the outcomes of SFR modelling.

SAMEVATTING

Eksperimente wat in bebosde opvanggebiede in Suid-Afrika uitgevoer is, het getoon dat uitheemse bome aansienlike verminderings in opvanggebied-afloop kan veroorsaak (Scott et al, 2000).

Ter erkenning van die impak wat uitheemse bome op die land se waterbronne kan hê, is kommersiële bebossing verklaar as 'n stroomvloei-verminderingsaktiwiteit (SVVA) in terme van die Nasionale Waterwet (NWW) (Nr. 36 van 1998). Die Departement van Waterwese en Bosbou het ook die Werk-vir-Water Program (WvW) in 1995 geloods met, as een van die doelwitte, die herwinning van waterbronne wat deur uitheemse indringerplante (UIPe) opgebruik word. Hierdie inisiatiewe het die behoefte om SVV te kan kwantifiseer verskerp; by voorbeeld; for liksensiëringsdoeleindes om die vereistes van die NWW te bevredig, of om die impakte van UIP-opruiming in WvW-projekte te voorspel. Van besondere belang vir waterbron-praktisyns is die impak van SVV op gemiddelde jaarliks afloop (GJA), op lae vloeie en op die lewering van waterbronne, of –stelsels.

In Suid-Afrika is twee basiese metodes vir SVV-raming ontwikkel vir kommersiële bebossing en UIPe, soos volg:

- losstaande empiriese verbande in die vorm van die WNNR se SVV-krommes, wat gebruik word saam met die maandelikse, kalibrasie-gebaseerde, Pitman-model wat in die SHELL-sagteware-omgewing ingebou is.
- Modules wat komponente vorm in die fisies-gebasserde, grondgebruik-gevoelige ACRU reënval-afloop opvanggebiedmodel, wat op 'n daaglikse tydstap loop, met relatiewe fyn subopvanggebied-indelings.

Daar bestaan al lank 'n sterk behoefte aan 'n takserende vergelyking van die impakte van SVV soos geraam via hierdie twee metodes. Hierdie navorsing het beoog om hierdie behoefte te bevredig deur beide metodes in 'n aantal kommersiële bebossings- en UIP-scenario's in drie stelsels, die Berg, Sabie en Mhlatuze, te gebruik. Sodoende word drie verskillende bio-klimaatstreke gedek. Die maandelikse SVV-tydreekse van die twee ramingsmetodes was toe ingevoer in 'n waterbronstelselmodel (WRYM) om die impak van die SVV op die lewering te bepaal. Die ontledings het tussen oewer- en nie-oewer-SVV, asook tussen SVV wat deur verskillende boom-klasse veroorsaak is, onderskei.

Die gevolgtrekkings uit die studie het die volgende punte ingesluit:

- Beide die ACRU- en SHELL-modelle is in staat om 'n redelike ooreenkoms in seisoenale hoë en lae vloeie met waargenome gemiddeldes te verskaf, alhoewel die eintlike gemiddeldes wat deur die twee modelle gelewer word, aansienlik kan verskil.
- Oor die algemeen simuleer ACRU laer SVV as SHELL en klein toenames in vloeie na bebossing of indringing deur UIPe kan soms tydens droë tydperke deur ACRU gesimuleer word. Die keuse van gewasfaktore vir verskillende planttipes het 'n groot invloed op die relatiewe waterverbruik van die planttipes wat in ACRU gemodelleer word.
- Die impakte op lewering van SVV te wyte aan beide UIPe en bebossing neig om groter te wees as die impak op GJA, en die impakte neig om meer ernstig te wees vir klein subopvanggebiede as vir die totale opvanggebied. 'n Gesimuleerde vermindering in GJA kan soms saamval met 'n gesimuleerde toename in lewering teen 'n spesifieke betroubaarheid, as die gedeelte van die tydreeks wat gedurende die kritieke tydperk voorkom, heelwat UIP-gebaseerde stroomvloei-toenames bevat en vice versa.

Navorsingsaanbevelings fokus op die verbetering van die beskikbaarheid van betroubare veldwaarnemings van parameters en prosesse wat vereis word vir betroubare modellering van SVV.

Riglyne vir SVV-modellering is geformuleer, gebaseer op die resultate van hierdie navorsing, met 'n fokus op die keuse van SVV-ramingsmetode, die behandeling van verskeie parameters en oorwegings wat die uitslag van SVV-modellering sou kon beïnvloed.

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GLOSSARY OF TERMS AND ABBREVIATIONS

ACRU : Agricultural Catchments Research Unit (name of a hydrological model)

BREB : Bowen Ratio .Energy Balance (technique for measuring Evapotranspiration)

CalcPPTCor : Utility for assigning rainfall stations to subcatchments in ACRU

CATCHRN : Utility for preparing rainfall files for use in SHELL

CAY : ACRU input parameter; average monthly crop coefficient

CCWR : Computing Centre for Water Research (This organisation is now defunct)

CMA : Catchment Management Agency

COIAM : ACRU input parameter; coefficient of initial abstraction

CONST : ACRU input parameter; fraction of PAW at which total evaporation drops below maximum evaporation during drying of soil

CSIR : Council for Scientific and Industrial Research

cav : Current scenario with IAPs cleared modelled in this document

cfo : Current scenario with commercial afforestation cleared modelled in this document

cur : Current scenario modelled in this document

DWA : Department of Water Affairs

DWAF : Department of Water Affairs and Forestry

EFRDEP : ACRU input parameter; effective root depth

EIA : Environmental Impact Assessment

ET : Evapotranspiration

euc : Eucalyptus afforestation scenario modelled in this document

HPV : Heat pulse velocity (technique for measuring transpiration)

HRU : Hydrological Research Unit

IAP : Invasive Alien Plant

IWRM : Integrated Water Resources Management

MAE : Mean Annual Evaporation

MAP : Mean Annual Precipitation

MAR : Mean Annual Runoff

nat : Baseline scenario modelled in this document

NLC : National Land-Use Coverage

NWA : National Water Act (No 36 of 1998)

NWRS : National Water Resource Strategy

PAW : Plant available water content

PET : Potential evapotranspiration

pin : Pine afforestation scenario modelled in this document

Pitman : Rainfall-runoff model used in SHELL

rmt	:	Riparian medium tree scenario modelled in this document
Res yield	:	Reservoir yield in this document
ROOTA	:	ACRU input parameter; fraction of effective rooting system in the topsoil horizon
ROR yield	:	Run-of-river yield in this document
rts	:	Riparian tall shrub scenario modelled in this document
rtt	:	Riparian tall tree scenario modelled in this document
SBEEH	:	School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal
SHELL	:	User interface, which facilitates the use of a number of component programs at a monthly temporal resolution
SFR	:	Streamflow Reduction
SFRA	:	Stream Flow Reduction Activity
subc	:	Subcatchment in this document
umt	:	Upland medium tree scenario modelled in this document
uts	:	Upland tall shrub scenario modelled in this document
utt	:	Upland tall tree scenario modelled in this document
VEGINT	:	ACRU input parameter; interception loss by vegetation
WfW	:	Working for Water
WMA	:	Water Management Area
WRC	:	Water Research Commission
WRSM90	:	Water Resources Simulation Model–90, a version of the Pitman model
WRYM	:	Water Resources Yield Model

1 INTRODUCTION

1.1 Background

1.1.1 Effects of Catchment Land-Use Changes

Land cover changes can have significant impacts on runoff produced by catchments. For example, the replacement of indigenous or agricultural plants with commercial tree plantations or invasive alien plants (IAPs), which consume more water than the indigenous or agricultural plants, can lead to "streamflow reduction" (SFR); likewise, the clearing of trees from a catchment can lead to increases in streamflow.

The change in catchment runoff, caused by changes in land cover, is attributed to the differences in biotic characteristics of the vegetation types and the changes in catchment hydrological response characteristics brought about by the change in vegetation cover. In the case of alien trees replacing indigenous vegetation, changed biotic characteristics include:

- Canopy cover and perenniality;
- Leaf density and size distribution;
- Root depth and distribution;
- Surface litter build up;
- Consumptive demand or evapotranspiration (ET);
- Growth rates and cycles; and
- Drought and water stress response.

Changed hydrological response characteristics include:

- Canopy and litter interception of rainfall;
- Infiltration and percolation of rainfall through the soil profile;
- Soil water balance;
- Groundwater recharge and release;
- Riparian and alluvial water dynamics;
- Overland flow characteristics; and
- Flood transmission through stream channels.

1.1.2 *Overview of Streamflow Reduction in South Africa*

Chapter 2 of this document provides details of research conducted in South Africa. At the national scale it is estimated that 1 400 million m³ of South Africa's surface runoff, which represents about 3 per cent of the national mean annual runoff (MAR) of 49 000 million m³, is intercepted by IAPs, which are thought to cover 10 million ha of land in South Africa (DWAF, 2004). Commercial afforestation, which is thought to cover 1.4 million ha of land, is estimated to use 1 500 million m³ per year in excess of water used by natural vegetation (DWAF, 2004). These figures, cited in the National Water Resource Strategy (NWRS) (DWAF, 2004), have been obtained through a series of country-wide situation assessments, carried out at desktop level, using data from research reports, associated studies, existing databases, local authorities and DWAF.

The situation assessments were carried out at quaternary catchment scale, using hydrological data from the WR90 Studies (Midgley *et al*, 1994). Information on areas under alien vegetation was drawn from mapping carried out under the supervision of the Council for Scientific and Industrial Research (CSIR). A number of shortcomings and limitations of this mapping were noted (DWAF, 2003), however, these databases were the best countrywide mapping of IAPs and commercial afforestation available at the time.

The NWRS estimates (DWAF, 2003) of SFR by commercial afforestation were based on the so-called CSIR curves (Scott and Smith, 1997), empirical curves for the determination of long-term average SFR, based on long-term measurements of SFR in commercial afforestation experimental catchments (Scott *et al*, 2000). The observations in these catchment experiments have contributed largely to the knowledge that water used by alien plants can be greater than that used by natural vegetation, and can result in significant SFR in some of the catchments where alien trees occur, and that clearing infestations, especially from the riparian zone, can increase streamflow.

In addition to the commercial afforestation experiments, South African research on water use by alien plants is being conducted through the direct measurement of consumptive use or ET by trees. This research has been valuable for developing and verifying SFR estimation methods, however, bio-climatic conditions vary significantly across South Africa and differing conditions between research sites and study catchments mean that estimates of SFR, based on experimental results, are not perfect and further research is necessary to improve the accuracy of these estimates.

1.1.3 *Streamflow Reduction Estimation Methods and Models*

Models can be described as simplified representations of some part of the real world, predicting effects from causes (Jewitt and Görgens, 2000). In very general terms, hydrological models can be classified as either empirical or physically-based. Empirical models rely on calibration of pseudo-physical parameters against an observed record, while the parameters required as input to physically-based models are obtained from field measurements, maps and other sources of information (Hughes, 1991), i.e., calibration is not usually included. Hydrological models are operated at different spatial (local to global) and temporal (hourly to annual and longer) scales (Hayes, 2003).

The empirical CSIR curves, used for the SFR estimates in the NWRS, form one of two basic methods of SFR estimation, which have been developed in South Africa for commercial afforestation and IAPs. The second method consists of component modules in the physically-based, land-use sensitive ACRU rainfall-runoff catchment model.

The CSIR curves have been used in conjunction with the Pitman catchment model, a calibration-based rainfall-runoff model, which runs at a monthly time step and relatively coarse spatial scale, while the ACRU Model operates on a daily time step and finer spatial scale than the Pitman Model (the largest recommended subcatchment area for ACRU applications without finer sub-division is 50 km^2).

The data input requirements for ACRU are much more rigorous than for Pitman combined with the empirical CSIR curves. This, combined with the finer temporal and spatial scales at which the model operates, means that more detailed output can be obtained from ACRU. This also means that configuring ACRU generally requires more resources and time than configuring Pitman combined with the empirical CSIR relationships.

1.2 Motivation for the Study

With the evidence obtained through research that exotic trees can have a significant impact on the country's water resources, commercial afforestation has been declared a streamflow reduction activity (SFRA) in terms of the National Water Act (NWA) (No. 36 of 1998), which allows for the regulation of land-based activities, which reduce streamflow, by declaring such activities to be SFRAs. Also, in response to the understanding that IAPs cause SFR, the Department of Water Affairs and Forestry (DWAF) launched the Working for Water (WfW) Programme in 1995, with the recovery of water resources lost to IAPs as one of the Programme's objectives. These initiatives have intensified the need to quantify SFR; for example, for licensing purposes to satisfy the requirements of the NWA and for predicting the effects of IAP clearing by WfW projects. Of interest to water resources practitioners, is the impact of SFR on the mean annual runoff (MAR), on low flows and on the water resource system, or reservoir, yield.

In selecting a method for the estimation of SFR, water resources practitioners must consider the extent of resources available for the estimation process and the level of detail of output required. There is, therefore, a need for an assessment and comparison of the impacts of SFR estimated via the two SFR estimation methods described above, in terms of impacts on MAR and utilisable water (defined as system or reservoir yield of a given assurance), and for the development of guidelines for the use of each method in a water resource evaluation setting.

The SFR estimation methods have been used separately in studies to determine the potential impacts of SFR due to commercial afforestation and alien vegetation on MAR. There have been a few studies done on SFR impacts on utilisable water or yield (Le Maitre and Görgens, 2001) (Larsen *et al*, 2001), but these have primarily been based on the combination of the CSIR curves with output from the monthly Pitman Model. This project serves to conduct the much needed comparison and reconciliation of SFR and SFR impacts estimated by these two very different modelling approaches.

1.3 Objectives and Primary Tasks

The objectives of this research were as follows:

1. To assess and reconcile SFR impacts caused by alien vegetation and commercial afforestation, modelled at different levels of scale and resolution and over a range of bio-climatic regions.
2. To quantify SFR impacts caused by alien vegetation and commercial afforestation on reservoir and system yield-reliability characteristics, as well as for run-of-river water supplies for a range of South African river systems.
3. To develop generic guidelines for the treatment of scale and resolution in assessment of SFR due to alien infestation and commercial afforestation in Integrated Water Resources Management (IWRM) in South Africa.

The primary tasks of this research include configuring the ACRU, SHELL and WRYM Models for a number of catchments representing different bioclimatic conditions in South Africa, using the model configurations to estimate SFR and the impact of SFR on yield for a number of different IAPs and commercial afforestation scenarios in the study catchments, assessing and reconciling the SFR and SFR impacts estimated via ACRU and SHELL, and developing guidelines on the use of ACRU and SHELL based on the assessments of the results obtained via the two models.

Potential users of the study findings include:

- Water Resource Managers in DWAF and Catchment Management Agencies (CMAs);
- Professional water resource planning practitioners;
- Consultants and researchers;
- WfW planners; and
- Forestry regulators, planners and consultants.

Potential applications of the findings include use in:

- Regional water balance calculations as part of the NWRS formulations;
- Determination of the Reserve;
- Water allocations at Water Management Area (WMA) level;
- The SFRA Commercial Afforestation Water Use Licensing System;
- Prioritisation of WfW projects; and
- Environmental impact assessments (EIAs).

1.4 Layout of Document

Chapter 1 describes the background of the study and states the objectives of the study.

Chapter 2 is a summary of literature relevant to SFR aspects of the project.

Chapter 3 describes the models used in the study, including concerns about the models and improvements made to the models.

Chapter 4 describes in detail the methodology and research process of the study. This includes a description of the river systems selected for the study, sources of modelling information, and any problems relating to obtaining the modelling input information. The configuration of the catchment models is also described here in detail.

Chapter 5 describes the scenarios run and the results obtained from the ACRU and SHELL modelling packages. The results from the two modelling packages are compared, and differences are reconciled in terms of the differences between the models and the bioclimatic differences between study systems.

Chapter 6 describes the results of yield modelling using flow sequences from ACRU and SHELL, for the different study systems.

Chapter 7 formulates guidelines for the use of the different models in SFR modelling.

Chapter 8 describes conclusions reached.

Chapter 9 lays out recommendations drawn from the study.

2 LITERATURE REVIEW

2.1 Introduction

In this chapter, research into the effects of alien plants in South Africa is described according to four levels, as defined by Görgens and van Wilgen (Görgens and van Wilgen, 2004). The levels, illustrated in **Figure 2-1** and described in **Table 2-1**, are:

1. Fundamental / field / process research.
2. Applied / predictive research.
3. Integrative tools research.
4. Management support research.

This research project is centred on integrative tools research and management support research.

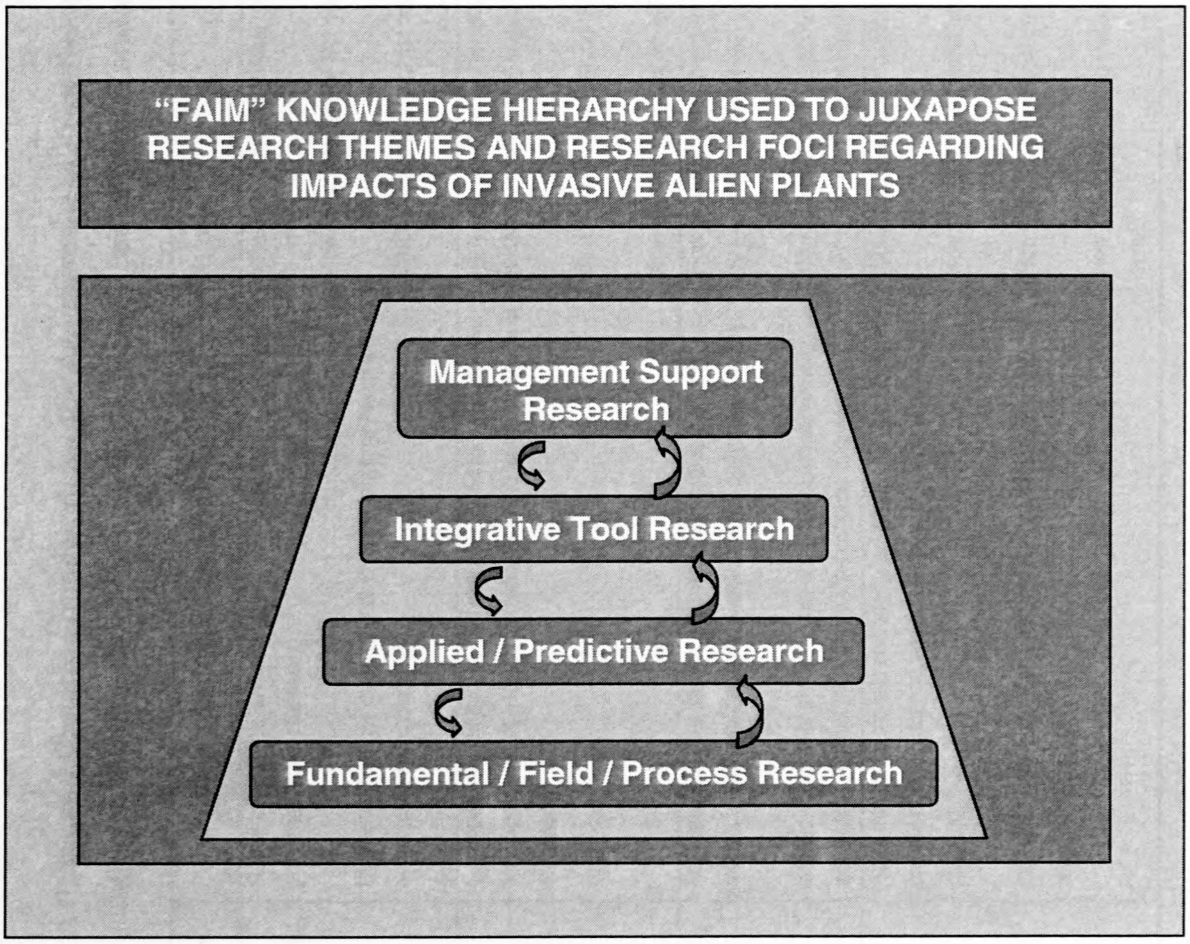


Figure 2-1: **The FAIM Knowledge-Generation Hierarchy (Görgens and van Wilgen, 2004).**

Table 2-1: A Proposed Generic Framework for the Assessment of Knowledge-Generation, and the Key Questions for Research relating to the Effects of IAPs on Water Resources (Görgens and van Wilgen, 2004)

Level of Research	Generic Knowledge-Generation Processes	Key Questions for Assessing the Effects of IAPs
Fundamental observations in the field or laboratory	Gather detailed understanding of individual bio-physical processes in specific settings. Directly or indirectly measure individual bio-physical responses or dynamics in specific settings.	What factors and processes govern water use by IAP species in a particular setting? How does water use by IAP species differ from indigenous (or other baseline vegetation) in a particular setting? Which characteristics of the water resource are changed by alien plant invasions or their clearing?
Applied and/or predictive research	Conceptualize, extrapolate and scale-up from an individual site-specific process or a localized response to the generic process or response.	How should spatial and temporal variability in biophysical factors and processes be accommodated in generalized methods for quantifying some, or all, aspects of water use, streamflow or groundwater impacts? By how much, generally, do IAP species, or their clearing, change individual characteristics of the water resource? At what rates, generally, do IAP types, or their clearing, change the characteristics of the water resource?
Integrative and/or interface research	Integrate numerous factors, processes and scales in a variety of models to estimate biophysical responses at aggregated scales. Interface outputs of predictive bio-physical response methods with spatial analysis tools and socio-economic information.	How should changes in streamflow, groundwater and dam yield, following invasion by or clearing of alien plants, be predicted at a catchment or river system scale? How should predictions of IAP impacts on water resources be supported by spatial information and juxtaposed with socio-economic information?
Management support research	Apply integrated models and interfaced information creatively to provide decision support for natural resource management and planning. Quantify, describe and prioritize options for natural resource managers.	Which invaded areas in a catchment, or a whole region, will respond to clearing with greatest hydrological benefit? How important is IAP water use relative to other anthropogenic impacts on catchment and regional scales? How does the benefit-cost profile of clearing projects compare with other water resource augmentation options? How should IAP management decisions influence water and land resource management and planning, and vice versa?

2.2 Fundamental Research

In South Africa, field observations of the effect of exotic trees on water resources have occurred in the form of long-term catchment afforestation experiments and riparian clearing experiments, where the changes in streamflow due to the vegetarian changes are measured, and direct measurement of consumptive use or ET by the vegetation.

2.2.1 Long- term Catchment Afforestation Experiments

"The afforested catchment experiments represent the most extensive and detailed measurement of the hydrological effects of a land-use change in South Africa" (Scott *et al*, 2000). The experiments were initiated over 60 years ago and involved the long-term monitoring of a series of paired catchments. One catchment of the pair was left untreated (in its natural state) and a calibration relationship between streamflows in the paired catchments was used to assess the impact of treatment on the treated (afforested) catchment. Treatment of the catchments consisted of planting and clearing of commercial plantations.

Experimental catchments are located in Jonkershoek in the Western Cape, Cathedral Peak in the Drakensberg, Mokobulaan and Witklip on the Mpumalanga escarpment and Westfalia in Limpopo Province (**Figure 2-2**). The experimental catchments are located in regions of South Africa with mean annual precipitation (MAP) exceeding 1 100 mm/year. Only 30% of commercial forestry in South Africa is located in areas as wet as the experimental catchment sites; thus, the results of the experiments are not representative of the bulk of commercial forestry areas in the country (Scott *et al*, 2000).

Table 2-2 summarises some results of the catchment experiments. Pine and eucalyptus trees were used in the treatment of the catchments.

The findings by the catchment experiments provide an excellent reference point for expected SFR by commercial afforestation. Analysis of the results revealed that SFR, due to afforestation by pines and / or eucalypts, increases sigmoidally, flattens out and then decreases as the trees become mature. The results also revealed that proportional reduction of "low" flows can be expected to be higher than proportional reduction of "higher" flows.

Findings, based on records from the experimental catchments, form the basis of the CSIR curves (Scott and Smith, 1997) for estimating SFR by afforestation. The curves were developed by estimating percentage SFRs after afforestation for each post-treatment year, based on the relationship between the treated and untreated catchments. Curves were then fitted to the average age / SFR points.

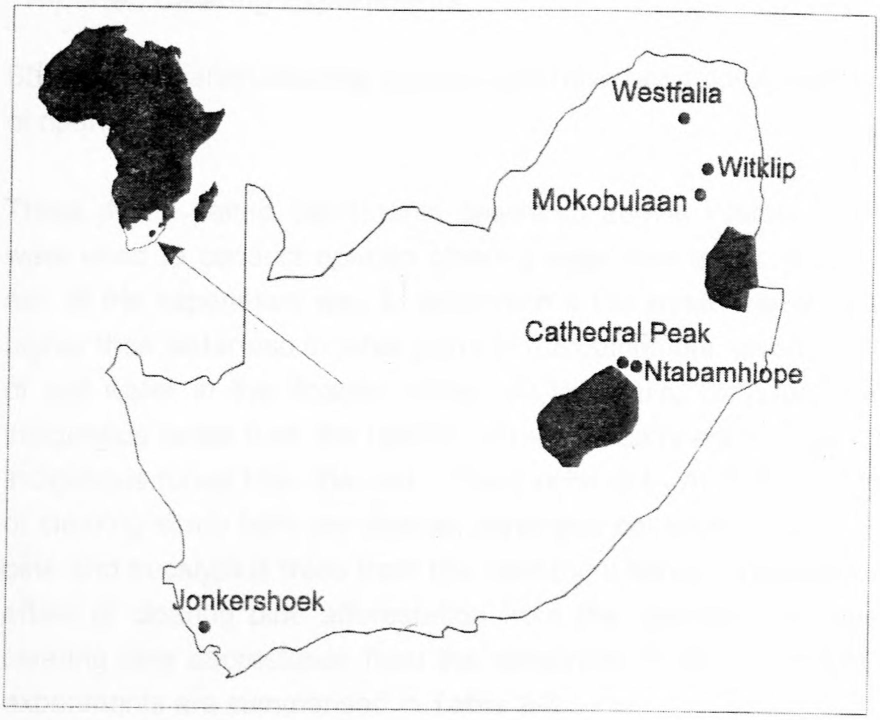


Figure 2-2: **General Location Map of the Hydrological Catchment Experiment Sites in South Africa (Scott *et al*, 2000)**

Table 2-2: **Long-Term SFR measured in Experimental Catchments after Commercial Afforestation (Scott *et al*, 2000)**

Experimental Catchments	Treatment	Catchment Area Range (ha)	Mean Annual Rainfall Range (mm)	Mean Annual SFR (mm)
Jonkershoek	Afforestation with pine	30 - 250	1 300 -2 300	130 - 300
Cathedral Peak	Afforestation with pine	60 - 190	1 400	260
Witklip	Afforestation with pine and eucalyptus	110 - 160	1 475	280
Mokobulaan	Afforestation with pine and eucalyptus	25	1 150	340
Westfalia	Afforestation with eucalyptus	30 - 60	1 600	200

2.2.2 Riparian Clearing Experiments

Short-term riparian clearing experiments have been conducted to investigate the SFR of riparian trees.

Three of the paired catchments described above, Westfalia, Witklip and Biesievlei were used to conduct riparian clearing experiments (Scott and Lesch, 1995). The aim of the experiment was to determine if the water use of riparian vegetation was higher than water use in other parts of the catchment, given the increased availability of soil water in the riparian zone. At Westfalia, Limpopo, the effects of clearing indigenous forest from the riparian zone was compared to the effect of then clearing indigenous forest from the rest of the catchment. At Witklip, Mpumalanga, the effect of clearing scrub from the riparian zone was compared to the effect of then clearing pine and eucalyptus trees from the catchment flanks. In Biesievlei, Jonkershoek, the effect of clearing pine afforestation from the riparian zone was compared to then clearing pine afforestation from the remainder of the catchment. The results of the experiments are summarised in **Table 2-3**.

Table 2-3: Comparative Water Use of Riparian and Upland Vegetation in Three Forestry Catchments (Scott and Lesch, 1995)

Catchment	Experimental Treatment	First year Increase in Runoff	
		m3/ha	%per10%
Westfalia D	Clearfelling - indigenous riparian forest	5 445	9
	Clearfelling - indigenous forest outside the riparian zone	2 700	3.5
Witklip 2	Cut & poison-riparian scrub	7 965	44
	Clearfelling- pines outside riparian zone	4 045	37
Biesievlei (Jonkershoek)	Clearfelling - riparian pines	11 505	44
	Clearfelling - pines outside riparian zone	3 430	14

The following observations arose from the experiments (Scott and Lesch, 1995):

- Riparian vegetation is likely to use more water than vegetation in other parts of the catchment.
- Indigenous vegetation is likely to use less water than commercial afforestation.
- Reversal of flow increases, observed at Westfalia in the second year after clearing, raised the point that mature and slow growing vegetation is likely to use less water than young and fast-growing vegetation.
- The water use characteristics of indigenous forests can vary substantially between sites with similar climatic characteristics.

- It is likely that the gains observed over a long period of time will be less than observed for these experiments, as the greatest vegetation change occurs in the first year after treatment.
- The availability of soil water, and hence the ratio of actual to potential evapotranspiration, is a key determinant of potential SFR impacts. Outside the riparian zone, where there is less available soil water, the clearing of afforestation had a lower impact than when afforestation in the riparian zone was cleared. This highlights the dangers of predicting SFR impacts by extrapolating results obtained from relatively 'wet' catchments to catchments which are relatively 'dry' or where soil conditions are substantially different.

An experiment carried out, with portable flow-gauging weirs in the Kalmoesfonteinspruit catchment near Lydenberg, is another example of the experimental measurement of the impacts of clearing of riparian zones (Dye and Poulter, 1995). The portable weirs were placed 500 m apart on the stream and the streamflow at each weir observed before and after clearing of all riparian trees between the weirs. The trees cleared, consisted of pine and wattle species. The following changes in streamflow between the two weirs were observed after clearing of the trees in the riparian zone between them:

- Streamflow gain of 120% was observed at the lower weir after clearing.
- Equal streamflow was observed at both weirs where, before clearing, streamflow at the lower weir had been less than at the upstream weir.

At both weirs, a daily fluctuation in streamflow was observed, which indicated that diurnal ET patterns of the trees have an effect on streamflow (the trees transpired only during the day). Increases in streamflow during cloudy, rain-free weather, when the transpiration rate is expected to drop, also pointed to transpiration by the riparian trees having an effect on streamflow.

This portable weir experiment points to riparian trees having an immediate and direct influence on streamflow.

2.2.3 Measurement of Evapotranspiration

Knowledge of the ET by invasive alien trees contributes towards an understanding of their effect on streamflow. A few studies have been done that involve the measurement of ET by such trees. ET of indigenous plants is also of interest to gauge the water use of invasive alien trees in excess of that used by the natural vegetation they replace.

Dye *et al* (2001) conducted a study, which compared the water use, over one year, of wattle thickets and indigenous plant communities at two riparian sites, Jonkershoek in the Western Cape and Gilboa in the KwaZulu-Natal Midlands. The ET of the indigenous plant communities at the sites was measured directly using the Bowen Ratio Energy Balance (BREB) technique (Dye *et al*, 2001), whereas the ET of an imaginary wattle thicket at the same sites was obtained by extrapolating heat pulse velocity (HPV) (Dye *et al*, 2001) measurements made on wattle thickets at two other sites, Wellington and Groot Drakenstein in the Western Cape, to the Jonkershoek and Gilboa sites. A relationship between HPV measurements, tree size, mean daily vapour pressure deficit and number of day light hours was used to transfer measurements made at Wellington and Groot Drakenstein to Jonkershoek and Gilboa. The HPV technique measures transpiration rate directly and not ET, and to convert this to ET, estimates of canopy rainfall interception were added to the transpiration measured. The canopy rainfall interception was obtained from a combination of published estimates by Schulze *et al*, (1995) and rainfall measurements from a gauge situated near the Jonkershoek and Gilboa sites. Where daily rainfall was less than the published daily interception loss, interception loss was assumed to equal the daily rainfall. The BREB and HPV readings were taken under conditions of non-limiting soil water availability, i.e. when transpiration rates were not reduced by soil water deficits.

Table 2-4 shows the results published by Dye *et al.* The table shows that at the riparian sites investigated, black wattle can use more water than the indigenous vegetation. The clearing of black wattle from riparian zones and its replacement by indigenous vegetation could therefore lead to streamflow gains. The table also shows that the estimates of annual ET vary between the different sites, showing that changes in ET resulting from the clearing of alien trees at a site depend on the structural and physiological characteristics of both the alien trees and the indigenous vegetation, which replace the alien trees (Dye *et al*, 2001).

Table 2-4: A summary of ET differences between two study sites (Dye *et al*, 2001)

A Summary of Annual ET Differences among the Study Sites					
Locality	**Vegetation**	**Annual (ET) Estimate (mm)**			
		Transpiration	**Rainfall Interception**	**ET**	**Difference**
Jonkershoek	*A. mearnsii*	1318	185	1 503	171
	Fynbos			1 332	
Gilboa	*A. mearnsii*	1077	183	1 260	424
	Grassland			836	

Recently, Dye and Jarmain (2004) compared estimates of water use by black wattle (*Acacia mearnsii*) with that of indigenous vegetation at the same locations. Measurements of total evaporation (transpiration from dry canopies and evaporation from wet canopies), using the HPV and BREB techniques (Dye *et al*, 2001), were conducted for black wattle at Wellington and Groot Drakenstein in the Western Cape and Seven Oaks in Kwazulu-Natal. Measurements of total evaporation by indigenous species were also made for comparative purposes. These were done for fynbos at Jonkershoek in the Western Cape and grassland at Gilboa in Kwazulu-Natal.

Measurements done at riparian sites showed that annual total evaporation from riparian black wattle can exceed 1 500 mm, while annual total evaporation from indigenous fynbos and grassland shrubs varies from 600 to 850 mm. Differences in total evaporation following invasion or removal of black wattle in such vegetation are potentially large. In this case, the range is 170 to 600 mm (Dye and Jarmain, 2004).

2.3 Predictive Research

Predictive research in South Africa has centred mostly on the development of models for the prediction of SFR by commercial afforestation and IAPs, and the development and use of models to predict the spread of IAPs in catchments. This document is concerned with the development and use of the models for predicting SFR.

An empirical model for the prediction of long-term SFR by IAPs, known as the Age-Biomass-SFR Model (Le Maitre *et al*, 2001), was developed from experimental data, including data from the South African catchment experiments. The curves differentiate between three tree classes: tall trees, which grow to greater than 8 m in height; medium trees, which grow to taller than 2 m; and tall shrubs, which grow to taller than 1.5 m. The Age-Biomass-SFR Model is described in detail in **Chapter 3** of this report.

A commonly-used empirical model for the prediction of long-term SFR by commercial afforestation is referred to as the CSIR curves (Scott and Smith, 1997). The curves were derived from data from the South African catchment experiments (referred to in **Section 2.2.1**, and differentiate between pine and eucalyptus species, optimal and sub-optimal growth conditions and total and low flow reduction. The CSIR curves are described in detail in **Chapter 3** of this report.

2.4 Integrative Tools Research

In South Africa, integrative tools, most widely applied in the estimation of SFR by afforestation and IAPs, are monthly calibration-based modelling packages, which incorporate the age-biomass-SFR Models and CSIR curves, and the daily physically-based ACRU modelling package, which includes component models for the estimation of plant water-use. The monthly model used in conjunction with the SFR models in this report is the SHELL modelling package (Berg *et al*, 1991). The modelling packages are described in detail in **Chapter 3** of this report.

2.5 Management Support Research

Research at this level is concerned with predictive support to management decision-making regarding the impacts of SFR on water resources. The launching of the WfW programme has raised immense interest in the benefits to water resources of clearing IAPs from catchments. A number of methods are used to evaluate these impacts. Among them is the Water Resources Yield Model (WRYM), which is used to "simulate the distribution of water across a multi-user, multi-resource system on a monthly basis according to prescribed operating "rules" (Görgens and Van Wilgen, 2004). The WRYM is described in detail in **Chapter 6** of this report. Monthly time series of SFR simulated with the modelling systems mentioned above are fed into WRYM to determine the impacts of the SFR on system water yield. Examples of this determination of SFR impacts are described below.

2.5.1 Development of the Commercial Afforestation Tables (Gush Tables)

The commercial afforestation tables (Gush *et al*, 2002) are national tables of quaternary catchment SFR. They were developed after ACRU Model verifications of selected experimental catchments, and are currently said to be the best alternative to site-specific modelling available to water resources practitioners (Görgens,2003). The tables are described in detail in **Section 3.5** of this report.

2.6 Examples of SFR-related Research towards Predictive Tools, Integrative Tools and Management Support Research

2.6.1 The Impacts of SFR on Yield of Reservoirs and River Systems

Predictive, integrative and management support tools have been used in a combined way in studies to determine the impacts of SFR on yield (and its reliability) of reservoirs and river systems. Studies examined, as part of this research, include:

- Impacts of invasive alien vegetation on dam yields (Le Maitre and Görgens, 2001).
- Water resources planning with recognition of alien vegetation eradication (Larsen *et al*, 2001).
- Evaluating a riparian clearing programme as a water management strategy (Gillham and Haynes, 2001).

The study by Le Maitre and Görgens aimed to produce "first approximations of the impacts of invasions by alien plants on the assurance of supply from typical dams in typical catchments in the form of a limited-budget, short-term study (Le Maitre and Görgens, 2001)." Working at quaternary catchments scale SFR and resulting impact on yield at different assurances of supply, was estimated for current and projected future alien vegetation invasion scenarios in a number of river systems representing different bio-climatic conditions in South Africa. The river systems analysed were the Upper Mngeni above Midmar Dam, the entire Sonderend System, the Upper Wilge catchment and the Sabie-Sand System upstream of the Kruger National Park.

The Age-Biomass-SFR Model was used in conjunction with the Pitman Model to estimate SFR for upland and riparian alien invasions for the three classes of alien plants, and the SHELL modelling package was used for the determination of yield for the various scenarios. The impact on yield was investigated at two positions within each study system, at the end of the full system and at the end of a quaternary catchment at the upstream end of the system.

The reductions in MAR, estimated with the Age-Biomass-SFR Model, are shown in **Table 2-5**. Significant reductions were simulated for the Sonderend and Sabie-Sand catchments, predicted to worsen over the next ten years, whereas the reductions in the Upper Mngeni were less severe. The study found that the proportional (percentage) impact on low flows is more than on total flows for the summer rainfall catchments. In the Sonderend winter rainfall catchment, impacts of low flow are less severe than for total flows in the current scenario and become more severe in the future scenario.

Table 2-5: MAR and Reductions in Runoff from Current and Predicted Future Alien Invasions (Le Maitre and Görgens, 2001)

Catchment	Naturalised MAR (million m^3)	Reduction in Naturalised MAR as a Percentage	
		Current	Future (10 years)
Sonderend	457	4,8	6,6
Upper Wilge	450	1,2	1,6
Upper Mngeni	207	1,5	2,1
Sabie-Sand	721	9,7	12,7

Some results of the yield analysis are shown in **Table 2-6**.

The yield analysis in the study revealed the following about reductions in reservoir yield as estimated by the Age-Biomass-SFR Model, in conjunction with the Pitman Model.

The study found that the reduction in yield differed among river systems, with impacts on yield for Sabie-Sand and Sonderend, far exceeding those for Wilge and Mngeni.

The differences in impact on yield could have implications for prioritising of alien plant clearing projects (Le Maitre and Görgens, 2003). Yield analyses at quaternary catchments within the study systems revealed that impacts on yield for the quaternary may be very different from impacts on the full river system. It was found that for dam sizes over 50% of natural MAR there is little difference in proportional reductions at different assurances of yield.

The study on the impact of SFR on dam yield showed that it was feasible to estimate the potential impacts of SFR on water yields in South African river systems for which reliable databases on alien vegetation invasion exist (Le Maitre and Görgens, 2003).

Table 2-6: Potential Absolute Reductions in Yield for Recurrence Intervals of Failure for Current and Projected Future Invasions (Le Maitre and Görgens, 2001)

State of Invasion	River	Reduction in Yield for RI = 1:70 Years (Mm³)						State of Invasion	River	Reduction in Yield for RI = 1:2 Years (Mm³)					
		Live Storage as % of Nat. MAR								Live Storage as % of Nat. MAR					
Present		20	50	100	150	200	250	Present		20	50	100	150	200	250
	Mngeni	0.9	1.1	1.7	2.1	2.0	2.0		Mngeni	0.7	2.6	2.2	2.9	2.9	2.9
	Sonderend	4.9	10.1	12.8	15.5	15.6	115.5		Sonderend	2.7	12.6	17.6	26.0	25.6	27.8
	Wilge	0.7	1.2	1.3	1.3	1.7	1.7		Wilge	0.7	3.2	4.6	3.2	5.2	4.9
	Sabie	27.3	35.2	45.2	45.4	45.4	47.8		Sabie	32.7	43.7	51.9	49.4	78.5	68.4
Future								Future							
	Mngeni	1.2	1.1	2.4	2.9	2.8	2.8		Mngeni	1.2	3.7	3.1	4.1	4.1	4.1
	Sonderend	6.6	13.7	17.1	20.2	20.3	20.3		Sonderend	3.8	18.5	22.9	34.4	33.6	32.5
	Wilge	0.8	1.5	1.2	1.5	2.3	2.3		Wilge	0.8	4.2	6.1	4.2	4.9	6.1
	Sabie	38.0	52.7	63.9	64.9	64.1	64.1		Sabie	42.7	65.4	72.7	73.6	114.0	96.7

The studies by Larsen *et al* (2001) and Gilham and Haynes (2001) were aimed at investigating the viability of alien clearing programmes in specific river systems.

Larsen *et al* (2001) investigated the effect of SFR on the yield of existing and future augmentation schemes for the water supply of the town of George in the Western Cape. Projections were made of the spread of alien vegetation and the effect of SFR on the yield of the schemes was estimated for a number of clearing scenarios. Financial analyses of the clearing scenarios were carried out. The SFR was estimated, using the Age-Biomass-SFR curves, in conjunction with the Pitman Model, and the yield analyses were carried out with the WRYM.

The results of the study show that the implementation of augmentation schemes can be delayed substantially if alien vegetation is cleared and SFR is reversed, indicating that SFR can have a significant impact on the yield of water resource schemes. The financial analysis of the clearing scenarios revealed that if clearing were started immediately, a cost-saving results from all the clearing scenarios.

The study by Gilham and Haynes (2001) included a similar cost analysis of clearing scenarios to assess the viability of alien clearing as a water management strategy in the Mgeni catchment in Kwazulu Natal. This study investigated the benefits of clearing riparian vegetation, using the ACRU Model to estimate SFR and the WRYM to determine the impacts on yield. **Table 2-7** shows the additional yield (given the current 99% assurance yield of 310 million m^3/a) at Inanda Dam at the end of the study catchment, gained by clearing alien vegetation from subcatchments in the system.

Table 2-7: Influence of Clearing of Alien Riparian Vegetation (Gilham and Haynes (2001)

Subcatchments	Additional Yield at Inanda Dam (milion m^3/a)
Midmar + Albert Falls	12
Midmar + Albert Falls (future with no clearing)	-5
Midmar + Albert Falls + Nagel	14
Midmar + Albert Falls + Nagel (future with no clearing)	-7

The results of this study showed that water augmentation schemes could be delayed by up to 2 years, with considerable savings, by adopting a riparian clearing programme in the catchment.

3 STREAMFLOW REDUCTION ESTIMATION PROCEDURES INVESTIGATED IN THIS RESEARCH

3.1 Introduction

As outlined in **Section 1.1.3**, two basic methods of SFR estimation have been developed for commercial afforestation and IAPs. These are:

- Free-standing empirical relationships in the form of SFR curves (Scott and Smith, 1997).
- Component modules in the physically-based, land-use sensitive ACRU daily rainfall-runoff catchment model.

The empirical relationships have been used in conjunction with the monthly Pitman catchment model, while the ACRU Model estimates SFR via soil water budgeting on a daily time step and at a finer spatial scale than the Pitman Model.

3.2 Catchment Models Used in This Study

Catchment models used in this study are the monthly Pitman Model, incorporated in the SHELL interface, along with a number of other routines, and the daily ACRU Model.

3.2.1 SHELL

SHELL (Berg *et al*, 1991) is a user interface, which facilitates the use of a number of component programs at a monthly temporal resolution. These programs include:

- Pitman monthly catchment model for runoff simulation;
- Ressim for reservoir simulation;
- Irrdem for irrigation demand calculation;
- Forestry for afforestation-related SFR calculation; and
- AlienVeg for invasive alien vegetation-related SFR calculation.

Also included in the SHELL suite are programs, which carry out the following operations with the monthly data files:

- Addition, which may be used in simulating imports;
- Subtraction, which may be used in simulating exports and abstractions;
- Zeroing of negative values in interim model output files after subtraction; and
- Multiplication of monthly data files by a constant.

SHELL allows a sequence of operations (programs) that describe all major water use in a catchment (including dam operations), to be set up and saved as a configuration file, and links the component programs to their data files.

3.2.1.1 Pitman – The Runoff Simulation Model used in SHELL

Pitman (HRU, 1973) is a parameter-fitting model, where the subcatchment physical characteristics are represented by a number of calibration parameters, the values of which are adjusted to obtain a simulated monthly flow sequence, similar to an observed monthly flow sequence at the outlet of the subcatchment. The observed and simulated hydrographs are compared according to criteria set by the modeller. Typical criteria include graphical fit of the hydrographs, focusing on low and high flows, and deviation in MAR and standard deviation between observed and simulated flow sequences. Input into the model consists of monthly rainfall sequences and mean monthly evaporation data and a set of starting calibration parameters. Starting calibration parameters have been established for all the quaternary catchments in South Africa (Midgley *et al*, 1994). **Figure 3-1** depicts the essential elements of the Pitman Model.

The Pitman Model works at a monthly time step and relatively coarse subcatchment delineation.

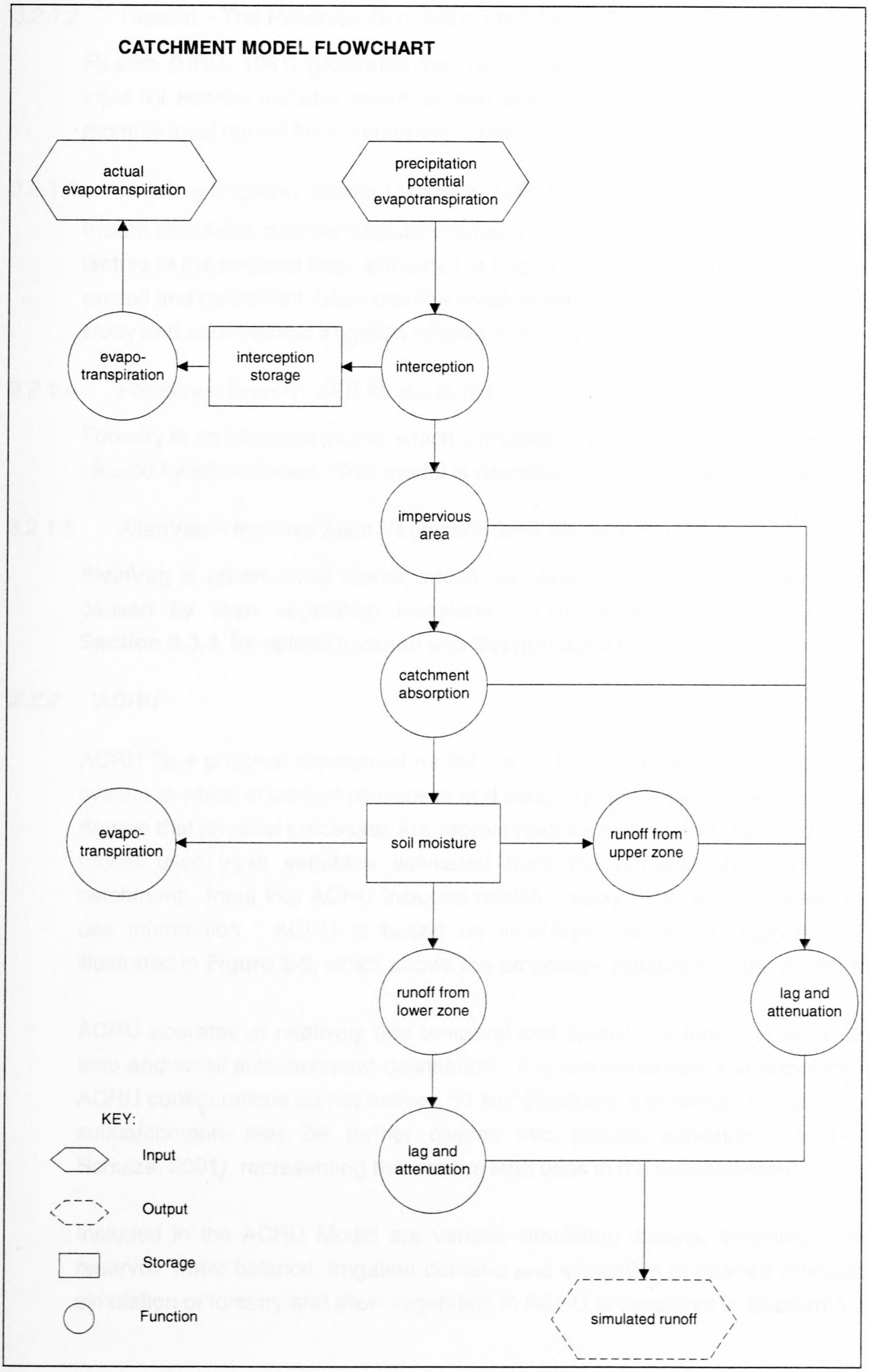


Figure 3-1: Pitman Catchment Model Flow Chart (HRU, 1973)

3.2.1.2 Ressim – The Reservoir Simulation Model in SHELL

Ressim (HRU, 1981) generates the monthly water budget for reservoirs. Required input for Ressim includes reservoir characteristics, monthly lake evaporation values, monthly local rainfall file and monthly inflow file.

3.2.1.3 Irrdem – Irrigation Demand Model in SHELL

Irrdem calculates monthly irrigation demand. Input into Irrdem includes monthly crop factors of the irrigated crop, efficiency of irrigation method, mean monthly effective rainfall and catchment mean monthly evaporation. Return flows were ignored for this study and conventional irrigation efficiencies were used.

3.2.1.4 Forestry – Forestry SFR Model in SHELL

Forestry is an empirical model, which calculates the reduction in catchment runoff caused by afforestation. This model is described in detail in **Section 3.3.1**.

3.2.1.5 AlienVeg – Invasive Alien Vegetation SFR Model in SHELL

AleinVeg is an empirical model, which calculates the reduction in catchment runoff caused by alien vegetation invasions. This model is described in detail in **Section 3.3.2** for upland invasion and **Section 3.3.3** for riparian invasion.

3.2.2 ACRU

ACRU “is a physical conceptual model, i.e., it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly” (Schulze, 1995, p2-2). The model uses input variables estimated from the physical characteristics of the catchment. Input into ACRU includes rainfall, evaporation, soil properties and land-use information. ACRU is based on multi-layer soil water budgeting. This is illustrated in **Figure 3-2**, which shows the processes simulated by the ACRU Model.

ACRU operates at relatively fine temporal and spatial resolution, using a daily time step and small subcatchment delineation. It is recommended that subcatchments in ACRU configurations do not exceed 50 km^2 (Smithers and Schulze, 1995), and these subcatchments may be further divided into pseudo subcatchments (Pike and Schulze, 2001), representing the various land uses in the subcatchment.

Included in the ACRU Model are various simulation options, including routines for reservoir water balance, irrigation demand and simulation of riparian processes. The simulation of forestry and alien vegetation in ACRU is described in **Section 3.4**.

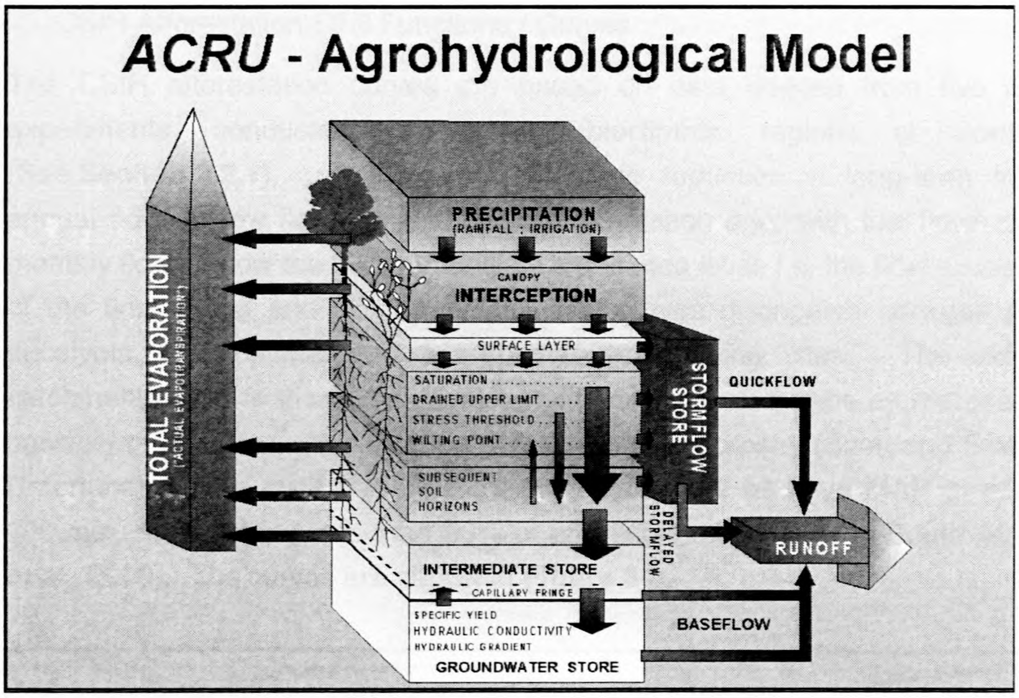


Figure 3-2: **A Conceptualised Illustration of the ACRU Model (Gush *et al*, 2001)**

3.3 Empirical SFR Estimation Methods Used in this Study

The empirical SFR relationships involve sigmoidal functions of proportional reductions in runoff, and are commonly used in conjunction with monthly Pitman catchment modelling, to derive estimates of monthly sequences of afforestation or IAP "water use". In this research, the empirical relationships, together with the Pitman Model, are applied through the SHELL Model.

For the purposes of producing guidelines for SFR estimation, it was necessary to verify that the application of the SFR estimation methods produced realistic results. To achieve this, tests were carried out on the methods and improvements were made where necessary.

This section describes how the empirical relationships are applied, the tests carried out on them and the resulting improvements.

3.3.1 Afforestation

The Forestry routine in SHELL applies the empirical SFR functions / curves developed by the CSIR (Scott and Smith, 1997) to calculate SFR resulting from afforestation.

3.3.1.1 CSIR Afforestation SFR Functions / Curves

The CSIR afforestation curves are based on data derived from five catchment experiments, conducted in different bioclimatic regions of South Africa (See **Section 2.2.1**), and express percentage reduction in long-term mean total annual flow, or low flow, as a function of plantation age, with low flows defined as monthly flows below the 75th percentile exceedance level, i.e. the flow exceeded 75 % of the time (Scott and Smith, 1997). The curves distinguish between pines and eucalypts, and optimal and sub-optimal tree-growing sites. The experimental catchments used in the curve development were selected to be as representative as possible of the geographical range of South African forestry (Scott and Smith, 1997). Unfortunately, the available experimental catchments all have MAP greater than 1 100 mm, representing less than 30% of afforested area MAPs in South Africa (Scott *et al.*, 2000). The curves are shown in **Figure 3-3.**

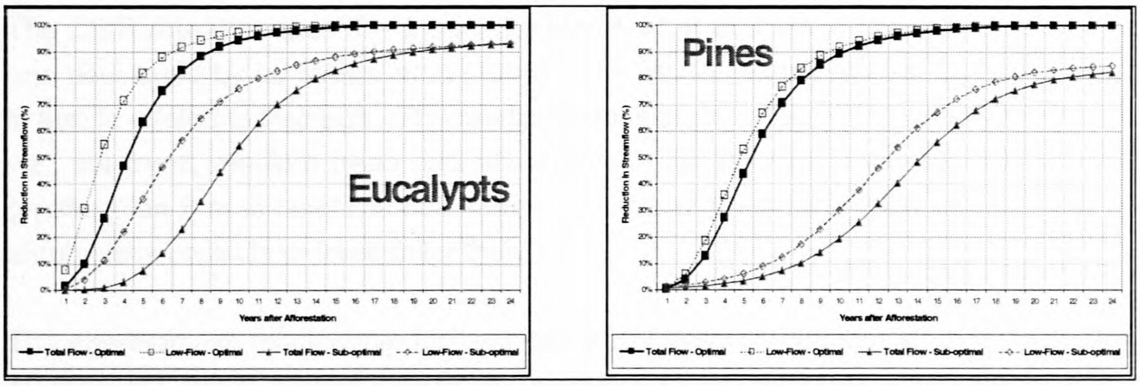


Figure 3-3: "Generalised Curves for Predicting the Percentage Reduction in Total (annual) Flows and Low Flows as a Function of Age after 100% Afforestation with Eucalypts and Pines, respectively (after Scott and Smith, 1997)" (Gush *et al*, 2001)

3.3.1.2 Application of CSIR Afforestation SFR Functions / Curves in SHELL

The functions / curves were developed for 100% afforested areas and are therefore applied to areas with 100% canopy cover. In the SHELL model, representative 100% afforested areas are therefore calculated for areas with canopy covers less than 100%. The SFR modelling process involves:

1. Using the Pitman Model to generate the streamflow sequence from the representative 100% afforested area, for an unafforested scenario.
2. Identifying low flow months as months having flows less than the 25th percentile flow value.
3. Determining, from the curves, the low flow and total annual flow reduction factors, based on the forestry parameters.

4. Determining the medium to high flow reduction factor by adjusting the total annual flow reduction factor, so that the overall flow reduction (low and medium to high) matches the total annual flow reduction.
5. Calculating a monthly SFR sequence by applying the low flow reduction factor to low flows and the medium to high flow reduction factor to medium to high flows.

Figure 3-4 summarises the SFR modelling process.

3.3.2 Upland Invasive Alien Vegetation

The AlienVeg routine in SHELL applies the empirical Age-Biomass-SFR functions / curves developed by the CSIR (Le Maitre *et al,* 2001) to calculate SFR resulting from invasion by alien vegetation.

3.3.2.1 Age-Biomass-SFR Model for Upland Invasive Alien Vegetation

The CSIR Age-Biomass-SFR Model (Le Maitre *et al*, 2001*)* is a revised version of the one developed by Le Maitre *et al* (1996). The model relates SFR to biomass, which in turn is related to tree age. The relationships were developed for three tree classes, viz., tall trees, medium trees and tall shrubs. The tall tree class consists of trees greater than 8 m in height, medium tree consists of trees taller than 2 m and the tall shrub class consists of trees taller than 1.5 m.

The age-biomass relationship for tall trees was based on biomass data from 29- and 40-year old *Pinus radiata* stands at Jonkershoek experimental catchments and a height growth model from a *Pinus radiata* stand in the Bosboukloof catchment at Jonkershoek. The age-biomass relationship for medium trees was based on data from literature on the topic. The Biomass Model for tall shrubs was based on data for a single 9-year old Hakea stand (Le Maitre *et al*, 2001).

The relationships between age and biomass for the different tree classes are as follows (Le Maitre *et al*, 2001):

Tall tree biomass (t/ha) = $300/(1+e^{3.67947}$ x (Age in years)-1.4109)..... **Equation 3-1**

Medium tree biomass (t/ha) = $96.0732\log_{10}$ (Age in years)-4.8081... **Equation 3-2**

Tall shrub biomass (t/ha) = $76/(1+e^{3.18628}$ x (Age in years)-1.25973)... **Equation 3-3**

The biomass-flow reduction curves were developed for two types of flow reduction, viz., long-lag and short-lag, which depend on the time lapse before the recording of a significant reduction in flow in the experimental catchment. Upland situations are typically long-lag and riparian situations are typically short-lag. These curves were further sub-divided into curves for low flow reduction and annual flow reduction. The long-lag curves were developed from Pinus radiata data from the Biesievlei catchment at Jonkershoek, and short-lag curves were developed from *Eucalyptus grandis* data from Westfalia catchment D (Le Maitre *et al*, 2001).

The relationships between biomass and streamflow are as follows (Le Maitre *et al*, 2001):

Long-lag curves:

Annual flow reduction (%) = 75/(1+e$^{14.2216}$xbiomass(t/ha)-2.9194..........**Equation 3-4**

Low flow reduction (%) = 100/(1+e$^{10.0252}$ x biomass(t/ha)-2.0927......... **Equation 3-5**

Short-lag curves:

Annual flow reduction (%) = 100/(1+e2.2958 x e(biomass(t/ha))
x (-0.02388))..................................... **Equation 3-6**

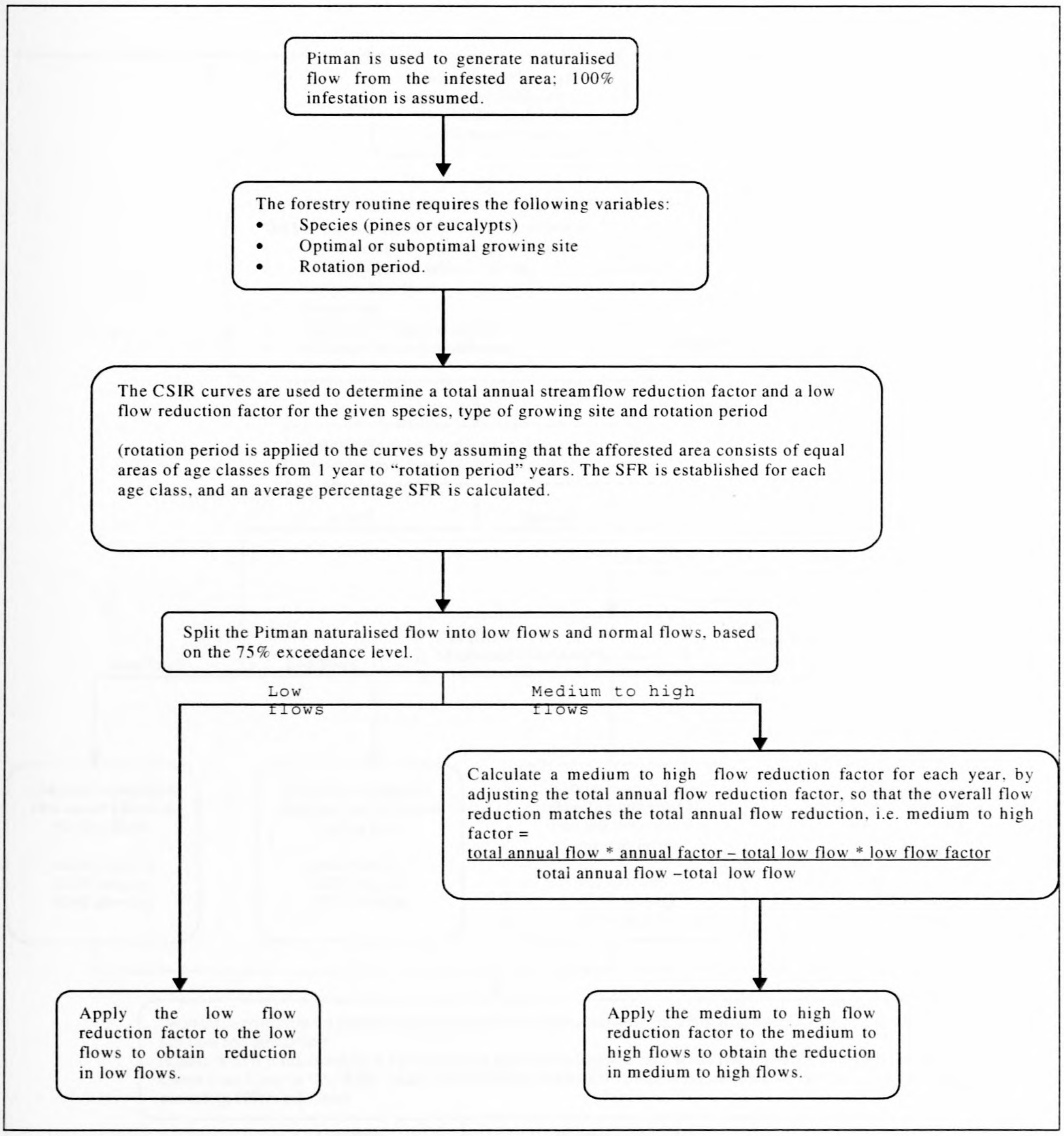
Annual flow reduction (%) = 100/(1+e$^{1.9677}$ x e(biomass(t/ha))
x (-0.02474)).................................... **Equation 3-7**

3.3.2.2 Application of the Age-Biomass-SFR Model for Upland Invasive Alien Vegetation in SHELL

It is recognised that SHELL deals with SFR as an empirical process and not through actual hydrological processes

The curves were developed for 100% infested areas. Therefore, the SHELL Model requires "condensed" areas of IAPs, which is the equivalent 100% infested area for subcatchments with canopy cover less than 100% (Le Maitre *et al*, 1999).

Figure 3-5 summarises the IAP SFR modelling process. The asymptote referred to in **Figure 3-5** is the numerator in the Biomass-SFR equation (**Equations 3-4 to 3-7**). The scaling factor, used in the calculation of the asymptote, is necessary, because the data used in developing the equations included SFRs much higher than the asymptotic values given by the equations (Le Maitre *et al*, 2001).



Pitman is used to generate naturalised flow from the infested area; 100% infestation is assumed.

The forestry routine requires the following variables:

- Species (pines or eucalypts)
- Optimal or suboptimal growing site
- Rotation period.

The CSIR curves are used to determine a total annual streamflow reduction factor and a low flow reduction factor for the given species, type of growing site and rotation period

(rotation period is applied to the curves by assuming that the afforested area consists of equal areas of age classes from 1 year to "rotation period" years. The SFR is established for each age class, and an average percentage SFR is calculated.

Split the Pitman naturalised flow into low flows and normal flows, based on the 75% exceedance level.

Calculate a medium to high flow reduction factor for each year, by adjusting the total annual flow reduction factor, so that the overall flow reduction matches the total annual flow reduction, i.e. medium to high factor =

$$\frac{\text{total annual flow} * \text{annual factor} - \text{total low flow} * \text{low flow factor}}{\text{total annual flow} - \text{total low flow}}$$

Apply the low flow reduction factor to the low flows to obtain reduction in low flows.

Apply the medium to high flow reduction factor to the medium to high flows to obtain the reduction in medium to high flows.

Figure 3-4: Flow Diagram of Afforestation Streamflow Reduction Modelling Process (after van Wilgen *et al*, 1999)

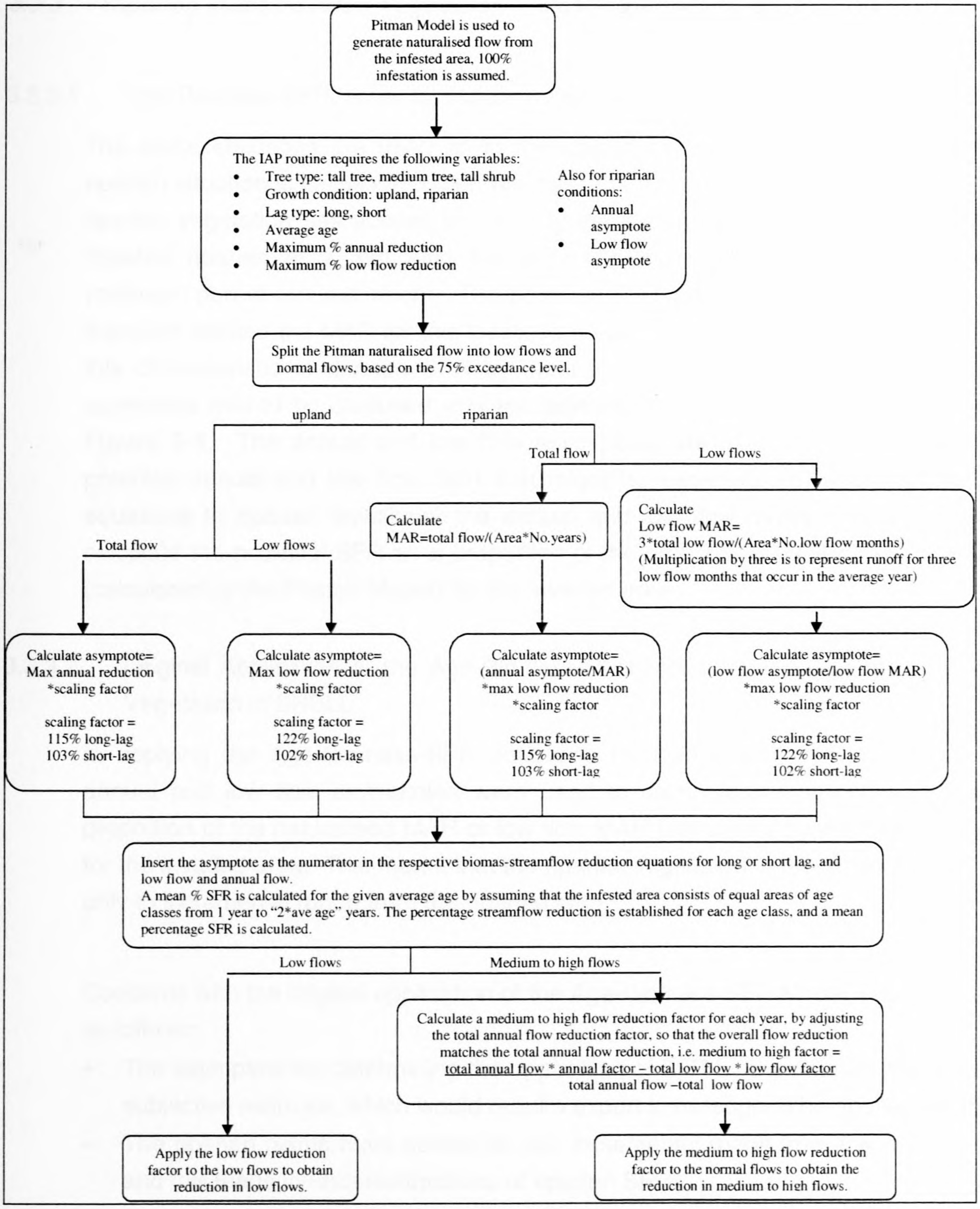


Figure 3-5: Flow Diagram of IAP SFR Estimation Process (Dave Le Maitre, CSIR, pers com, 2000)

3.3.3 Riparian Invasive Alien Vegetation – Existing Approaches

3.3.3.1 Age-Biomass-SFR Model for Riparian Invasive Alien Vegetation

The same equations are used as in the upland case, only the asymptote for the riparian situation is calculated differently from the asymptote for the upland, because riparian vegetation has access to not only the surface water and soil water of the infested riparian area, but also the water flowing in the watercourse from the upstream part of the catchment. The potential SFR in the invaded riparian area can therefore exceed the MAR for this localised area. The riparian SFR equations reflect this characteristic of riparian SFR by means of an annual asymptote or low flow asymptote (not to be confused with the asymptote mentioned above), as shown in **Figure 3-5**. The annual and low flow asymptotes are estimates of the maximum potential annual and low flow SFR that might be expected. In applying the SFR equations to riparian invasions, the annual and low flow asymptotes are used to calculate the potential SFR as a proportion of the naturalised MAR or low flow MAR (calculated by the Pitman Model) for the invaded area.

3.3.3.2 Original Application of the Age-Biomass-SFR Model for Riparian Invasive Alien Vegetation in SHELL

In applying the Age-Biomass-SFR equations to riparian invasions in SHELL, the annual and low flow asymptotes were used to calculate the potential SFR as a proportion of the naturalised MAR or low flow MAR (calculated by the Pitman Model) for the invaded area. This meant that the riparian vegetation in the model had access only to incremental runoff from the riparian strip.

Concerns with the original application of the Age-Biomass-SFR Model in SHELL were as follows:

- The asymptote for determining the upper limit of SFR by the riparian plants was a subjective estimate, which would require expert knowledge to be applied reliably.
- The riparian plants have access to only incremental runoff from the riparian strip and this leads to underestimations of riparian SFR.
- Since the SFR produced is a proportional reduction of runoff, the highest SFR occurs in the wet season and the lowest SFR in the dry season. This seasonality is not necessarily correct for riparian SFR.

3.3.4 Riparian Invasive Alien Vegetation – Improvements to Existing Approaches

To address the concerns about the existing method of estimating riparian SFR in SHELL, a new method was developed for use in this study. The method equates potential SFR by riparian trees to the incremental potential ET of the riparian trees relative to that of the natural vegetation being replaced.

The new "potential ET" (PET) method is based on the following assumptions:

1. Riparian plants have direct access to water in the stream or to lateral interflow from upland hill slopes adjacent to the riparian zone. Therefore, transpiration is limited by evaporative demand, availability of water from both the upstream subcatchments and runoff from the upland area of the subcatchment in question, and plant physiology.
2. A-pan evaporation measurements can be used as an index of evaporative demand.
3. Alien vegetation PET is equal to maximum potential SFR.
4. PET is some fraction of evaporative demand (A-pan). A-pan evaporation can be factored down to ET by applying "crop coefficients" to the A-pan evaporation. Differences in ET for the different tree classes are accounted for by having different crop coefficients for the different tree classes. ACRU crop coefficients were used in this case.

The relevant equations are as follows:

$\text{Potential SFR} = \text{Potential ET}_{\text{alien vegetation}} - \text{Potential ET}_{\text{natural vegetation}}$... **Equation 3-8**

where:

Potential ET = A-pan evaporation x Crop coefficient...................... **Equation 3-9**

The actual SFR is equal to the portion of potential SFR, which can be met by streamflow arriving at that point in the stream.

Figure 3-6 and **Figure 3-7** show a comparison between riparian SFR estimated, using the Age-Biomass-SFR method (old method) and the PET method (new method) for the Mhlatuze and Upper Berg, respectively. The seasonality of the two methods is different. Since the Age-Biomass-SFR method is based on a proportional reduction of natural runoff, the highest SFR for this method occurs in the wettest months. The highest SFR for the PET method occurs in the driest months, since this is when the difference in ET by natural vegetation and IAPs is highest (**See Appendix A**).

The PET method is the method used in this study to estimate SFR by IAPs in the SHELL modelling package.

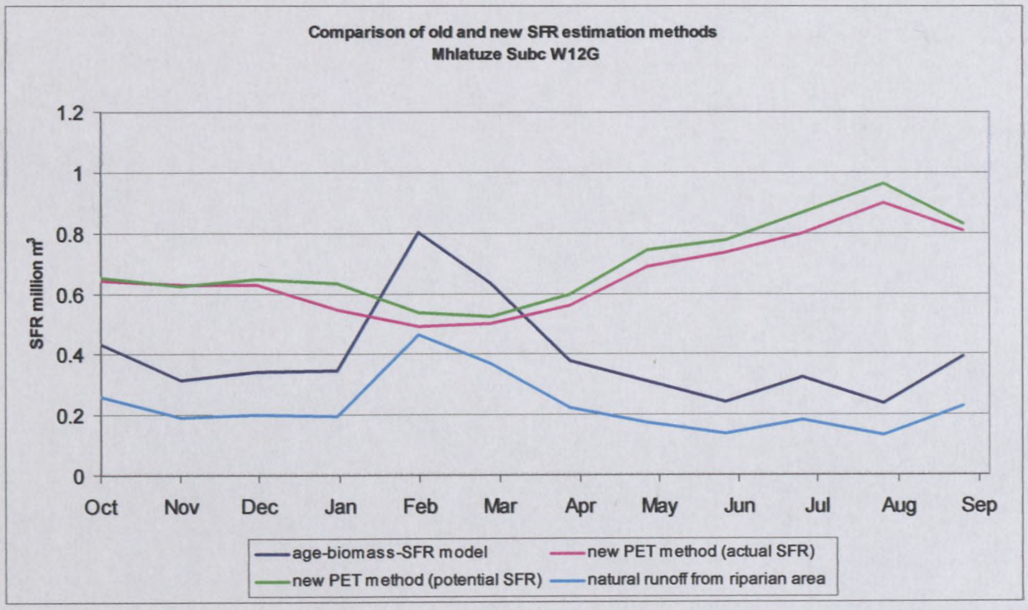


Figure 3-6: Comparison of Old and New Riparian SFR Estimation Models for a Subcatchment in the Mhlatuze

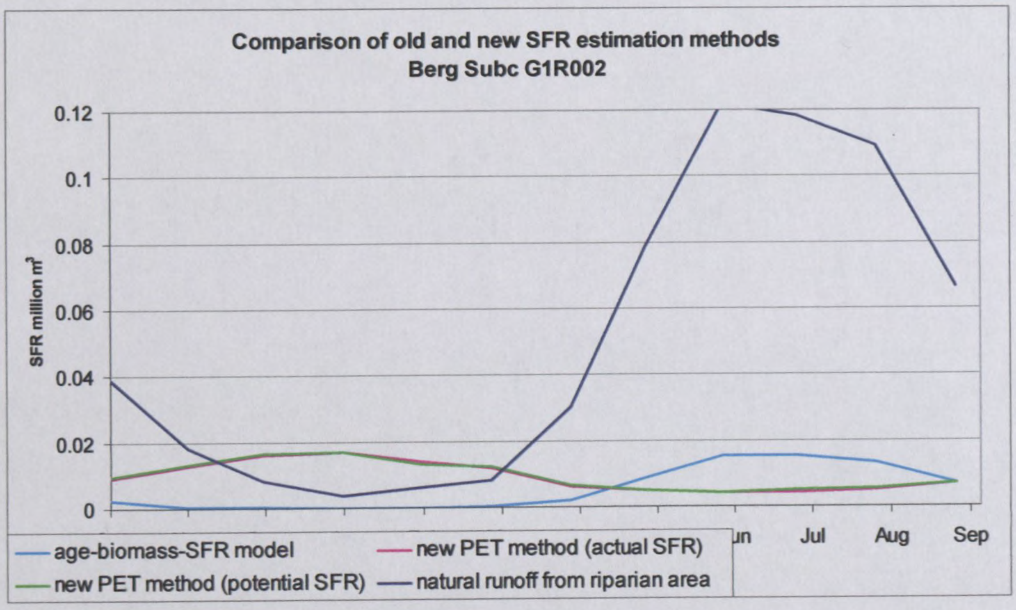


Figure 3-7: Comparison of Old and New Riparian SFR Estimation Models for a Subcatchment in the Upper Berg

3.4 Physically Based Methods

Physically based methods consist of the routines within the ACRU Model, introduced in **Section 3.2.2.**

3.4.1 Upland Vegetation

In ACRU, water use of plants is estimated using parameters, which describe the consumptive use characteristics of the plant species, and SFR by plants is a function of the consumptive use of the plants and the runoff generating properties of the soil.

Parameters which affect the water use of plants include:

- Crop coefficient (CAY), "the fraction of water 'consumed' by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan in a given period." (Smithers and Schulze, 1995). When the plant experiences stress, this fraction is reduced in ACRU.
- The fraction of the plant available water of a soil horizon at which total evaporation is assumed to drop below maximum evaporation during drying of soil (CONST).
- Interception loss through the leaves and canopy of the plant (VEGINT).
- The fraction of the root system in each soil horizon (The variable ROOTA represents the fraction of the root system in the top soil horizon).
- Effective root depth (EFRDEP).

Landcover input parameters used for the study are presented in **Appendix A**.

3.4.2 Riparian Vegetation

3.4.2.1 Adaptations to the ACRU Model and Input to Account for Enhanced Riparian Water Availability

The following description is paraphrased from DWAF (2001):

"When simulating riparian zone impacts ACRU routes the contributing areas surface and near-surface flow into the riparian zone as stormflow (Qs) (**Figure 3-8**). Baseflows are routed from the contributing areas to the riparian zone as sub-surface flows (Qb), which increase the soil moisture of the riparian zone. The sub-surface flow into the riparian zone first "fills" the lower soil horizon to saturation. Once that is exceeded, then the upper soil horizon is filled, and should that reach saturation, the excess water overflows from the soil, and is aggregated to the stormflows from the catchment. This increased soil moisture in the riparian zone is then available to the vegetation for plant water use. The remaining sub-surface (baseflow) and stormflows of the riparian zone are combined before being routed downstream as streamflow. Any streamflow exceeding the capacity of the channel, during high flows, becomes overflow from the channel and is available for re-infiltration into the upper soil horizon of the riparian zone. Any outflow from the riparian zone is then routed into the downstream subcatchment".

3.4.2.2 Modification to the ACRU Riparian Module for Modelling Complex River Systems

The original ACRU riparian module was developed for a simple river system consisting of one upland sub—catchment, flowing into its accompanying riparian subcatchment; therefore the module was programmed to route baseflows from all contributing upstream areas to the B-horizon of the riparian zone. When this module was applied to the complex subcatchment configurations in this study, it was found that the B-horizon of each riparian subcatchment was receiving baseflows from all the contributing upstream subcatchments. For example, the riparian subcatchment at the flow exit point of the Upper Berg catchment was receiving the baseflows simulated for the complete (620 km^2) Upper Berg catchment. The ACRU development team corrected this problem in the riparian module by reprogramming the module to allow the user to dictate which subcatchment baseflows may enter the B-horizon of a downsteam riparian subcatchment. In this way, the user can ensure that the only baseflows allowed to enter the riparian subcatchment are the baseflows generated in its accompanying upland subcatchment.

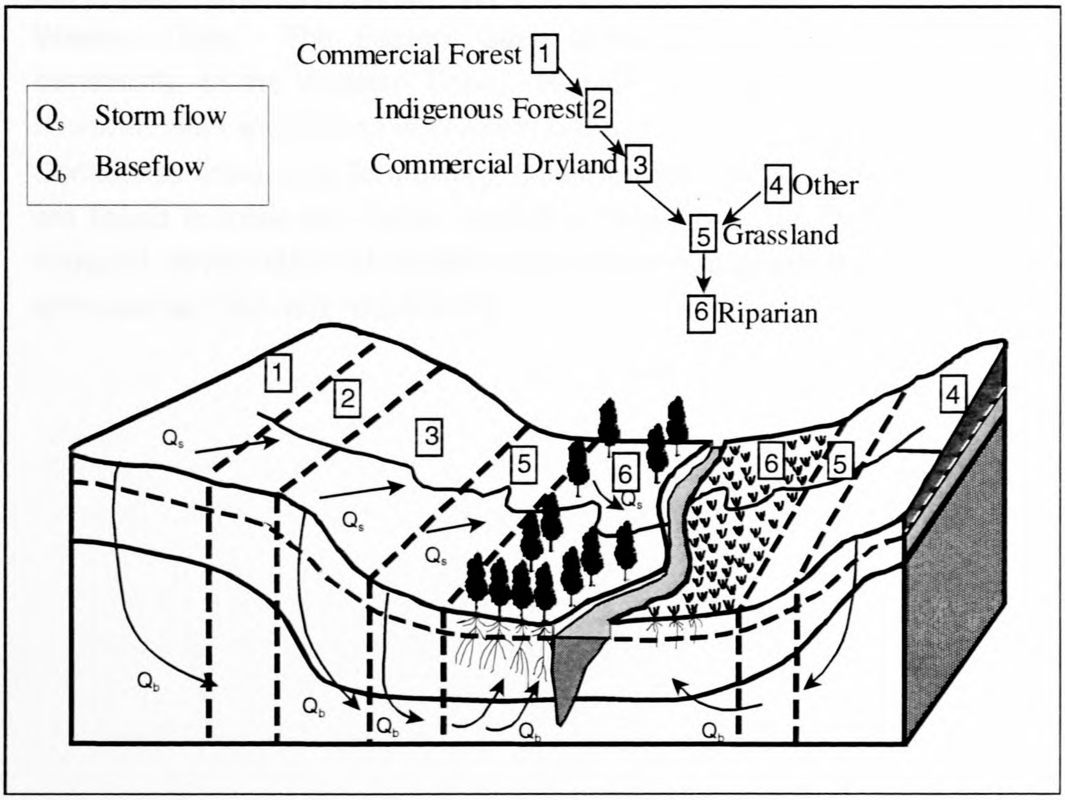


Figure 3-8: **Example of the Configuration of the ACRU Model to Simulate Riparian Zones (DWAF 2001)**

3.5 Commercial Afforestation Tables (Gush Tables)

The afforestation tables (Gush *et al*, 2001) present typical mean or median long-term annual reductions in streamflow (total and low flows) within 843 quaternary catchments across South Africa, for afforestation with either pines, eucalypts, or wattle. The mean and median SFRs, i.e. streamflow from afforestration versus streamflow from Acocks land covers, were obtained from ACRU Model applications in affected quaternary catchments. The ability of ACRU to model baseline streamflows and streamflows on afforested catchments was verified in a selection of experimental catchments (see **Section 2.2.1**). Parameter settings, indicated by the verification, were applied to simulating forestry SFRs on a national scale.

The following details are important:

- One soil texture, sandy-clay-loam, was assumed for all the quaternary catchments, as the most representative texture of soils in South African forestry areas.
- Median and mean annual SFRs were produced for 3 depths, viz., 0.6 m, 0.9 m and 1.2 m, for each of the land covers, viz., forestry or Acocks, and for both total- and low flow.
- ACRU variables (leaf area index, rainfall interception, and percentage roots in the A-horizon), which were classified according to climatic zones, are not available for the Western Cape; so, Eastern Cape values of these variable were assigned to the Western Cape. The Eastern Cape is considered to be the closest region, climatically, to the Western Cape. Rainfall, temperature and evaporation data, however, were specific to the Western Cape.
- Confidence limits were formulated, based on the model shortcomings. The limits are linked to three site water availability categories, viz., humid, sub-humid and marginal, having MAPs of greater than 1 050 mm, between 850 mm and 1 050mm, and less than 850 mm, respectively.

4 METHODOLOGY AND RESEARCH PROCESS

Three river systems were selected for the study. Each system was configured using the ACRU, Pitman (SHELL) and WRYM Models, respectively. As far as possible, the same model input information was used for the ACRU and SHELL configurations of each river system, so that the results from ACRU and SHELL could be compared for each system. The ACRU and SHELL configurations were run for a number of scenarios and deductions were made regarding the SFR estimated by the two different models under different bio-climatic conditions. The output from ACRU and SHELL was then run through the WRYM to investigate the impacts on yield, of SFR produced by the two different models under different bio-climatic conditions.

This chapter describes the process followed in building catchment model configurations for selected river systems. The process consisted of the following stages:

- Selection of study river systems.
- Assembly of model information and land-use coverages.
- Configuration of catchment models.

The stages are described below for each of the selected river systems.

4.1 Selection of Study River Systems

The project aimed to use, as far as possible, existing model configurations of river systems, and to select a set of systems covering a range of bio-climatic conditions in South Africa. An assessment was therefore made of all available ACRU, Pitman (SHELL / WRSM90) and WRYM configurations for all major South African river systems. The selection process comprised the short-listing of suitable systems, followed by the final selections of three systems.

The systems selected for the study are the Upper Berg, Upper Sabie and Mhlatuze catchments, which represent different South African bio-climatic regions. **Figure 4-1** shows the location of the study systems. Existing ACRU configurations were made available for the Sabie and Mhlatuze catchments, existing Pitman configurations for all three catchments and existing WRYM configurations for the Upper Berg and Mhlatuze catchments.

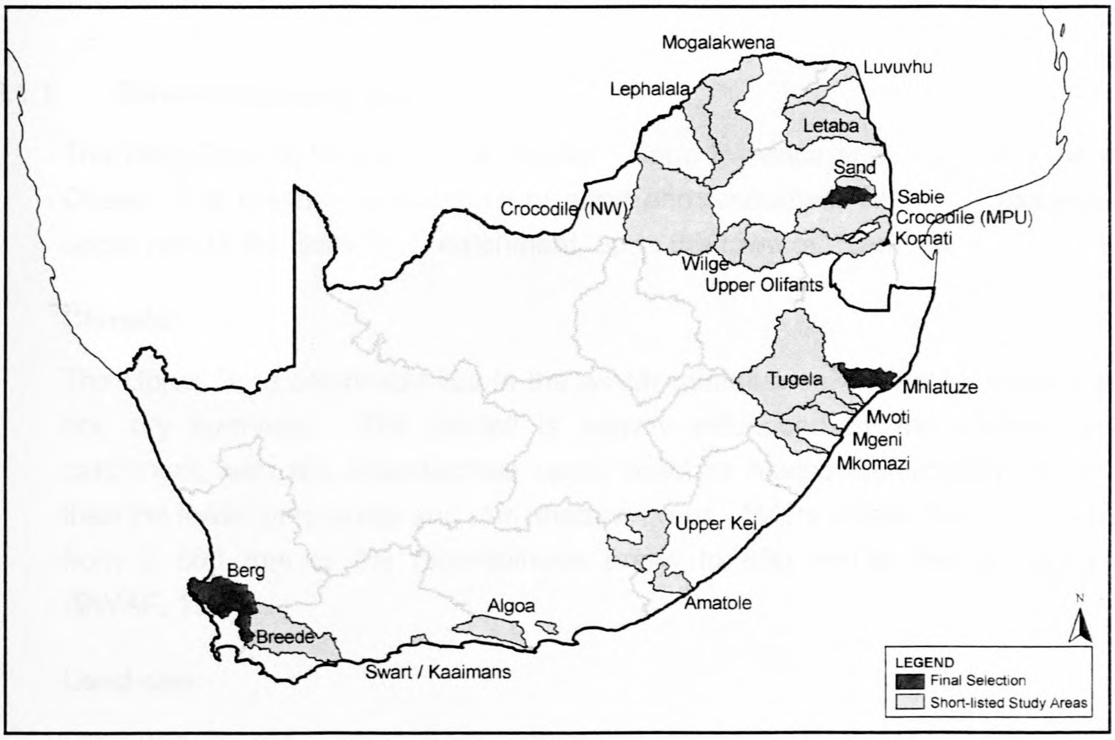


Figure 4-1: **Location of Study Areas, showing Short-listed Areas and Final Selection**

4.2 River Systems Studied

The systems used in the project were selected to represent a range of bio-climatic conditions in South Africa. The three systems, with their unique climate and vegetation types meet this requirement. The characteristics of the study systems are summarised in **Table 4-1** below.

Table 4-1: **Characteristics of Study Systems**

Characteristic	**Upper Berg**	**Upper Sabie**	**Mhlatuze**
Total area (km^2)	620	1946	3628
Total afforestation (km^2)	81	781	531
IAP area - Total (km^2)	326	1946	3 098
IAP area - Condensed (km^2)	39	10	81
Total irrigated area (km^2)	34	76	151
Total farm dam storage $10^6 m^3$	16	6	40
Total large dam storage $10^6 m^3$	59	13.6	303

4.2.1 Upper Berg

4.2.1.1 General Characteristics

The Berg River is located in the Western Cape Province and drains into the Atlantic Ocean. For reasons of economy of effort and resources, this study focuses on the upper part of the Berg River catchment, up to the town of Paarl.

Climate:

The Upper Berg catchment lies in the winter rainfall area, with cold, wet winters and hot, dry summers. The rainfall is heavily influenced by the mountains in the catchment, with the mountainous upper reaches having significantly higher MAPs than the lower lying areas and rain shadow areas. MAPs across the catchment range from 2 600 mm in the mountainous areas to 800 mm in the low-lying areas. (DWAF, 1997)

Land-use:

Land-use in the Upper Berg catchment includes farm land and farm dams, commercial afforestation and alien vegetation infestation.

The dominant agricultural land-use in the Upper Berg catchment is wine farming, followed by fruit farming. Farming of other crops, like vegetables and lucerne also occurs to a limited extent. The crops are irrigated directly from the Berg River and its tributaries, or from farm dams. Irrigation releases are made into the Upper Berg River from Theewaterskloof Dam and Wemmershoek Dam. (DWAF, 1997).

Commercial afforestation occurs throughout the catchment, but is mainly concentrated upstream of the confluence with the Franschoek River.

Invasive alien vegetation also occurs throughout the catchment, but is mostly of low density and consists mainly of pines.

4.2.1.2 Modelling Information

Configuration:

The configuration used to model the Upper Berg, is shown in **Figure 4-2**.

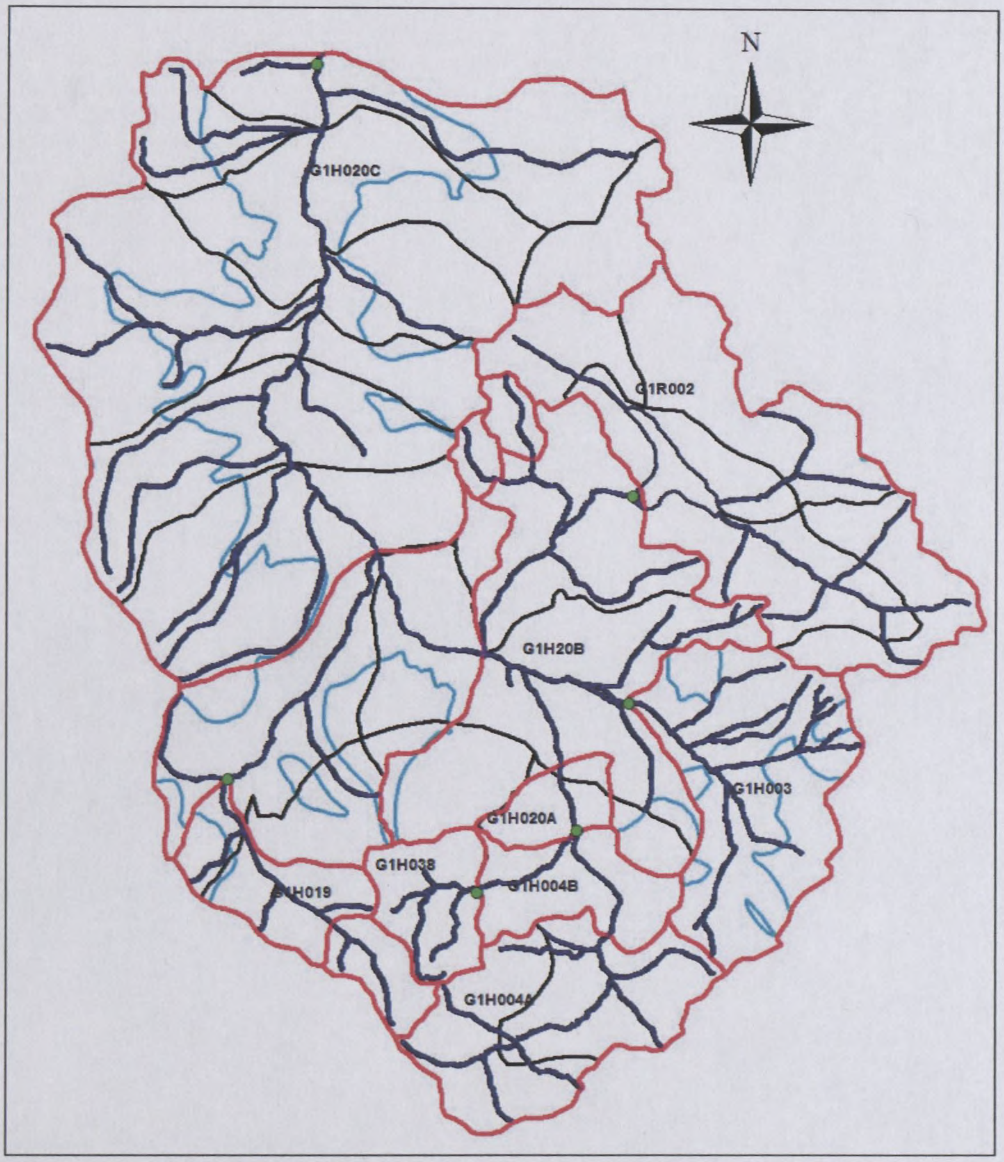


Figure 4-2: Subcatchment Configuration of the Upper Berg

The thick red line represents the subcatchments modelled in SHELL and the subcatchments to which the ACRU pseudo subcatchments (see **Section 4.4.1.1**) were aggregated for comparisons with SHELL. The subcatchments are named after the gauging stations at their outlets (green dots). The light blue line represents the division between the part of the subcatchment located upstream of farm dams and the part of the subcatchment located downstream of farm dams. The naming of the SHELL subcatchments in the model is as in **Table 4.2**.

The black lines represent the smaller ACRU subcatchments, making up the larger SHELL catchments.

The riparian subcatchments are visible as the dark blue line (double lines) along the river course.

There is only one major dam in the catchment, Wemmershoek dam. It lies at the outlet of subcatchment G1R002 and has a full supply capacity of 59 million m^3.

Table 4-2: Description of Subcatchments in the Configuration of the Upper Berg

Subc	Description
h03d	catchment gauged by G1H003, portion downstream of farm dams
h03u	catchment gauged by G1H003, portion upstream of farm dams
h04a	catchment gauged by G1H004, higher MAP portion
h04b	catchment gauged by G1H004, lower MAP portion
h19d	catchment gauged by G1H019, portion downstream of farm dams
h19u	catchment gauged by G1H019, portion upstream of farm dams
h20a	catchment gauged by G1H020, section A
h20bd	catchment gauged by G1H020, section B, portion downstream of farm dams
h20bu	catchment gauged by G1H020, section B, portion upstream of farm dams
h20cd	catchment gauged by G1H020, section C , portion downstream of farm dams
h20cu	catchment gauged by G1H020, section C, portion upstream of farm dams
h38	catchment gauged by G1H038
r02	catchment gauged by G1R002

Input Data:

The input data, common to both ACRU and SHELL, is shown in **Table 4-3**.

Table 4-3: Input data for the Upper Berg

Subc	Area (km^2)	MAP (mm)	A-PAN Evaporation (mm)											
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
h03d	33.9	1018.3	146.0	193.3	243.1	259.1	210.3	188.7	107.1	71.6	58.3	64.2	77.3	101.2
h03u	12.4	1018.3	146.0	193.3	243.1	259.1	210.3	188.7	107.1	71.6	58.3	64.2	77.3	101.2
h04a	39.9	2147.5	91.6	122.6	179.5	186.3	147.3	135.6	63.2	52.6	56.4	65.0	69.2	76.4
h04b	16.2	1966.5	91.6	122.6	179.5	186.3	147.3	135.6	63.2	52.6	56.4	65.0	69.2	76.4
h19d	19.6	1720.7	106.4	140.5	198.8	198.8	166.1	149.0	72.5	58.8	57.2	64.9	72.3	82.5
h19u	3.2	1720.7	106.4	140.5	198.8	198.8	166.1	149.0	72.5	58.8	57.2	64.9	72.3	82.5
h20a	11.3	1519.7	158.5	210.2	260.2	271.0	227.0	199.6	111.4	73.6	58.8	63.1	78.4	104.1
h20bd	121.4	1128.5	158.5	210.2	260.2	271.0	227.0	199.6	111.4	73.6	58.8	63.1	78.4	104.1
h20bu	22.3	1128.5	158.5	210.2	260.2	271.0	227.0	199.6	111.4	73.6	58.8	63.1	78.4	104.1
h20cd	103.9	870.8	158.5	210.2	260.2	271.0	227.0	199.6	111.4	73.6	58.8	63.1	78.4	104.1
h20cu	137.7	870.8	158.5	210.2	260.2	271.0	227.0	199.6	111.4	73.6	58.8	63.1	78.4	104.1
h38	13.1	2496.6	60.0	82.4	139.7	137.9	106.4	105.7	37.2	45.0	55.2	67.7	65.6	63.8
r02	85.3	1349.4	122.8	167.5	211.9	224.9	177.7	166.1	89.8	66.2	56.8	66.8	73.6	90.8

4.2.2 Upper Sabie

4.2.2.1 General Characteristics

The Sabie catchment is located in the Mpumalanga Province. The Upper Sabie, modelled in this study, is upstream of the confluence with the Sand River. After the confluence with the Sand, the Sabie River flows through the Kruger National Park.

Climate:

The Sabie River catchment has a warm to hot sub-tropical climate, with wet summers and dry winters. The rainfall season lasts from about November to March. The MAP in the catchment ranges from 2 000 mm in the high altitude areas towards the Drakensberg Mountains, to 600 mm in the lowveld areas. The rainfall is mainly due to thunderstorms, although orographic rain is common near the Drakensberg Mountain.

Land-use:

Land-use in the Upper Sabie catchment consists mainly of irrigation, dry land farming and afforestation. There is very little invasion by alien vegetation. Irrigated crops include bananas, avocados, citrus, tobacco, maize and vegetables, and dry land crops include beans, cassava, maize, mangoes, pumpkins, sisal, sorghum and sweet potatoes. The afforestation in the catchment is mostly pines, with some eucalyptus, about 5% of the total afforestation, also being planted (Pike and Schulze, 2001).

4.2.2.2 Modelling Information

Configuration:

The configuration, used to model the Upper Sabie, is shown in **Figure 4-3**.

The thick red line represents the subcatchments modelled in SHELL and the subcatchments to which the ACRU information was aggregated for comparisons with SHELL. The gauging stations, used to calibrate SHELL (X3H004, X3h011, X3H021) or verify ACRU (X3H004), are shown in **Figure 4-3**.

The black lines represent the smaller ACRU subcatchments, making up the larger SHELL catchments.

The riparian subcatchments are visible as the grey lines along the river course.

There is only one major dam in the catchment, Da Gamma dam. It lies at the outlet of subcatchment 13 and has a full supply capacity of 13.6 million m^3

The ACRU configuration was run only up to the end of subcatchment 30, because running the model up to gauge x3h021 required more computer resources than was available to the Project Team, however, it was necessary to run SHELL up to gauge X3H021 for calibrating the model.

Input Data:

The input data, common to both ACRU and SHELL, is shown in **Table 4-4**.

Table 4-4: Input Data for the Upper Sabie

Subc	Area (km^2)	MAP (mm)	A-PAN Evaporation (mm)											
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
1	46.2	724.7	190.3	177.6	183.8	175.8	168.5	164.8	145.6	131.8	107.4	115.1	146.0	168.9
2	55.9	845.3	194.2	180.2	189.3	184.0	171.7	167.5	143.2	129.2	105.9	114.7	145.1	169.6
3	173.3	785.3	190.8	178.4	187.0	182.3	165.7	165.7	144.2	130.8	106.7	115.2	146.5	169.9
8	67.2	1337.0	192.8	182.0	187.8	183.4	175.2	166.9	139.7	126.5	104.7	114.3	144.2	166.9
9	89.1	928.4	191.6	182.0	188.1	183.7	175.4	167.1	140.1	126.7	104.9	114.4	144.1	166.7
10	83.7	1277.9	192.4	180.3	187.0	182.3	174.7	167.0	140.6	127.1	104.8	114.1	143.6	166.4
11	107.6	736.8	192.2	181.9	190.3	186.3	175.9	168.0	140.4	126.5	104.5	113.6	143.2	166.4
12	293.9	750.9	191.0	179.8	188.5	185.1	170.0	166.2	140.2	126.7	104.0	113.6	143.3	166.7
13	61.0	967.6	188.7	187.9	195.9	194.0	176.7	169.0	137.9	123.6	103.0	114.0	143.9	166.6
19	56.5	923.2	188.1	186.0	196.0	195.3	173.8	168.0	136.4	122.6	102.0	112.9	143.0	165.6
20	37.4	830.0	188.4	186.5	193.0	191.1	174.8	167.6	137.5	124.3	103.4	114.0	144.1	166.3
21	138.7	1033.8	189.0	189.2	199.6	198.8	178.1	169.7	136.2	121.9	101.6	112.7	143.0	166.0
22	93.2	1400.0	189.7	194.7	209.3	209.6	184.0	174.0	137.6	120.2	100.9	112.5	142.5	168.2
23	143.6	763.7	190.1	188.3	197.8	196.0	179.2	170.3	138.1	123.2	102.7	113.6	143.4	166.7
30	426.6	717.7	190.4	195.9	210.9	210.9	187.3	175.6	139.2	120.5	101.4	113.1	142.9	169.3
31	33.4	812.6	190.6	194.3	208.7	208.0	185.0	173.6	137.0	120.2	101.0	112.6	142.9	167.9
32	38.7	1137.0	188.9	192.3	204.9	205.2	179.7	171.4	136.4	120.9	101.1	112.7	143.0	167.2

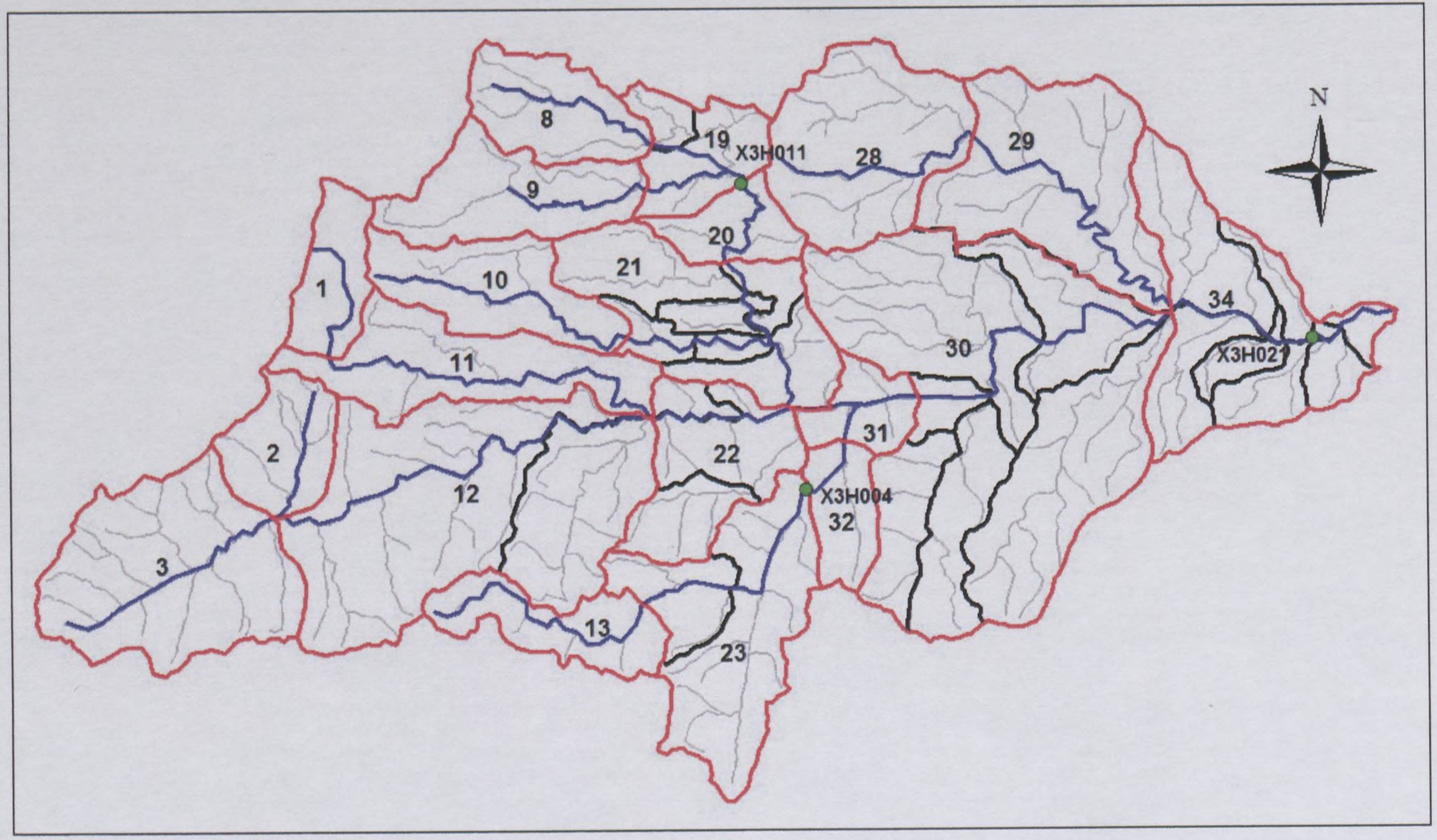


Figure 4-3: Subcatchment Configuration of the Upper Sabie

4.2.3 Mhlatuze

4.2.3.1 General Characteristics

The Mhlatuze catchment is located at the extreme south of the Kwazulu-Natal Province. The Mhlatuze River drains into the Indian Ocean at Richards Bay.

Climate:

The Mhlatuze catchment has humid summers and relatively warm winters. Most rainfall occurs between January and May. Rainfall in winter is associated with frontal weather or moist air from the Indian Ocean Anticyclone. MAP ranges from about 1 200 mm at Richards Bay to below 900 mm at the top of the catchment.

Land-use:

Major land-use in Mhlatuze comprises irrigation, afforestation and dry-land sugar cane. The largest water use in the catchment is from irrigation. Sugar cane is the main crop irrigated, followed by a significant amount of citrus. Industry, consisting of the Mondi Paper Mill and Richards Bay Minerals, is the other major water user in the catchment (DWAF, 2002).

4.2.3.2 Modelling Information

Configuration:

The configuration, used to model the Mhlatuze, is shown in **Figure 4-4**.

The thick red line represents the subcatchments modelled in SHELL, and the subcatchments to which the ACRU information was aggregated for comparisons with SHELL. The gauging stations, used to calibrate SHELL (W1h009) or verify ACRU (W1h005), are shown as green dots.

The black lines represent the smaller ACRU subcatchments, making up the larger SHELL catchments.

The riparian subcatchments are visible as the grey line along the river course.

There is only one major dam in the catchment, Goedertrouw dam. It lies at the outlet of subcatchment W12B and has a full supply capacity of 303 million m^3.

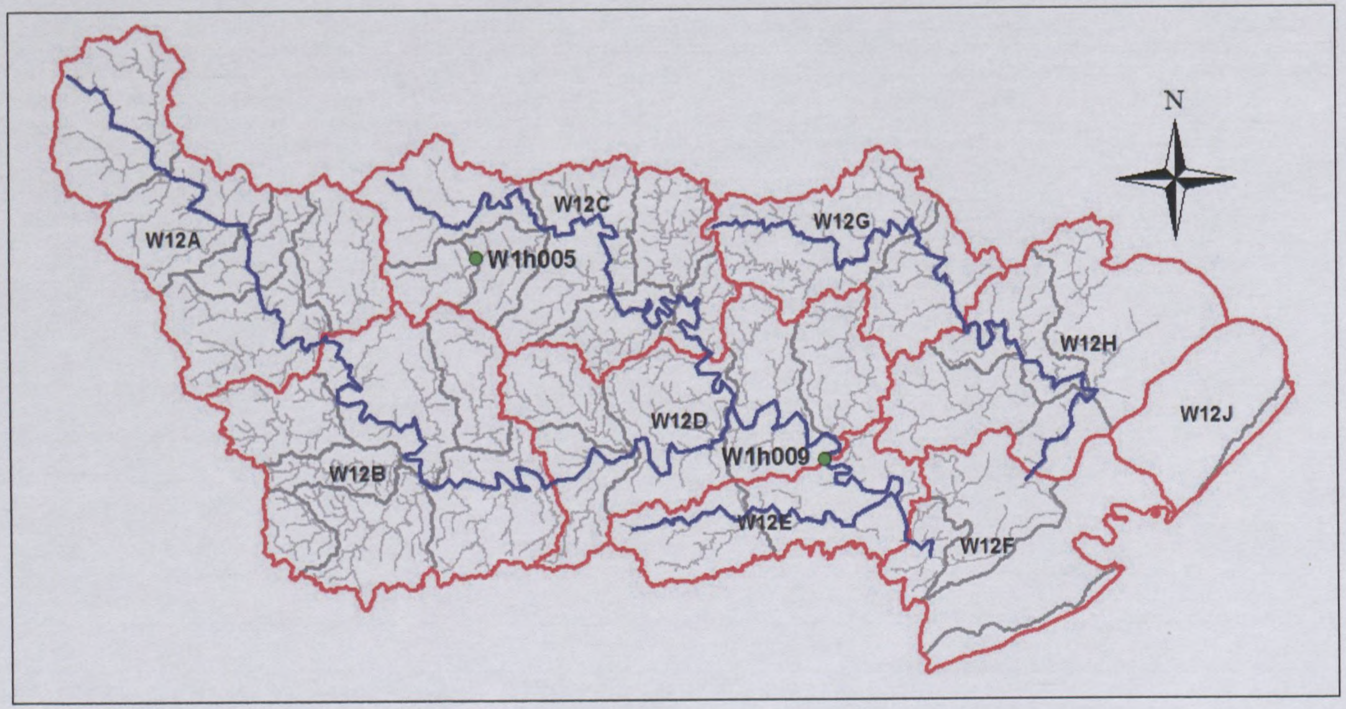


Figure 4-4: Subcatchment Configuration of the Mhlatuze

Input Data:

The input data common to both ACRU and SHELL is shown in **Table 4-5**.

Table 4-5: Input Data for Mhlatuze

Subc	Area (km^2)	MAP (mm)	A-PAN Evaporation (mm)											
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
12A	609.3	876.3	167.3	162.1	190.5	186.3	159.0	151.4	130.2	113.1	98.7	108.6	137.7	154.2
12B	662.6	933.7	169.9	167.9	192.7	190.7	164.5	158.3	129.7	112.0	95.1	104.7	132.1	150.1
12C	570.7	848.1	168.2	167.0	195.4	191.3	163.7	157.4	129.4	112.8	95.9	105.4	133.5	150.7
12D	567.0	847.0	170.3	173.7	200.4	197.0	169.4	164.9	130.9	114.1	94.5	103.4	128.5	145.9
12E	244.3	1048.7	169.5	170.5	198.6	194.5	167.9	165.2	134.6	112.0	89.9	103.7	126.8	141.4
12F	167.0	1247.2	169.7	169.4	201.3	194.9	168.1	167.3	140.6	108.6	82.6	104.0	125.5	138.8
12G	322.1	834.3	171.2	174.5	204.0	199.4	170.4	165.7	132.0	113.8	92.6	103.4	129.6	148.0
12H	484.5	1043.5	169.6	171.0	203.5	197.0	168.8	166.3	135.9	112.0	87.2	103.8	127.0	142.3

4.3 Assembly of Model Information and Coverages

This section describes the sources of modelling information and coverages used in this project. Where possible, information from existing model configurations of the study systems was used. Where this was not available, information was sourced from elsewhere, or reasonable assumptions were made.

In assembling the information, the following points were borne in mind:

- Rainfall is the fundamental driving force and pulsar input behind most hydrological processes. Since it is the most variable hydrological element, an accurate estimate of aerial rainfall is the fundamental input to catchment rainfall-runoff models (Schulze, 1995). It is therefore important that, when the output from two different catchment models is to be compared, every effort be made to ensure that the same rainfall is used for the model configurations.
- As with rainfall, evaporation is important in hydrological processes, especially in Southern Africa where an estimated 91% of MAP is lost as evaporation (Schulze, 1995). It is therefore also important to ensure that the same evaporation is used for different catchment models, if their output is to be compared.
- The terms of reference for this study stated that the most recent IAP information would be used in the model configurations.

4.3.1 Assembly of Model Information and Coverages for the Upper Berg

Most of the modelling information used for the Upper Berg catchment was taken from the Skuifraam Dam Feasibility Study (DWAF, 1997).

4.3.1.1 GIS Coverages

Coverages of subcatchment delineation and land-use from the Skuifraam Study (DWAF, 1997) were adapted to this study; however, the alien vegetation coverages were replaced with updated coverages from the CSIR.

4.3.1.2 Information and Data for ACRU

A new ACRU configuration was set up, based on data and information from the Skuifraam Dam Feasibility Study (DWAF, 1997), however, a large part of the input data required for ACRU is not included in the SHELL-based study, and had to be sourced from elsewhere. This data includes:

- daily rainfall;
- soils information;
- monthly A-pan evaporation; and
- crop parameters.

The sources of this data are described below.

Daily rainfall:
The same rainfall stations, as used for the Skuifraam Study (DWAF, 1997) were used for this study. Patched daily rainfall for the stations was extracted from the CD of Rainfall Databases (Lynch, 2002).

Soils information:
Soils information per pseudo subcatchment required for ACRU was extracted from the CCWR minute-by-minute grid and provided by the ACRU research team.

Monthly A-pan evaporation:
Monthly A-pan evaporation required for ACRU was extracted from the CCWR minute-by-minute grid and provided by the ACRU research team.

Crop parameters:
Crop parameters for most land-uses were obtained from the ACRU database (Smithers and Schulze, 1995), (http://www.beeh.unp.ac.za/acru/), however, parameters for tall shrub species were not included in the database and had to be developed specifically for this study, based on ACRU crop parameters for Acocks vegetation in the Upper Berg, namely macchia and coastal rhenosterveld (Le Maitre, 2002). In developing the tall shrub crop parameters, the Upper Berg Acocks parameters in the ACRU database were assessed and modified to better represent the potential evapotranspiration of these vegetation types.

Changes made to crop parameters of Acocks vegetation in the Upper Berg:
On assessing the Acocks parameters in the ACRU database for macchia and coastal rhenosterveld, it was decided that the seasonal distribution of the parameters was not representative of the seasonal potential evapotranspiration of these plants in the Upper Berg (Le Maitre pers comm., June 2004.). **Table 4-6** shows that some of the original ACRU crop coefficients for Macchia and Rhenosterveld are higher in winter than in summer. These vegetation types are deep-rooted and should have access to sufficient water all year round, therefore their crop coefficients should rather be higher in summer when there is higher evaporative demand, as shown in **Table 4-7**, which shows the crop parameters adopted in this study for Acocks vegetation in the Upper Berg.

Table 4-6: Original Land Cover Input Parameters from the ACRU Database for Upper Berg Acocks Vegetation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Coastal Rhenosterveld	CAY	0.4	0.4	0.4	0.45	0.5	0.5	0.5	0.5	0.5	0.45	0.4	0.4
	VEGINT	0.8	0.8	0.8	1	1.2	1.2	1.2	1.2	1	0.8	0.8	0.8
	ROOTA	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.95	0.954	0.95	0.95
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Macchia	CAY	0.45	0.45	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.55	0.5	0.45
	VEGINT	1	1	1.1	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1	1
	ROOTA	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table 4-7: Revised Land Cover Input Parameters for Upper Berg Acocks Vegetation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Coastal Rhenosterveld	CAY	0.4	0.3	0.4	0.45	0.4	0.4	0.4	0.45	0.55	0.6	0.6	0.5
	VEGINT	0.8	0.8	0.8	1	1.2	1.2	1.2	1.2	1	0.8	0.8	0.8
	ROOTA	0.85	0.8	0.85	0.9	0.9	0.95	0.95	0.98	0.98	0.98	0.98	0.95
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Macchia	CAY	0.55	0.5	0.5	0.5	0.5	0.45	0.4	0.5	0.6	0.65	0.7	0.65
	VEGINT	1	1	1.1	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1	1
	ROOTA	0.7	0.65	0.7	0.75	0.8	0.8	0.8	0.85	0.95	0.95	0.9	0.8
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Development of crop parameters for tall shrubs:

Monthly crop coefficients (CAY) for tall shrubs were developed by scaling up the monthly crop coefficients of macchia by 16,5%. (Le Maitre, 2002). Monthly values of VEGINT were estimated, using the Von Hoynigen-Heune method built into the ACRU Model (Smithers and Schulze, 1995), using a leaf area index of 3.5 (Le Maitre, 2002). Monthly values of ROOTA for tall shrubs were assumed to be the same as for macchia (Le maitre, 2002). The parameters used for tall shrubs in this study are shown in **Table 4-8** below.

Table 4-8: Land Cover Input Parameters for Upper Berg Tall Shrubs

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Tall Shrubs (Hakea)	CAY	0.64	0.58	0.58	0.58	0.58	0.52	0.47	0.58	0.70	0.76	0.82	0.76
	VEGINT*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ROOTA	0.7	0.65	0.7	0.75	0.8	0.8	0.8	0.85	0.95	0.95	0.9	0.8
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

* Estimated using the Von Hoynigen-Heune method in the ACRU Model

4.3.1.3 Information and Data for SHELL

The existing SHELL configuration of the Upper Berg (DWAF, 1997) was adapted for use in this study. Data changes to the configuration were necessary to ensure that the SHELL setup was comparable with the ACRU setup. Affected input data variables included monthly rainfall and monthly S-pan evaporation.

Monthly rainfall:

The monthly rainfall from the Skuifraam Study (DWAF, 1997) was discarded and replaced with monthly sequences of aggregated daily rainfall from the new Berg ACRU configuration.

Monthly evaporation:

The new monthly A-pan evaporation used for the ACRU configuration was converted to S-pan, using the Bosman equation (Midgley *et al*, 1994), and lake evaporation, using A-pan-to-lake factors (Smthers and Schulze, 1995), for use in the SHELL configuration,. The monthly S-pan and lake evaporation from the Skuifraam Study (DWAF, 1997) was discarded.

Problem noted with A-pan evaporation data for the Upper Berg:

In assessing the Upper Berg A-pan data, it was noted that for some subcatchments in the higher reaches of the catchment, the A-pan evaporation for June to August was higher than for April and May, which is unlikely to occur in reality. A comparison was made with A-pan data used in the same area for the Skuifraam Dam Study (DWAF, 1997) and it was found to follow a similar trend, only in this case the A-pan evaporation for June to August was higher than for May and lower than for April. The sample A-pan values are shown in **Table 4-9**. An investigation into the reasons for these apparent discrepancies was considered beyond the scope of this study, which was focussed on relative differences between models and methods. As already highlighted it is, nevertheless important in any hydrological study to use appropriate input data and thus any comparisons between observed and simulated flows in this catchment may have been compromised by these apparent anomalies in evaporation data. It is recommended that following studies should look more closely at this concern.

Table 4-9: Sample of A-pan Data used for this Study and for the Skuifraam Dam Study (DWAF, 1997)

	A-PAN (mm)											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**
Skuifraam Study	86	114	151	163	135	105	57	38	44	43	49	60
Current study	50	71	123	123	105	89	36	39	56	64	64	58

4.3.2 Assembly of Model Information and Coverages for Upper Sabie

The existing ACRU configuration (Pike and Schulze, 2001) and WRSM90 configuration (DWA, 1990) of the Sabie catchment were obtained for this study.

4.3.2.1 GIS Coverages

The same coverages used in setting up the existing ACRU configuration (Pike and Schulze, 2001) were adopted for the current study. These consisted of a subcatchment delineation coverage, rivers and tributaries coverage (Pike and Schulze, 2001), and a land-use coverage extracted from the National Land-Use Coverage (NLC) (Thompson, 1999). A coverage of alien vegetation was obtained from the CSIR.

4.3.2.2 Information and Data for ACRU

The ACRU Model configuration from Pike and Schulze (2001) was used for this study. Information on land cover and land use, including irrigation, was extracted from this existing ACRU model (For details on sources of crop types and areas under irrigation the reader is referred to Pike and Schulze (2001). No changes were made to the assumptions and parameters used in the model; however, scenarios of alien vegetation coverage, which are necessary for this study, were not included in the previous study. Crop parameters for alien vegetation had to be chosen for this study.

Crop parameters:
Crop parameters for tall and medium tree species were obtained from the ACRU database (Smithers and Schulze, 1995), (http://www.beeh.unp.ac.za/acru/). Parameters for tall shrub species were not included in the ACRU database. These parameters were obtained from Hayes (2003).

4.3.2.3 Information and Data for SHELL

The WRSM90 configuration of the Sabie catchment (DWA, 1990) was used as the basis for the current SHELL configuration. The subcatchment delineation and starting Pitman parameters for the current SHELL configuration were taken from the WRSM90 configuration; however, the rainfall, evaporation and, as far as possible, the land-use information from the ACRU configuration of the Sabie (Pike and Schulze, 2001) was used in place of the rainfall, evaporation and land-use information from the WRSM90 configuration. The Pitman Model was then recalibrated with the new modelling information. Affected input data variables included monthly rainfall; and monthly S-pan evaporation.

Monthly rainfall:
The monthly rainfall from the WRSM90 configuration of the Sabie (DWA, 1990) was discarded and replaced with monthly sequences of aggregated daily rainfall used for the Berg ACRU configuration.

Monthly evaporation:
The mean monthly A-pan evaporation used for the ACRU configuration was converted to S-pan, using the Bosman equation (Midgley *et al*, 1994), and lake evaporation, using A-pan-to-lake factors (Smthers and Schulze, 1995), for use in the SHELL configuration. The monthly S-pan and lake evaporation from the previous study (DWA, 1990) was discarded.

4.3.3 Assembly of Model Information and Coverages for Mhlatuze

There was an existing ACRU configuration (Kevin Meier, Land Resources International, pers com, 2002) and WRSM90 configuration (DWAF, 2003) of the Mhlatuze catchment, and these were obtained for this study.

4.3.3.1 GIS Coverages

The same coverages, used in setting up the existing ACRU configuration, were adopted for the current study. These consisted of a subcatchment delineation coverage (Kevin Meier, Land Resources International, pers com, 2002) and a land-use coverage extracted from the NLC (Thompson, 1999). A 1:50 000 rivers and tributaries coverage was obtained from DWAF. The DWAF coverage was layered according to stream order, and this presented the opportunity to test the effect of stream order on the riparian analysis; however, due to resource constraints, an ACRU and SHELL configuration were set up only for tributary orders greater than 2. On this coverage, stream order increases with the size of tributary.

4.3.3.2 Information and Data for ACRU

The ACRU Model configuration obtained from Land Resources International was used for this study. No changes were made to the assumptions and parameters used in the model; however, scenarios with alien vegetation, which are necessary for this study, were not included in the previous study. Crop parameters for alien vegetation had to be chosen for this study. (For details on irrigation, crop types and areas under irrigation, the reader is referred to Land Resources International.)

Crop parameters:
Crop parameters for tall and medium tree species were obtained from the ACRU database (Smithers and Schulze, 1995*)*. Parameters for tall shrub species were not included in the ACRU database. These were obtained from Hayes (2003).

4.3.3.3 Information and Data for SHELL

The WRSM90 configuration of the Mhlatuze catchment (DWAF, 2003) was used as the basis for the current SHELL configuration. The subcatchment delineation and starting Pitman parameters were taken from the WRSM90 configuration, however, the rainfall and evaporation from the ACRU configuration of the Mhlatuze (DWAF, 2003) was used. As far as possible, the land-use from the ACRU configuration was used for the SHELL configuration. The Pitman Model was then recalibrated with the new modelling information.

Monthly rainfall:
The daily rainfall from the ACRU configuration was aggregated to provide a monthly rainfall sequence for SHELL. The data from the rainfall stations in the ACRU subcatchments, making up the larger SHELL subcatchment, was averaged, using CATCHRN (DWAF, 1997) to form one rainfall sequence for each SHELL subcatchment.

Monthly evaporation:
The A-pan evaporation from the ACRU configuration was used for the SHELL configuration and converted to S-pan and lake evaporation, as required, using the Bosman equation (Midgley *et al*, 1994) and A-pan-to-Lake factors (Smithers and Schulze, 1995).

4.4 Configuration of Catchment Models

This section describes the important processes involved in configuring the catchment models for each of the study systems.

4.4.1 Configuration of Catchment Models for the Upper Berg

Setting up the catchment models for the Upper Berg consisted of configuring the ACRU Model from the beginning and adapting the existing SHELL configuration (DWAF, 1997) to this study.

4.4.1.1 ACRU Model Configuration of the Upper Berg

The following processes included in configuring ACRU for the Upper Berg catchment, are described in this section:

- Subcatchment configuration;
- Preparation of daily rainfall; and
- Modifying of plant rooting depths.

Subcatchment configuration:

The existing SHELL subcatchment configuration for the Upper Berg (DWAF, 1997) was adopted and adapted for the ACRU configuration in the following steps:

i) Division to meet the scale requirements of ACRU.
ii) Division into riparian and upland areas.
iii) Division according to land-use.
iv) Lumping of farm dams and farm dam catchments.

These steps are described below.

i) Division to meet the scale requirements of ACRU:

Since ACRU supports a finer subcatchment delineation than SHELL, and one of the aims of this project is to investigate the effects of scale on modelled results, the subcatchments from the existing SHELL configuration were further divided to form a finer ACRU configuration. The existing subcatchments were divided along:

- physiographic boundaries; and
- MAP boundaries.

MAP boundaries were set at 1 150 and 2 200 mm, respectively (for a range of MAPs from 500 to 3 300 mm). In areas where the MAP gradient is steep, as in the upper reaches of the catchment, subcatchment boundary lines were drawn across the watershed, following the MAP boundary, to avoid the incidence of very small subcatchments. Care was taken that the total area contributing to the observed flow gauges remained unchanged.

ii) Division into riparian and upland areas:

In each new subcatchment, a 30 m wide strip was delineated on either side of the river centre line to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its own riparian subcatchment, while runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

iii) Division according to land-use:

The new subcatchments were further divided according to land-use, to form "pseudo subcatchments" (Pike and Schulze, 2001). Each "pseudo subcatchment" represents a major land-use or land cover in its parent subcatchment.

iv) Lumping of farm dams and farm dam catchments:

Farm dams in a subcatchment were represented as a lumped dam sited at the outlet of that point of the subcatchment representing the area upstream of farm dams.

Figure 4-2 shows the new subcatchment configuration. The bold boundaries in the figure are the catchment boundaries from the Skuifraam Study.

Preparation of daily rainfall:

The same rainfall stations used for the SHELL Model configuration of the Upper Berg (DWAF, 1997) were selected for use in the ACRU Model. The rainfall stations were assigned to the ACRU subcatchments, using the CalcPPTCor utility (Pike and Schulze, 2001), which assists in selecting the most representative rainfall station, and calculates monthly rainfall adjustment factors required by ACRU, for each subcatchment. Patched, daily rainfall data for the selected stations was extracted from the CD of Rainfall Databases (Lynch, 2002).

Problems encountered with the CalcPPtCor utility:

The CalcPPtCor utility produced underestimates of rainfall for the mountainous subcatchments in the upper reaches of the Upper Berg, namely the subcatchments upstream of flow gauges G1H038, G1H004 and G1H019. This was discerned from the extremely low streamflow simulated at these flow gauges. The underestimating of rainfall may be explained as follows:

CalcPPTCor calculates the monthly rainfall adjustment factors based on the monthly median rainfall minute by minute grids, by comparing the median monthly rainfall for each subcatchment with the median monthly rainfall at the location of the selected rain station for the subcatchment. For two of the rainfall stations, rainfall from the grid was overestimated, leading to an underestimation of the monthly adjustment factors. This is shown in **Equations 4-1** and **4-2,** and in **Table 4-10**. The equations show how the adjustment factor is calculated and the table shows how the station rainfall calculated from the grids is overestimated, compared to the measured station rainfall (from the CCWR database).

Subcatchment rainfall = adjustment factor * station rainfall .... **Equation 4-1**

Adjustment factor = subcatchment median rainfall / station median rainfall....
....**Equation 4-2**

Table 4-10: Comparison of Actual Station MAP from CCWR Database and Station MAP from Monthly MAP Grid

Rain Station	MAP mm (CCWR)	MAP mm (CalcPPTCor, from MAP Grid)
0021838W	1152	2107
0022029W	2159	3306

The rainfall problem was dealt with by substituting the problem rain stations with the highest MAP rain station in the group of stations selected for the Upper Berg, 0022116W (MAP = 1 834 mm), and manually calculating the monthly adjustment factors using **Equations 4-1** and **4-2**. The highest MAP station was selected, because the affected subcatchments lie in the highest rainfall areas of the catchment.

Modifying of plant rooting depths for fynbos:

Fynbos in the Western Cape is deep-rooted. Evidence of this is the general lack of signs of stress during dry periods (Le Maitre, pers. com, 2004.). To reflect this, a further 0.25 m was added to the rooting depth of fynbos.

4.4.1.2 SHELL Model Configuration of the Upper Berg

Changes were made to the existing SHELL configuration (DWAF, 1997) to tailor it to the requirements of this study. Changes were made to subcatchment configuration, monthly rainfall and monthly evaporation.

Subcatchment configuration:

The existing subcatchment configuration from DWAF (1997) was used for this study. The only change made to the configuration was the separation of riparian and upland land-use as described below.

Division into riparian and upland areas:
A 30 m wide strip was delineated on either side of the river centre line to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its companion riparian subcatchment, and runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

Preparation of monthly rainfall:
It was important to use the same rainfall for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the rainfall from the former SHELL configuration (DWAF, 1997) was replaced with the rainfall used for the ACRU configuration. The daily ACRU rainfall was aggregated to form monthly rainfall for SHELL. The data from the rainfall stations in the ACRU subcatchments, making up the larger SHELL subcatchment, was averaged, using CATCHRN (DWAF, 1997) to form one rainfall sequence for the SHELL subcatchment.

Preparation of mean monthly evaporation:
As with rainfall, it was important to use the same evaporation for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the evaporation from the former SHELL configuration (DWAF 1997) was replaced with the evaporation used for the ACRU configuration. The ACRU mean monthly A-pan evaporation was converted to the S-pan evaporation and lake evaporation required by the Pitman Model, using Bosman's equation (Midgley *et al*, 1994) and A-pan to lake factors (Smithers and Schulze, 1995), respectively. The evaporation values from the ACRU subcatchments, making up the larger SHELL subcatchment, were area-weighted to form one set of evaporation values for the SHELL subcatchment.

4.4.2 Configuration of Catchment Models for the Upper Sabie

Configuration of catchment models for the Upper Sabie consisted of adapting the existing ACRU (Pike and Schulze, 2001) and WRSM90 (DWA, 1990) configurations to this study.

4.4.2.1 ACRU Model Configuration of the Upper Sabie

The only change made to the existing ACRU configuration (Pike and Schulze, 2001), was the separation of riparian and upland areas in the subcatchment configuration. This is described below.

Subcatchment configuration:

The existing subcatchment configuration (Pike and Schulze, 2001) was adapted to this study by dividing the subcatchments into upland and riparian areas. The subcatchment configuration used in this study is shown in **Figure 4-3.**

Division into riparian and upland areas:

In each existing subcatchment, a 30 m wide strip was delineated on either side of the river centre line, to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its riparian subcatchment, and runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

4.4.2.2 SHELL Model Configuration of the Upper Sabie

The existing WRSM90 configuration (DWA, 1990) was used as the basis for the SHELL configuration for this study. Changes were made to the data and information in the existing configuration to meet the requirements of this study. Changes were made to subcatchment configuration, monthly rainfall, monthly evaporation and land cover and land-use information.

Subcatchment configuration:

The existing subcatchment configuration from DWA, 1990 was used for this study. The only change made to the configuration was the separation of riparian and upland land-use as described below.

Division into riparian and upland areas

A 30 m wide strip was delineated on either side of the river centre line, to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its companion riparian subcatchment, and runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

Preparation of monthly rainfall:

It was important to use the same rainfall for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the rainfall from the former WRSM90 configuration (DWAF, 1997) was replaced with the rainfall used for the ACRU configuration. The daily ACRU rainfall was aggregated to form monthly rainfall for SHELL. The data from the rainfall stations in the ACRU subcatchments, making up the larger SHELL subcatchment, was averaged, using CATCHRN (DWAF, 1997) to form one rainfall sequence for the SHELL subcatchment.

Preparation of mean monthly evaporation:

As with rainfall, it was important to use the same evaporation for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the evaporation from the former WRSM90 configuration (DWA, 1990) was replaced with the evaporation used for the ACRU configuration. The mean monthly ACRU A-pan evaporation was converted to the S-pan evaporation and lake evaporation required by the Pitman Model, using Bosman's equation (Midgley *et al*, 1994*)* and A-pan to lake factors (Smithers and Schulze, 1995), respectively. The evaporation values from the ACRU subcatchments, making up the larger SHELL subcatchment, were area-weighted to form one set of evaporation values for the SHELL subcatchment.

Changes to land-use information:

Land-use information in the ACRU subcatchments, contained in the larger SHELL subcatchments, was lumped to form information for the SHELL subcatchments, to ensure that the output from the models were comparable.

4.4.3 Configuration of Catchment Models for the Mhlatuze

Configuration of catchment models for the Mhlatuze consisted of adapting the existing ACRU and WRSM90 (DWAF, 2003) configurations to this study.

4.4.3.1 ACRU Model Configuration of the Mhlatuze

The only change made to the existing ACRU configuration was the separation of riparian and upland areas in the subcatchment configuration. This is described below. The subcatchment configuration is shown in **Figure 4-4**.

Subcatchment configuration:

The existing subcatchment configuration was adapted to this study by dividing the subcatchments into upland and riparian areas.

Division into riparian and upland areas

In each existing subcatchment, a 30 m wide strip was delineated on either side of the river centre line, to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its own riparian subcatchment, and runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

4.4.3.2 SHELL Model Configuration of the Mhlatuze

The existing WRSM90 configuration (DWAF, 2003) was used as the basis for the SHELL configuration for this study. Changes were made to the data and information in the existing configuration to meet the requirements of this study. Changes were made to subcatchment configuration, monthly rainfall, monthly evaporation and land cover and land-use information.

Subcatchment configuration:

The existing subcatchment configuration from DWA (1990) was used for this study. The only change made to the configuration was the separation of riparian and upland land-use as described below.

Division into riparian and upland areas

A 30 m wide strip was delineated on either side of the river centre line, to represent 60 m wide riparian subcatchments (Scott and Smith, 1997). Runoff from each upland subcatchment flows into its companion riparian subcatchment, and runoff from each riparian subcatchment flows into the riparian subcatchment downstream of it.

Preparation of monthly rainfall:

It was important to use the same rainfall for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the rainfall from the former WRSM90 configuration (DWAF, 1997) was replaced with the rainfall used for the ACRU configuration. The daily ACRU rainfall was aggregated to form monthly rainfall for SHELL. The data from the rainfall stations in the ACRU subcatchments, making up the larger SHELL subcatchment, was averaged, using CATCHRN (DWAF, 1997) to form one rainfall sequence for the SHELL subcatchment.

Preparation of monthly evaporation:

As with rainfall, it was important to use the same evaporation for the ACRU and SHELL configurations, so that the model output could be comparable. To this end, the evaporation from the former WRSM90 configuration (DWA, 1990) was replaced with the evaporation used for the ACRU configuration. The mean monthly ACRU A-pan evaporation was converted to the S-pan evaporation and lake evaporation required by the Pitman Model, using Bosman's equation (Midgley *et al*, 1994) and A-pan to lake factors (Smithers and Schulze, 1995), respectively. The evaporation values from the ACRU subcatchments, making up the larger SHELL subcatchment, were area-weighted to form one set of evaporation values for the SHELL subcatchment.

Changes to land-use information:

Land-use information in the ACRU subcatchments, contained in the larger SHELL subcatchments, was lumped to form information for the SHELL subcatchments, to ensure that the output from the models was comparable.

4.4.4 Problems Encountered in Matching Rainfall Input for ACRU and SHELL

Since rainfall is the most important input into hydrological models, it was important that ACRU and SHELL used the same rainfall input, so that their output could be compared. Due to the different methods of processing rainfall used by the two models, the actual rainfall finally used in the model calculations can be very different.

4.4.4.1 Method used for Processing ACRU Rainfall

As described in **Section 4.4.1.1**, rainfall for ACRU is prepared by determining a correction factor for each subcatchment for each month and adjusting the rainfall input of the subcatchment's driver station by this factor. The factor is determined as the ratio between the median monthly grid rainfall at the location of the rain station and the median monthly grid rainfall of the whole subcatchment.

4.4.4.2 Method used for Processing SHELL Rainfall

A number of representative rain stations are selected to make up the rainfall of each SHELL subcatchment. The data for each selected rain station (each monthly data value) is expressed as a percentage of the MAP of the rain station data. The percentage rainfall sequences of the selected rain stations are then averaged to form one average percentage rainfall sequence for the subcatchment. The subcatchment rainfall is determined by applying the percentages to the MAP of the subcatchment.

4.4.4.3 Comparison of Rainfall Produced for Use in ACRU and SHELL

The actual rainfall used in the models, once the rainfall input had been processed, using the different methods for each model, is shown in **Table 4-11** to **Table 4-14**.

Table 4-11 shows that, the MAP used for SHELL and ACRU, is similar for the Upper Berg. The closeness of rainfall between the two models is also influenced by the modifications to the stations selected by CalcPPTcor, as explained in **Section 4.4.1.1**, which increased the MAP of the high MAP subcatchments in ACRU. If these changes had not been made, the ACRU MAP values would have been much lower.

Table 4-12 shows that, though the same rain stations were input for the ACRU and SHELL Models of the Upper Sabie, the resulting rainfall, after the different processing methods were applied, is very different. In this case, for the purposes of the objectives of this study, the MAP of the SHELL subcatchments was adjusted to equal that of the ACRU subcatchments and the result of this can be seen in **Table** 4-13.

Table 4-14 shows that matching rainfall for ACRU and SHELL is not a problem for the Mhlatuze.

From this exercise, it appears that ACRU rainfall processing methods produce rainfall which is lower than that produced by SHELL methods. An explanation of this could be that the rainfall grid used for calculating rainfall correction factors for ACRU does not capture the large variation in MAP between the mountainous areas in the Upper Berg and the escarpment areas in the Upper Sabie and the lower lying areas. These variations do not occur in the Mhlatuze.

Table 4-11: Comparison of Model-Processed Rainfall for ACRU and SHELL for the Upper Berg

BERG	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
subc	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)
G1H003	1 018	1 011	-1	219	217	-1	86	85	-2
G1H004a	2 807	2 764	-2	557	546	-2	216	215	-1
G1H004b	2 354	2 227	-5	467	423	-9	181	174	-4
G1H019	1 753	1 633	-7	315	300	-4	129	120	-6
G1H020A	1 565	1 410	-10	328	266	-19	120	114	-5
G1H020B	1 162	1 112	-4	244	229	-6	89	85	-5
G1H020C	897	889	-1	188	182	-3	69	70	1
G1H038	2 535	2 368	-7	456	449	-2	198	181	-8
G1R002	1 381	1 311	-5	291	280	-4	105	103	-2

Table 4-12: Comparison of Model-Processed Rainfall for ACRU and SHELL for the Upper Sabie Initial Model Run

SABIE Superceded	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
subc	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)
1	1 349	721	-47	416	224	-46	136	74	-45
2	1 229	816	-34	379	256	-32	124	84	-33
3	1 161	772	-34	358	240	-33	117	79	-32
8	1 482	1 481	0	330	333	1	126	127	1
9	1 256	898	-29	387	278	-28	127	92	-28
10	1 387	1 326	-4	366	353	-4	123	118	-4
11	1 238	703	-43	381	217	-43	125	71	-43
12	1 110	749	-33	342	232	-32	112	77	-31
13	1 091	922	-15	413	350	-15	114	97	-15

SABIE Superceded	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
subc	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)
19	991	846	-15	321	264	-18	97	83	-14
20	945	769	-19	291	237	-18	95	78	-18
21	969	994	3	282	277	-2	89	90	2
22	877	1 358	55	240	351	46	79	117	47
23	868	736	-15	267	225	-16	88	74	-16
30	640	705	10	208	219	5	62	71	13
31	723	783	8	273	297	9	75	82	9
32	753	1 233	64	190	311	64	66	110	67

Table 4-13: Comparison of Model-Processed Rainfall for ACRU and SHELL for the Upper Sabie Final Runs

SABIE Final	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
subc	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)
1	695	721	4	214	224	5	70	74	6
2	811	816	1	250	256	2	82	84	2
3	753	772	2	232	240	4	76	79	4
8	1482	1 481	0	330	333	1	126	127	1
9	890	898	1	274	278	1	90	92	2
10	1 311	1 326	1	346	353	2	116	118	2
11	706	703	-1	218	217	0	71	71	-1
12	720	749	4	222	232	5	73	77	6
13	913	922	1	345	350	1	95	97	2
19	878	846	-4	285	264	-7	86	83	-3
20	796	769	-3	245	237	-3	80	78	-3
21	1 009	994	-2	294	277	-6	92	90	-2

SABIE									
Final	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
22	1 364	1 358	0	373	351	-6	124	117	-6
23	732	736	1	226	225	0	74	74	0
30	683	705	3	221	219	-1	66	71	6
31	767	783	2	290	297	3	80	82	3
32	1 179	1 233	5	297	311	5	103	110	7

Table 4-14: Comparison of Model-Processed Rainfall for ACRU and SHELL for Mhlatuze

MHLATUZE	MAP mm			ST DEVIATION (annually)			ST DEVIATION (monthly)		
subc	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)	SHELL	ACRU	% difference (ACRU from SHELL)
W12A	900	879	-2	175	173	-1	66	65	-1
W12B	976	984	1	201	222	10	70	70	0
W12C	898	860	-4	227	215	-5	66	67	1
W12D	838	852	2	263	264	0	70	71	2
W12E	1 068	1 090	2	328	330	1	84	86	2
W12F	1 317	1 238	-6	411	337	-18	107	86	-20
W12G	863	814	-6	269	278	3	72	70	-3
W12H	1 070	1 049	-2	309	324	5	80	85	6

5 ADDRESSING SCALE AND RESOLUTION ASPECTS, AS WELL AS BIO-CLIMATIC VARIATION, RELATED TO STREAMFLOW REDUCTION ESTIMATION: UPGRADING, RECONCILIATION AND INTEGRATION

5.1 Introduction

The objective of this section is to compare and reconcile the differences in SFR produced by two different models, ACRU and SHELL, for three bio-climatic regions in South Africa. Although the same inputs, as far as possible, were used for the two models, for each catchment configured, the inherent differences in the models led to differences in output. This chapter describes these differences in output and attempts to account for them in terms of the differences in the models and the differences in model performance across bio-climatic regions.

The reader is reminded that the configured models reflect the water use and land-use conditions in the respective catchments.

5.2 Results of SHELL Calibration and ACRU Verification

In the sub-sections below, the outcome of the calibration and verification in each study area is compared for selected flow gauges. It should be noted that for the calibration of SHELL, missing observed monthly values were patched with simulated values, and incomplete observed monthly values were patched with simulated values when the simulated values exceeded the incomplete observed values. This leads to apparently good model fits when a large proportion of unreliable observed flow data is used for calibration. Missing observed flow values have a less significant effect on simulated flow in the case of ACRU, since observed flow is used only as a verification of model performance and for sensitivity testing of variables affecting streamflow (Smithers and Schulze, 1995). For each study system, SHELL was calibrated and ACRU was verified for the same 10 year period.

5.2.1 Upper Berg

The results of the calibration of SHELL and verification of ACRU were compared at flow gauging station G1H020, at the flow exit point of the study catchment.

Figure 5-1 presents comparisons between simulated and observed flow for the Upper Berg at flow gauging station G1H020. **Figure 5-2** presents cumulative exceedence frequency plots of the flows. **Figure 5-3** presents seasonality plots of the flows. **Table 5-1** presents a comparison of statistics for the simulated and observed flows for the last 10 years of the simulation.

On average, flows at this point in the catchment are over-simulated by SHELL, however, it must be noted that **Figure 5-1** shows the result of a cumulative simulation, whereas the SHELL configuration was calibrated incrementally at a number of flow gauging stations within the catchment, with varying levels of fit to the observed data.

On average, the ACRU simulation produces lower wet month values than the observed flow, as illustrated in **Figure 5-1**, which might indicate that the rainfall used is too low or the soils are too deep. On average low flows are over-simulated by ACRU at this point in the catchment. The anomalously high wet season A-pan values in the average monthly A-pan data of some of the subcatchments (as described in **Section 4.3.1.3**) may contribute to the under-simulation of wet season flows.

From **Figure 5-3** it can be concluded that ACRU and SHELL both achieve reasonable average seasonal correspondence of high and low flows with the observed data.

Table 5-1: Results of SHELL Calibration and ACRU Verification for the Upper Berg

GAUGE	MAR						STANDARD DEVIATION				
	+PATCHED OBS	*OBS	ACRU	SHELL	%DIFF (ACRU - *OBS)	%DIFF (SHELL - *OBS)	*OBS	ACRU	SHELL	%DIFF (ACRU - *OBS)	%DIFF (SHELL - *OBS)
	(mm)	(mm)	(mm)	(mm)	(%)	(%)	(mm)	(mm)	(mm)	(%)	(%)
G1H020	637	595	638	695	7	17	136	104	129	-24	-5

* unpatched observed flow data

+ patched with simulated SHELL values

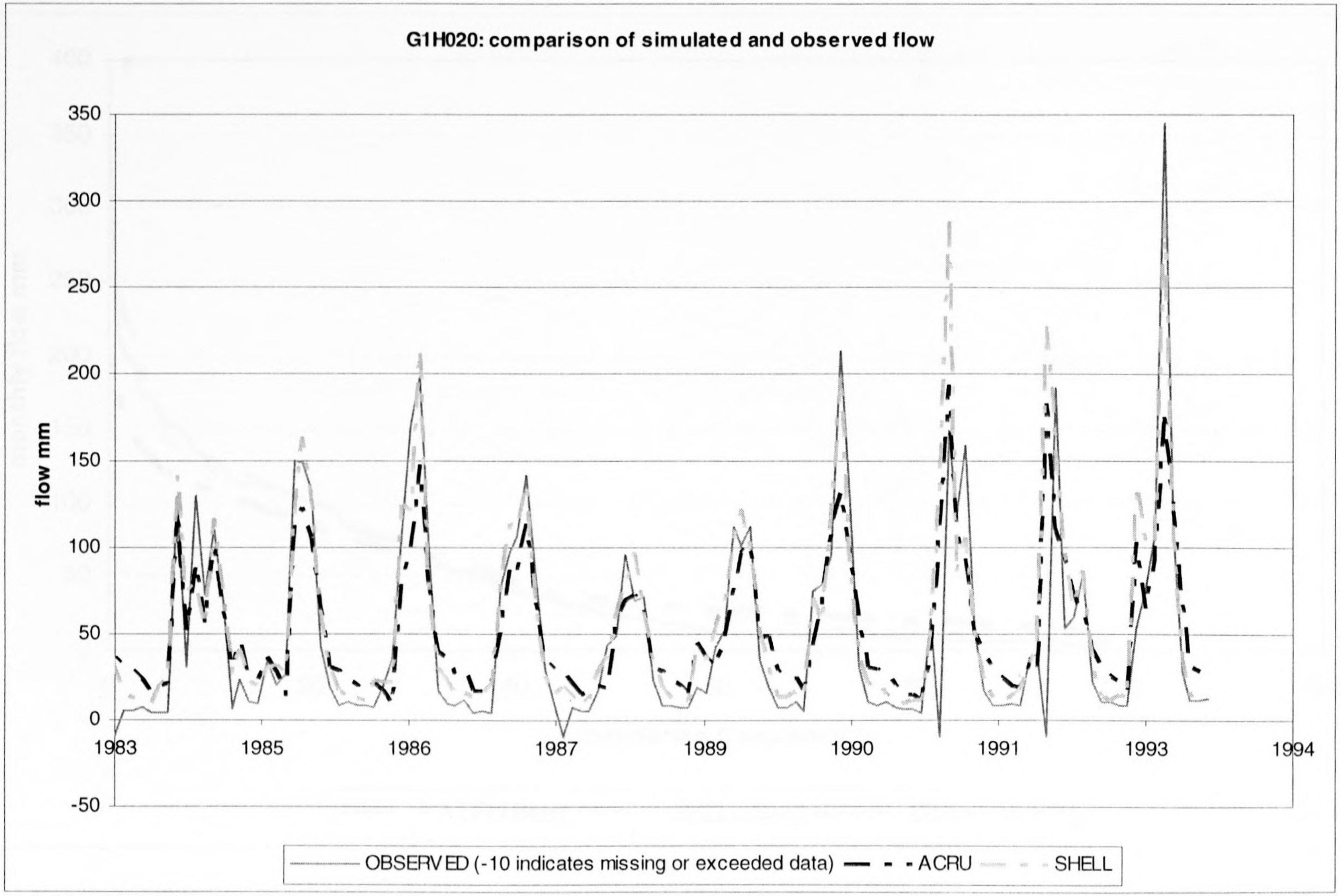


Figure 5-1: Monthly Observed and Simulated Flow for SHELL and ACRU at Gauge G1H020 in the Upper Berg

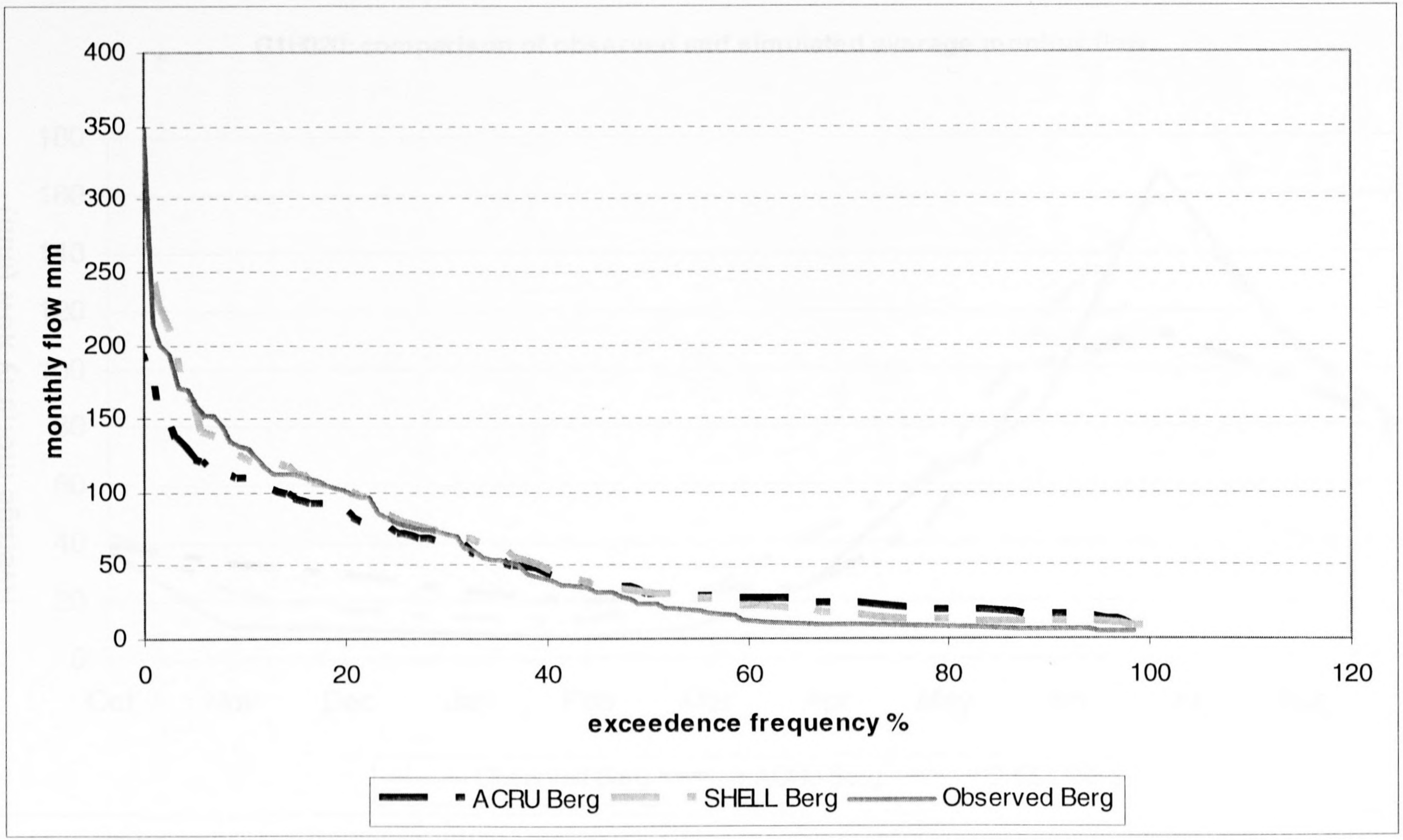


Figure 5-2: Cumulative Exceedence Frequency Plot of Monthly Observed and Simulated Flows from SHELL and ACRU at Gauge G1H020 in the Upper Berg

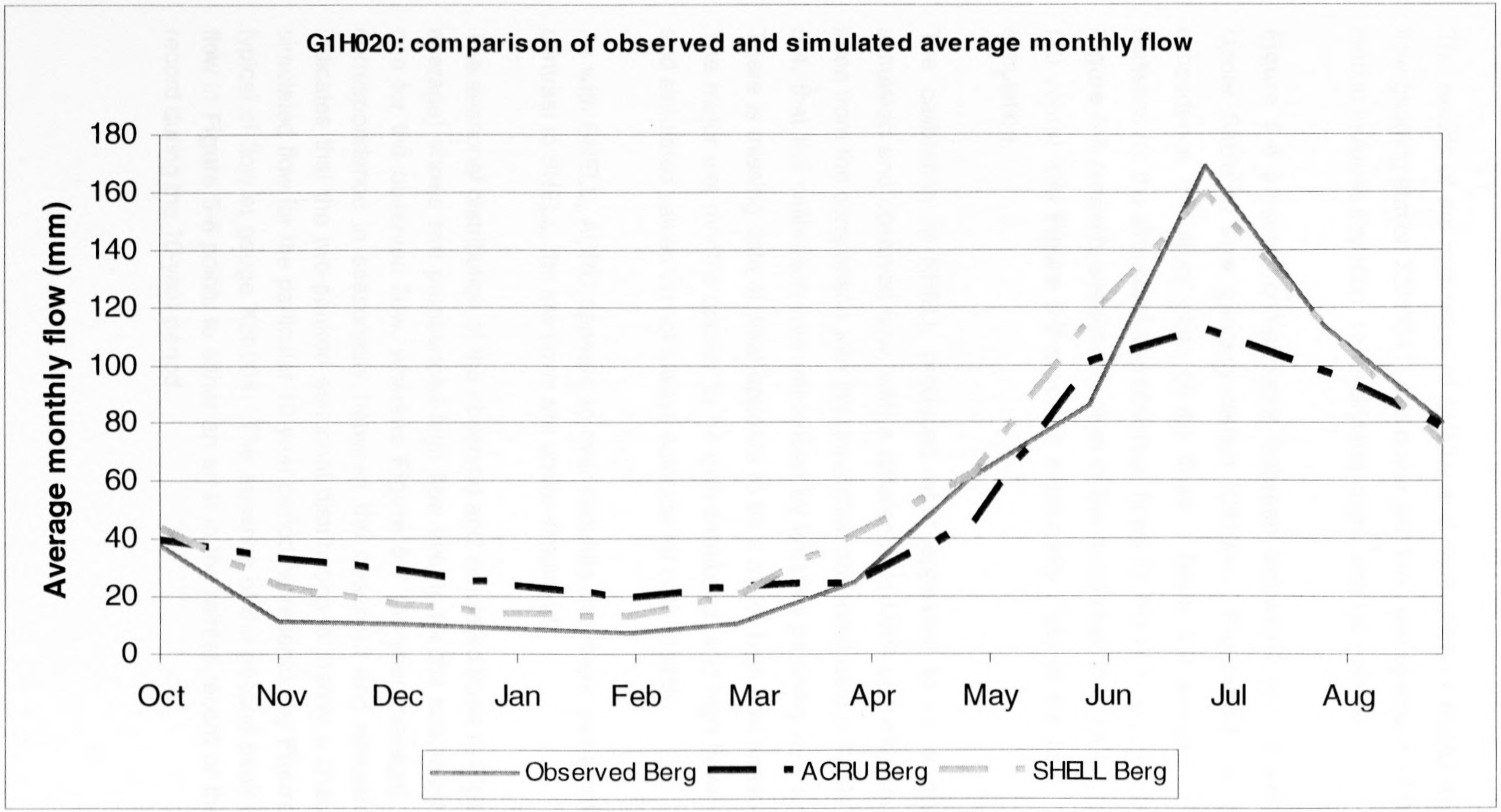


Figure 5-3: Average Monthly Plot of Observed and Simulated Flows from SHELL and ACRU at Gauge G1H020 in the Upper Berg

5.2.2 Upper Sabie

The results of the calibration of SHELL and verification of ACRU were compared at flow gauging station X3H004. Land cover and land use upstream of this flow gauging station includes irrigation, some dryland crops, and plantations.

Figure 5-4 presents comparisons between simulated and observed flow for the Upper Sabie at flow gauging station X3H004. **Figure 5-5** presents cumulative exceedence frequency plots of the flows. **Table 5-2** presents a comparison of statistics for the simulated and observed flows for the last 10 years of the simulation. **Figure 5-6** presents seasonality plots of the flows over the SHELL calibration period (10 years) and **Figure 5-7** presents seasonality plots of the flows for a forty year simulation.

The calibration of SHELL produced what appeared to be a good fit between simulated and observed flow, with a difference in MAR of 2.4%, however, it can be seen from the comparison with the unpatched observed data in **Table 5-2** and **Figure 5-4**, that the calibration was influenced by iterative patching with simulated values. There is missing data at what appears to be a major high flow season in 1995/1996. The major wet months appear to be over-simulated, and high flows in the modelled and simulated values do not always coincide for both models.

As with SHELL, ACRU appears to over-simulate the major wet months, however, in contrast to SHELL, the low flows are under-simulated.

The seasonal distribution of the observed and simulated flows in **Figure 5-6** (10 year average) shows two pronounced high flow events for the simulated flows and only one for the observed flow, whereas **Figure 5-7** (40-year average) shows a better correspondence in seasonality between the observed and simulated flows. This indicates that the two-peaked seasonal distribution is merely a characteristic of the simulated flow for the particular 10-year period represented by **Figure 5-6**, and is not typical of flow at gauge X3h004. The absence of the second peak in the observed flow in **Figure 5-6** points to either an error in the rainfall record or the observed flow record during the 10-year period.

Table 5-2: Results of SHELL Calibration and ACRU Verification for the Upper Sabie

GAUGE	MAR					STANDARD DEVIATION					
	+PATCHED OBS	*OBS	ACRU	SHELL	%DIFF (ACRU - OBS)	%DIFF (SHELL - OBS)	*OBS	ACRU	SHELL	%DIFF (ACRU - OBS)	%DIFF (SHELL - OBS)
	(mm)	(mm)	(mm)	(mm)	(%)	(%)	(mm)	(mm)	(mm)	(%)	(%)
X3H004	85	61	100	83	63	35	48	100	88	106	82

* unpatched observed flow data

\+ patched with simulated SHELL values

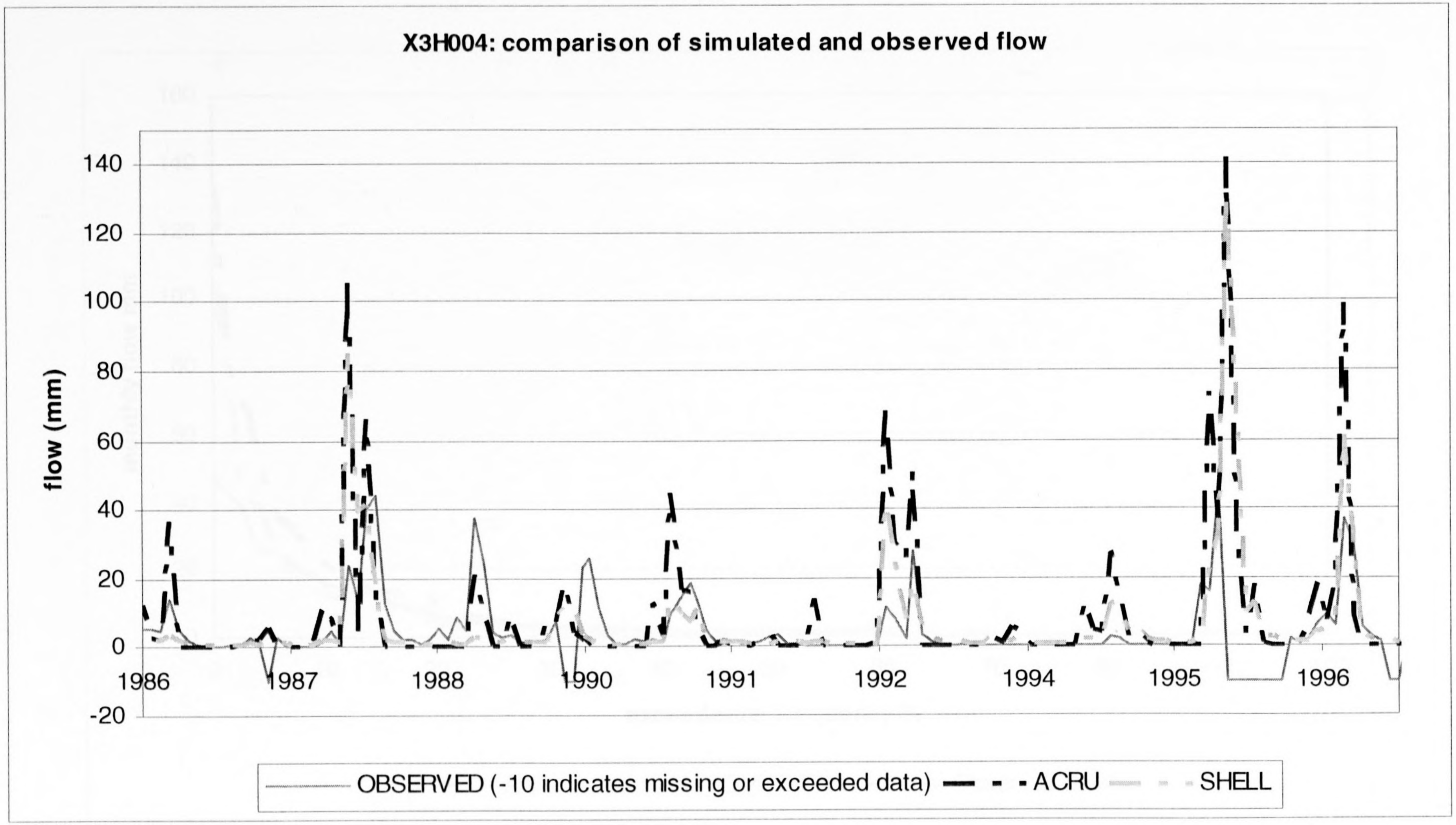


Figure 5-4: Monthly Observed and Simulated Flow for SHELL and ACRU at Gauge X3H004 in Upper Sabie

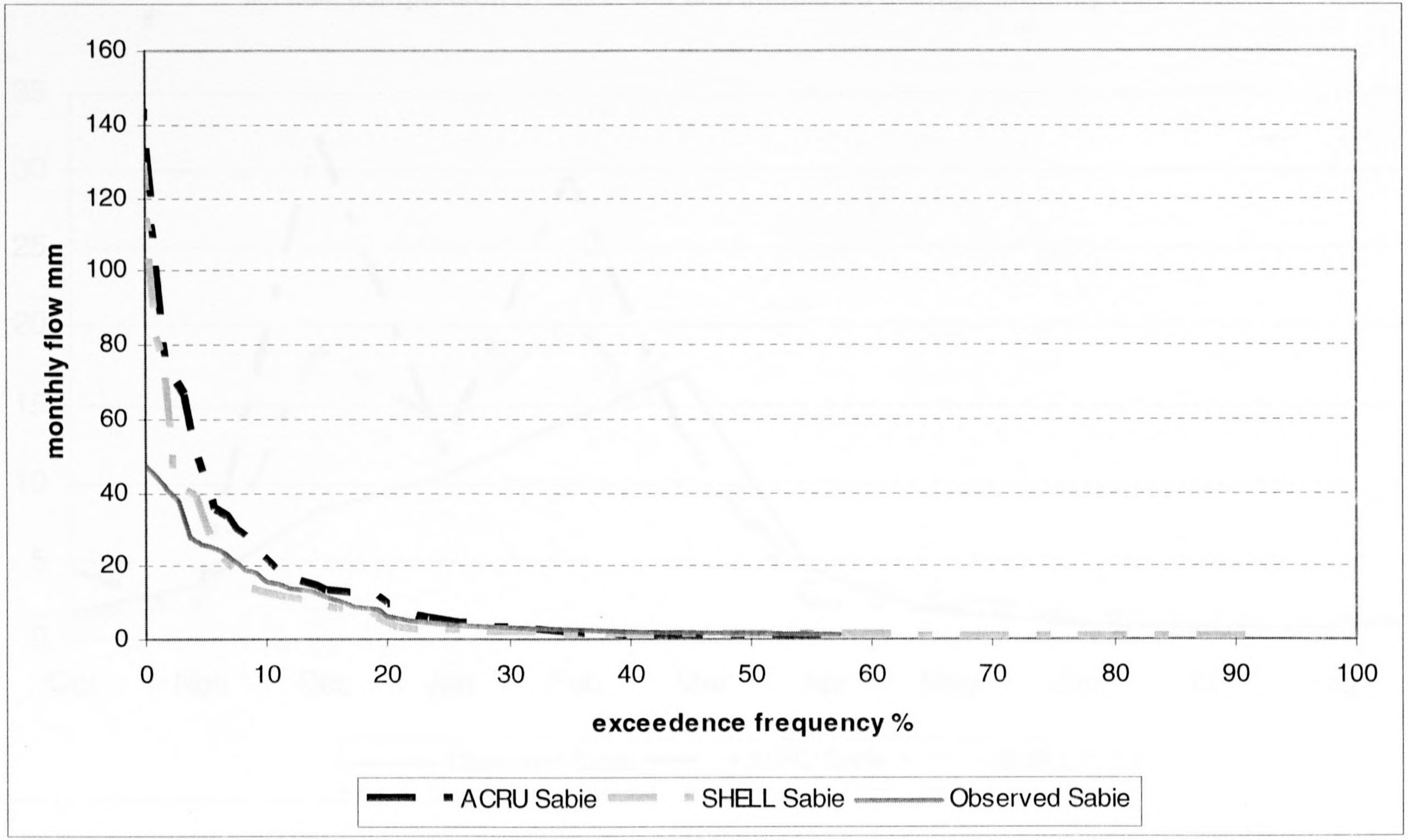


Figure 5-5: Cumulative Exceedence Frequency Plot of Monthly Observed and Simulated Flows from SHELL and ACRU at Gauge X3H004 in the Upper Sabie

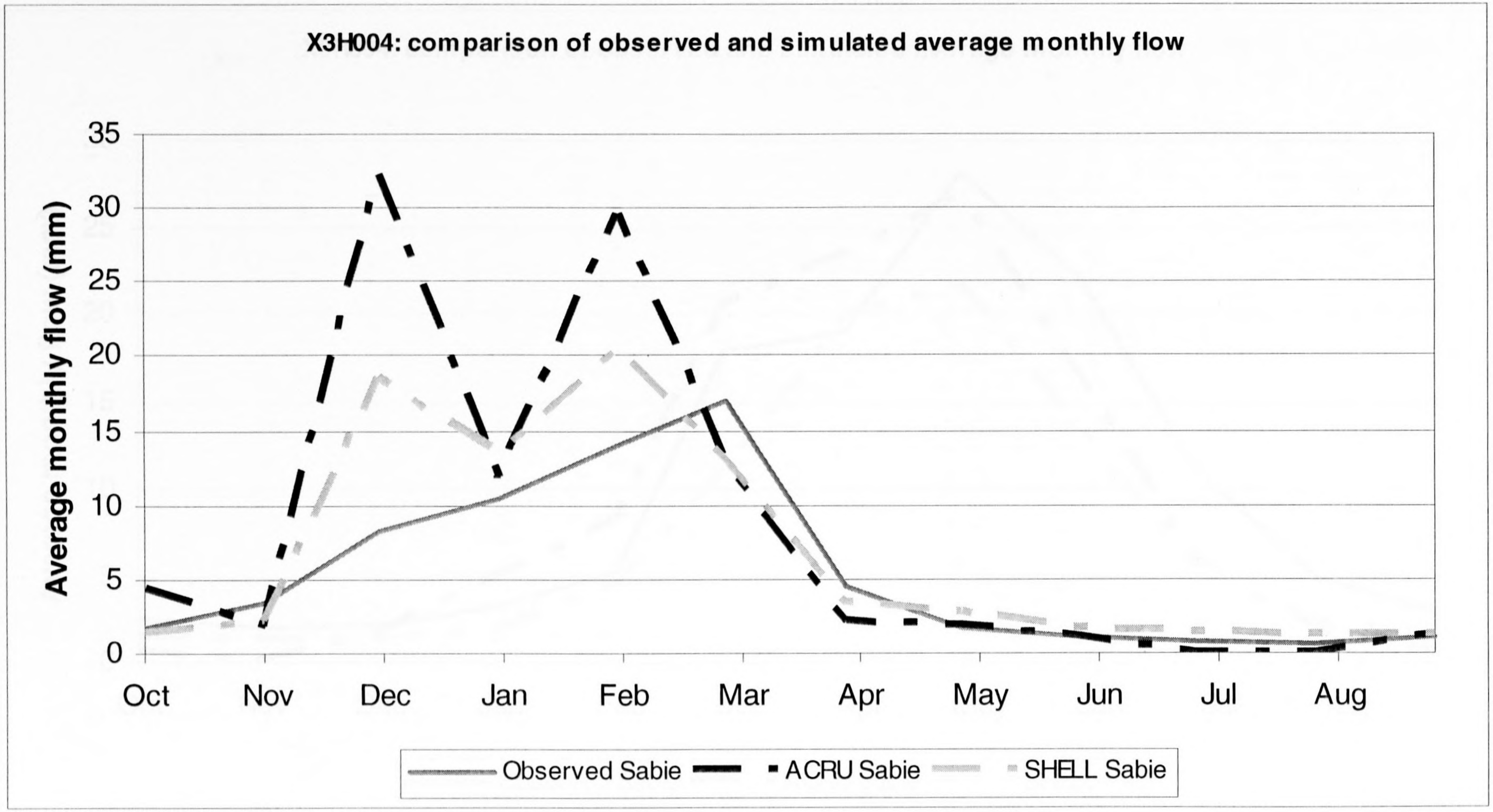


Figure 5-6: Average monthly plot of observed and simulated flows from SHELL and ACRU at gauge X3H004 in the Upper Sabie for a Ten Year Simulation Period (1986 to 1996)

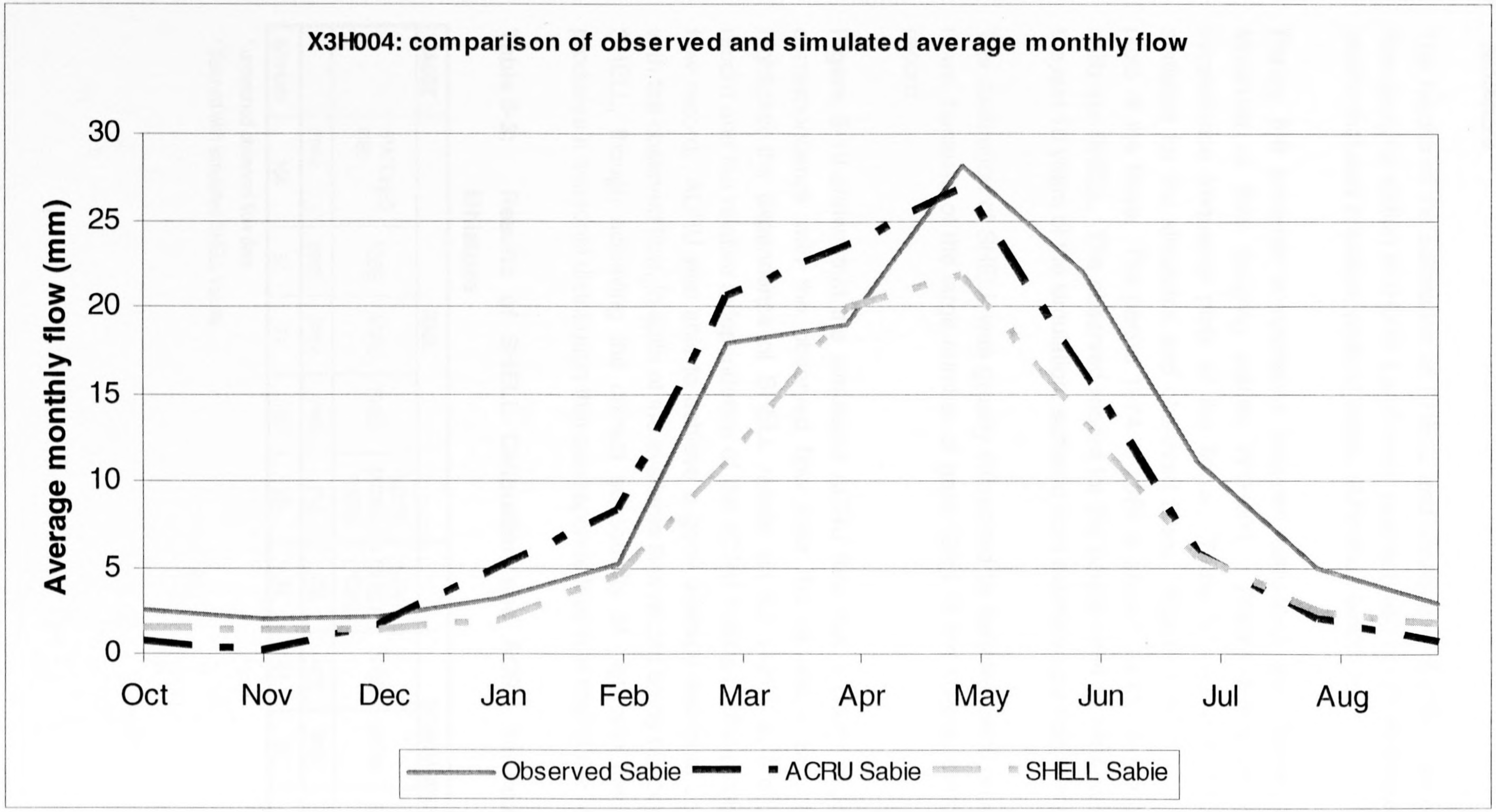


Figure 5-7: Average Monthly Plot of Observed and Simulated Flows from SHELL and ACRU at Gauge X3H004 in the Upper Sabie for a Forty Year Simulation Period (156 to 1996)

5.2.3 Mhlatuze

The results of the calibration of SHELL and verification of ACRU were compared at flow gauging station W1H009. Land cover and land use upstream of this flow gauging station includes irrigation, dryland crops, IAPs and plantations.

Figure 5-8 presents comparisons between simulated and observed flow for the Mhlatuze at flow gauging station W1H009. **Figure 5-9** presents cumulative exceedence frequency plots of the flows. **Table 5-3** presents a comparison of statistics for the simulated and observed flows. **Figure 5-10** presents seasonality plots of the flows. The period 1974 to 1984 is shown, as this is the period used to calibrate SHELL. The observed record for the period 1984 to 1994, which makes up the last 10 years of the simulation, suffered from extensive periods of missing flows.

The calibration of SHELL was greatly influenced by iterative patching with simulated flows, because of the large number of gaps (28% of the 10-year period) in the flow record.

Figure 5-10 shows that the simulated ACRU flow has a closer average seasonal correspondence with the observed flow than the simulated SHELL flow. This highlights the dependence of SHELL results on the quality of the observed flow record and the relative independence of the ACRU results on the available observed flow record. ACRU was able to achieve a good average seasonal correspondence with the observed flow, in spite of the available flow record being of poor quality, while SHELL, though achieving the correct seasonality of high and low flow periods, produces a seasonal distribution that corresponds less with that of the observed flow.

Table 5-3: Results of SHELL Calibration and ACRU Verification for the Mhlatuze

GAUGE	MAR					STANDARD DEVIATION					
	+PATCHED OBS	*OBS	ACRU	SHELL	%DIFF (ACRU - *OBS)	%DIFF (SHELL - *OBS)	*OBS	ACRU	SHELL	%DIFF (ACRU - *OBS)	%DIFF (SHELL - *OBS)
	(mm)	(mm)	(mm)	(mm)	(%)	(%)	(mm)	(mm)	(mm)	(%)	(%)
W1H009	104	57	74	100	29	74	51	63	95	24	85

* unpatched observed flow data

\+ patched with simulated SHELL values

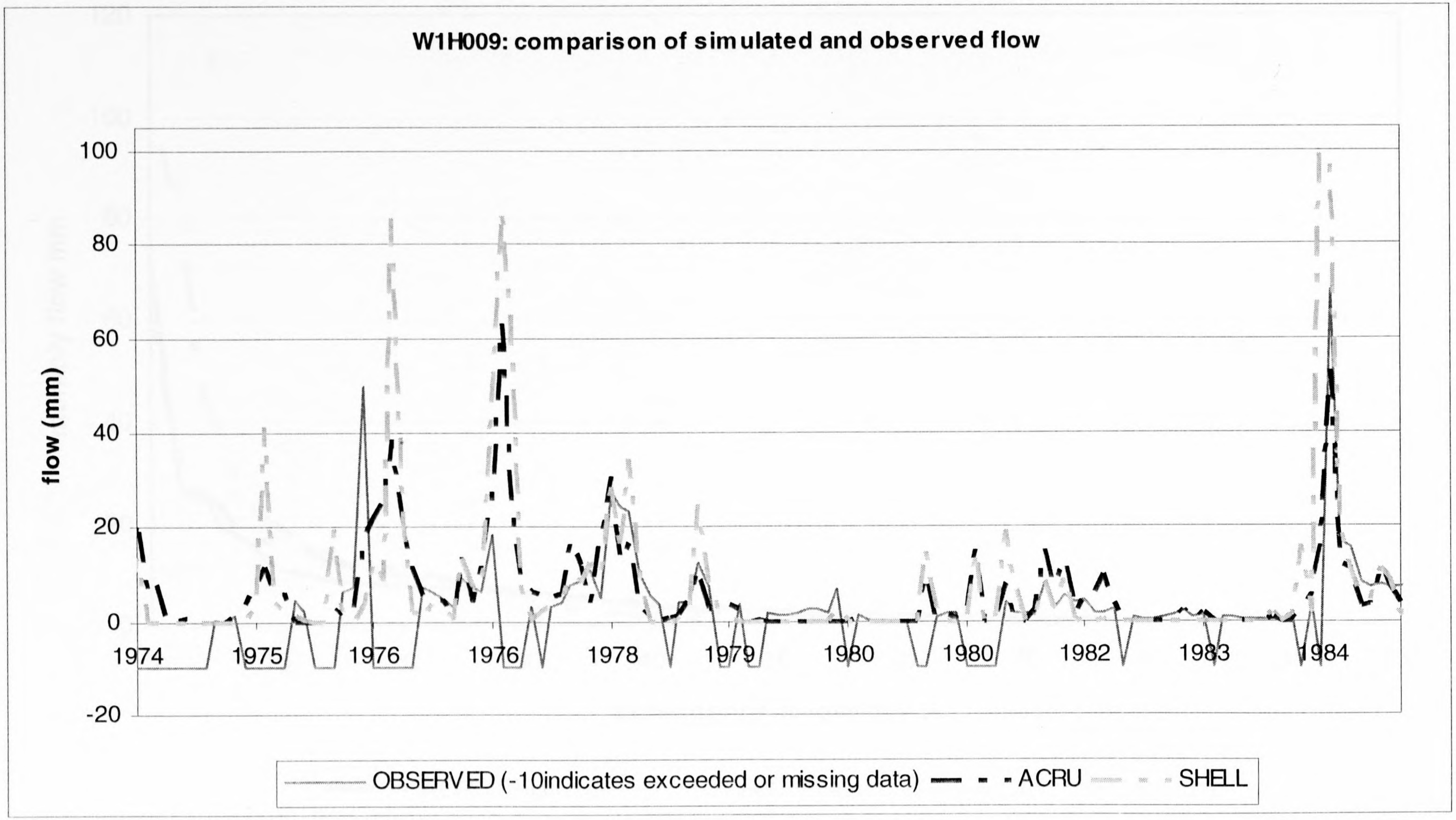


Figure 5-8: Monthly Observed and Simulated Flow for SHELL and ACRU at Gauge W1H009 in the Mhlatuze

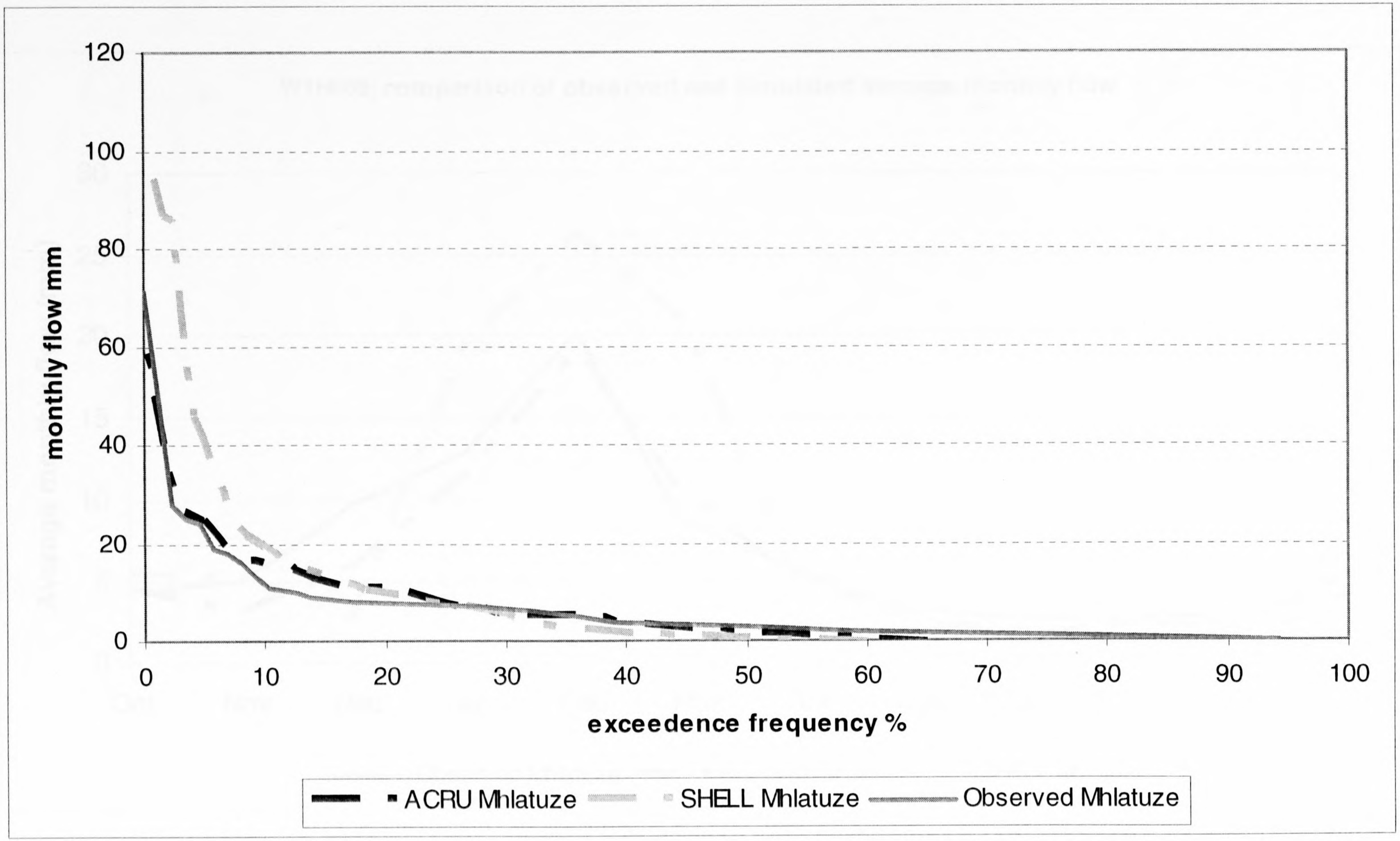


Figure 5-9: Cumulative Frequency Exceedence Plot of Monthly Observed and Simulated Flows from SHELL and ACRU at Gauge W1H009 in the Mhlatuze

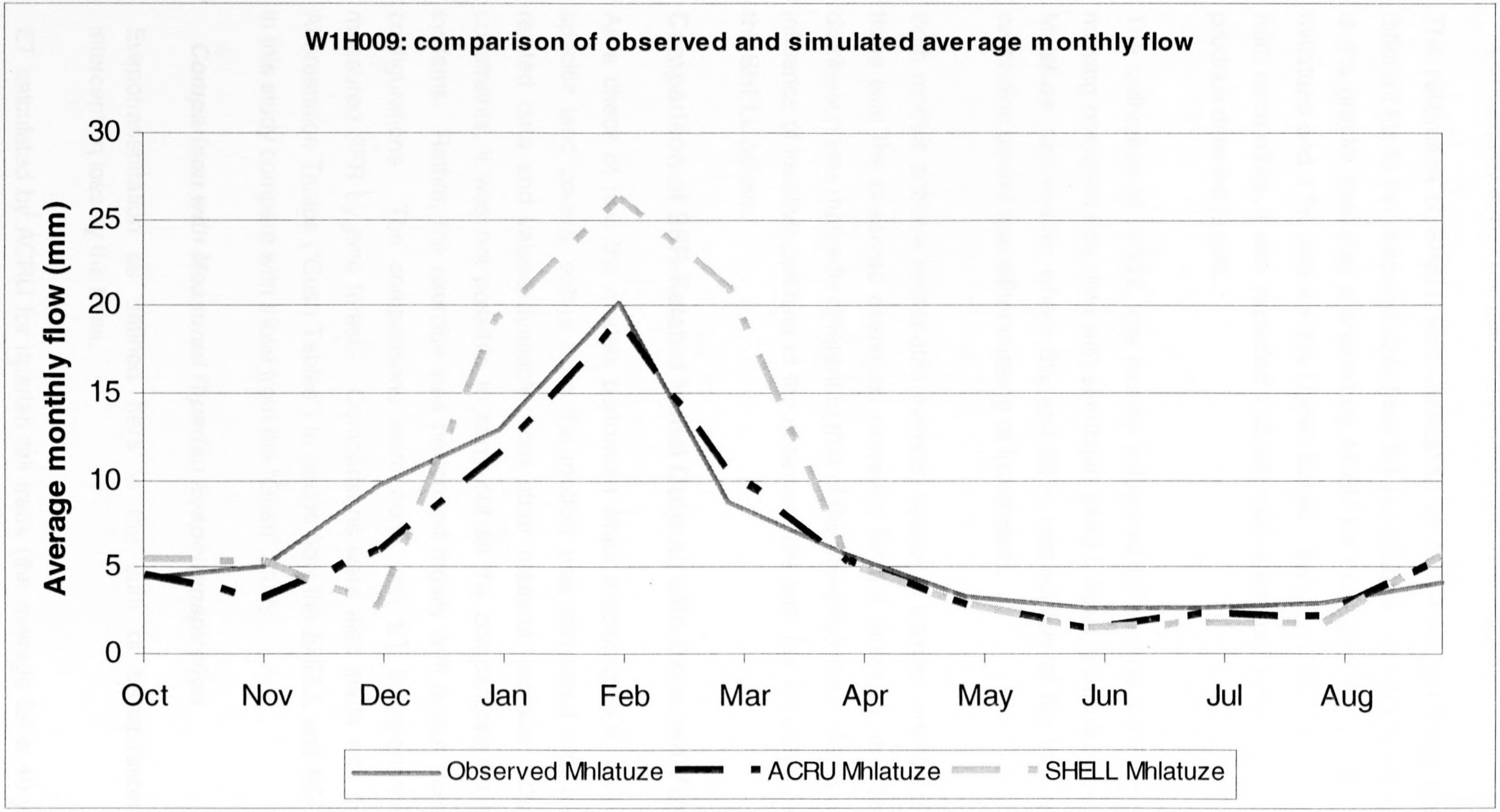


Figure 5-10: Average Monthly Plot of Observed and Simulated Flows from SHELL and ACRU at Gauge W1H009 in the Mhlatuze

5.2.4 Conclusion about the Performance of the Two Models

The calibration of SHELL and verification of ACRU for the study systems produce different fits to the observed data from the two models. The MAR produced by SHELL is 9% greater than that produced by ACRU for the Upper Berg, 35% greater for the Mhlatuze and 17% less for the Upper Sabie. Since the two models are so different from each other, it was expected that the calibration and verification exercises would produce different results.

The calibration of SHELL was heavily influenced by iterative patching of unreliable or missing observed flow data with simulated SHELL flows, particularly for the Sabie and Mhlatuze catchments, where 8% and 28%, respectively of the flow record over the calibration period was either missing or incomplete.

Both models achieve reasonable average seasonal correspondence of high and low flows with the observed averages, however, for the Mhlatuze, the SHELL seasonal distribution was markedly different to that of the observed flow. This is attributed to the influence of iterative patching of the observed flow with the simulated SHELL flows on the SHELL output.

5.3 Comparison of SFR-Related Model Outputs with Expected Values

As a check of how the models performed when modelling SFR, due to changes in specific land covers, output from the models was compared with measured SFR-related data and values available from other research projects. Due to resource constraints, it was not possible to carry out all the comparisons for all three study systems. Rather, the exercise was performed mostly with output from the Mhlatuze configurations. The comparisons were done with ET by riparian tall trees and measured SFR by pine forests. Comparisons were also made with the Commercial Afforestation Tables ("Gush Tables") to gauge how the SHELL and ACRU simulations in this study compare with those from the "Gush" Study.

5.3.1 Comparison with Measured Riparian Evapotranspiration

Evapotranspiration as defined here is the sum of transpiration and canopy interception loss by the trees.

ET calculated by ACRU for riparian tall trees (the average for a 40-year simulation period) was compared with the results of field measurements taken over one year in

Jonkershoek in the Western Cape and Gilboa in KwaZulu Natal (Dye *et al*, 2001). The estimates from Dye *et al* (2001) are shown in **Table 5-4** and the ACRU estimates are shown in **Table 5-5**.

The methodology used by Dye *et al*, to obtain the numbers in **Table 5-4**, is described in **Section 2.2.3** of this report. The rainfall interception in **Table 5-4** and **Table 5-5** were obtained from the same source (Schulze *et al*, 2005), which is why the values are similar.

Table 5-4 shows values of ET which exceed the catchment MAP. This is because riparian areas also have access to water coming from upstream catchments. **Table 5-4** also shows that ET from the Dye field measurements is of the same order of magnitude as catchment MAE. This is expected for tall trees in riparian areas, where transpiration is not limited by water availability. **Table 5-5,** however, shows that the ET simulated by ACRU for the Upper Berg and Mhlatuze is much lower than the catchment MAE, although the potential ET of the trees is governed by a monthly crop parameter of 0.95, which means that mean average PET of the trees is similar to MAE. This implies that, in this ACRU simulation, the ability of the trees to meet evaporative demand is somehow limited, either by water availability or tree physiology. This is further reinforced by the fact that the ET simulated in the ACRU subcatchments is much less than the ET values produced from the field measurements, although the MAE of the simulated catchments is generally greater than that of the experimental catchments. For the Mhlatuze it is possible (from the comparison of MAP to MAE in **Table 5-5**) that the total rainfall available to the model simulation is not sufficient to meet the evaporative demand of the simulation.

The simulated ET for the Upper Berg and Mhlatuze subcatchments are of the same order of magnitude, with the higher MAP Upper Berg subcatchments producing slightly lower values of ET than the lower MAP Upper Berg and Mhlatuze subcatchments.

Further reasons for the dissimilarity between experimental ET values and ET values, produced by ACRU, are as follows:

- Dye *et al* (2001) noted that “ET varies considerably in different plant communities,” and the numbers shown in **Table 5-4** represent only two riparian communities. The catchment conditions (including climate and soils) differ between the ACRU simulations of the Upper Berg and Mhlatuze and experimental sites at Gilboa in the KwaZulu Natal Midlands and Jonkershoek in the Western Cape.

- ACRU estimates represent averages over the long-term (40-year simulation period), whereas values from Dye *et al* are from measurements conducted over one year.
- ACRU estimates are for a different tall tree species from the Dye estimates. The ACRU estimates are for Eucalyptus, while the Dye estimates are for *Acacia Mearnsii*; eucalyptus trees are expected to use more water, generally, than *Acacia Mearnsii.*

The current available measured data on tree water use is not sufficient for meaningful comparisons with simulated water use. More work is currently being done in different site conditions. This includes work done by Jarmain *et al*, 2003 on water use by natural vegetation and Everson *et al*, 2001 on riparian water use by indigenous reeds and forest.

Table 5-4: Annual ET Reported by Dye *et al* (2001) for the Year 1998/1999

Locality	MAP (mm)	MAE (mm)	Vegetation	Transpiration (mm)	Rainfall interception (mm)	ET (mm)
Jonkershoek	1324	1475*	A. mearnsii	1318	185	1503
Gilboa	867	1600+	A. mearnsii	1077	183	1260

* Sourced from Gush et al (2002) +Sourced from Midgley et al (1994)

Table 5-5: Annual ET for Riparian Plants Simulated by ACRU for Subcatchments in the Upper Berg and Mhlatuze

Simulated subc	MAP (mm)	*MAE (mm)	Vegetation	Transpiration (mm)	Rainfall interception (mm)	ET (mm)
Upper Berg						
G1H004a	2147	1246	eucalyptus	363	201	564
G1H020A	1520	1816	eucalyptus	427	244	671
G1H020C	871	1816	eucalyptus	474	153	627
G1H038	2497	967	eucalyptus	245	260	505
Mhlatuze						
W12D	847	1793	eucalyptus	486	186	672
W12E	1049	1775	eucalyptus	437	191	628
W12F	1247	1771	eucalyptus	421	228	649
W12G	834	1805	eucalyptus	530	155	684

* From the A-pan grid data provided by the SBEEH

5.3.2 Comparison with Measured Upland SFR

SFR estimated by ACRU[1] and SHELL was compared with measured SFR from the South African catchment experiments (Scott *et al*, 2000). **Table 5-6** presents the mean annual total SFR measured for eight of the experimental catchments treated with pine in the upland areas only. **Table 5-7** presents mean annual total SFR simulated by ACRU and SHELL for the study catchments, the Mhlatuze, Upper Berg and Upper Sabie for the simulation periods 1954 to 1994, 1952 to 1992 and 1956 to 1996, respectively. The SFR has been presented for a number of subcatchments in the Mhlatuze, whereas for the Upper Berg and Upper Sabie, the SFR has been presented for the total catchment. This was done to save on time and resources. The SFR in the tables has been expressed as SFR in mm per 10% of catchment treated and SFR in % MAR per 10% of catchment treated, to enable comparison between catchments with different areas of afforestation and different MARs.

The tables show that the absolute SFR (mm per 10% treated) simulated by the models is generally lower than that measured at the experimental catchments. While some of the SHELL SFRs fall within the range of experimental catchment SFRs, the ACRU SFRs are extremely low compared to the experimental SFRs. The SFR simulated by SHELL is expected to bear a resemblance to the measured SFR, since the SFR estimation curves used in SHELL are based on data from the experimental catchments (see **Section 3.3.1**). The fact that the simulated SFRs, especially the ACRU values, are lower than the measured may be explained by variations in conditions between the experimental catchment sites and the simulated catchment. For example, the experimental catchments are all located in high rainfall regions with MAPs greater than 1100 mm, whereas the MAPs of most of the simulated subcatchments are well below 1100 mm. The SHELL figures (in mm per 10% of catchment treated) for the Upper Berg catchment and Mhlatuze catchments W12F and W12H, with high MAPs similar to those of the experimental catchments, resemble those of the experimental catchments. As well as MAP, the ACRU results are also determined by the choice of baseline vegetation. The baseline vegetation used for the study systems is shown in **Appendix A**.

As a proportion of MAR, the SHELL SFR is actually higher than the SFR of most of the experimental catchments in the table. The ACRU SFRs are still lower than those of the experimental catchments, when looked at proportionally; however, they are now closer to the order of magnitude of the proportional reductions of the experimental catchments. This indicates that the relative degree of wetness of the catchment has a strong influence on the amount of SFR caused by trees. This

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[1] It should be noted that the ACRU configurations and SFRs were checked by the SBEEH researchers (Jewitt, Smithers and Schulze) and can therefore be regarded as reliable.

aspect is also reflected in the riparian zone experimental results described in **Section 2.2.2**.

To summarise this comparison, the SHELL-estimated SFRs are based on the CSIR curves (functions of age and site optimality) (**Section 3.3.1.1**), which were derived from data sourced from experimental catchments with relatively humid conditions, where soil water stress plays a minor role. In the modelled catchments, soil water stress occurs more often than in the experimental catchments, therefore SHELL can be expected to over-estimate SFR for the modelled subcatchments. The physically-based ACRU-estimated SFRs therefore appear low in contrast to the SHELL values. Also, in ACRU, total evaporation by plants drops below maximum evaporation during drying of the soil. The point at which this happens is governed by the parameter CONST, which represents the fraction of plant available water at which total evaporation drops below maximum evaporation during drying of the soil. Plants with higher values of the parameter CONST are more conservative water users than plants with lower CONST. Pines are modelled with a relatively high value for CONST (0.9). This contributes to the lowness of SFR estimated by ACRU for pines.

Table 5-6: SFR Recorded from the South African Catchment Afforestation Experiments (Scott *et al*, 2000)

	Experimental catchment	**Pre-treatment MAR (mm)**	**MAP (mm)**	**Treatment**			***Average age (years)**	**% of catchment treated**	**Mean annual total SFR (mm)**	**Mean annual total SFR (mm per 10% of catchment treated)**	**Mean annual total SFR (% of MAR per 10% of catchment treated)**
Winter rainfall region	Bosboukloof	246	1100	afforestation	upland	pine	18	57	150	26	11
	Tierkloof	1077	1300	afforestation	upland	pine	18	36	109	30	3
	Lambrechtsbos B	518	1100	afforestation	upland	pine	16	82	169	21	4
	Lambrechtsbos A	564	1100	afforestation	upland	pine	10	89	205	23	4
Summer rainfall region	Catchment 2, Cathedral Peak	807	1400	afforestation	upland	pine	15	75	297	40	5
	Catchment 3, Cathedral Peak	683	1400	afforestation	upland	pine	11	86	184	21	3

* Average age over the SFR record period

Table 5-7: SFR Due to Pine Afforestation Estimated by ACRU and SHELL in this Study

Simulated subcatchment	Baseline Mar (mm)		MAP (mm)	Treatment			Average age (years)	% of catchment afforested	mean annual total SFR (mm)		Mean annual total SFR (mm per 10% of catchment treated)		Mean annual total SFR (% of MAR per 10% of catchment treated)	
	SHELL	ACRU							SHELL	ACRU	SHELL	ACRU	SHELL	ACRU
MHLATUZE														
W12A	125	125	876	afforestation	upland	pine	11	30	27	7	9	2	7	2
W12B	151	199	934	afforestation	upland	pine	11	8	9	0	11	0	7	0
W12C	196	161	848	afforestation	upland	pine	11	25	35	8	14	3	7	2
W12D	186	175	847	afforestation	upland	pine	11	2	2	1	14	4	7	2
W12F	300	320	1247	afforestation	upland	pine	11	9	19	4	22	5	7	2
W12H	298	257	1043	afforestation	upland	pine	11	27	57	9	21	3	7	1
UPPER BERG														
G1H020	780	705	1196	afforestation	upland	pine	16	13	53	6	41	4	5	1
UPPER SABIE														
30	263	216	873	afforestation	upland	pine	11	44	97	0	22	0	8	0

5.3.3 Comparison with Commercial Afforestation SFR Tables used by DWAF ("Gush Tables")

Given the paucity of available direct measurements of SFRs, it was thought useful to compare SFR estimated by ACRU and SHELL with SFR indicated by the Gush Tables (Gush *et al*, 2002) (see **Section 3.5**) for quaternary catchments in the study catchments afforested with pine, given that the Gush Tables have been accorded a regulatory status by DWAF during the past two years. The approach followed in producing the Gush Tables is described in **Section 3.5** of this report.

Table 5-8 presents total and low flow SFR indicated by the Gush Tables for Mhlatuze and **Table 5-9** presents total and low flow SFR simulated by ACRU and SHELL for Mhlatuze. The ACRU and SHELL simulated values for Mhlatuze were obtained from running scenarios where afforestation was the only additional impact added to the baseline scenario.

Table 5-10 presents total and low flow SFR indicated by the Gush Tables for the Upper Berg and **Table 5-11** presents total and low flow SFR simulated by ACRU and SHELL for the Upper Berg.

Table 5-12 presents total and low flow SFR indicated by the Gush Tables for the Upper Sabie and **Table 5-13** presents total and low flow SFR simulated by ACRU and SHELL for the Upper Sabie.

The SFRs are averages from a 40-year simulation period, 1952 to 1992 for the Upper Berg, 1956 to 1996 for the Upper Sabie, 1954 to 1994 for the Mhlatuze and 1950 to 1993 for the Gush simulations.

Low flows are defined here as flows below the 75th percentile exceedance level, i.e. the flow exceeded 75 % of the time. The SFR in the aforementioned tables has been expressed as absolute SFR per 10% of catchment afforested to enable comparison between catchments with different areas of afforestation. The total MAR and low flow MAR estimated with each method for the baseline scenario is included in the tables. It should be noted that the definition of the baseline scenario differs between this study's assumptions and the Gush approach. The Gush approach represents an Acocks baseline scenario, with one dominant Acocks vegetation type per quaternary catchment, whereas the SHELL and ACRU baseline scenarios included all land covers and land uses, which cannot be isolated in the SHELL configuration, superimposed on the "natural" (SHELL) or Acocks (ACRU), as explained in **Section 5.4.1** below.

The tables show a number of negative mean annual low flow SFR values simulated by ACRU in this study, but not in the Gush Study. These negative SFR values indicate average low flow gains in streamflow after afforestation with pines. This may be explained by the early curtailment of total evaporation by the pine trees below maximum evaporation during drying of the soil in the ACRU Model (as described at the end of **Section 5.3.2**). This could lead to water use by pines during periods of the dry season being lower than that of the natural vegetation being replaced. In ACRU, such water use is controlled by the land cover parameters presented in **Appendix A**.

5.3.3.1 Mhlatuze

On average total MAR, estimated by both SHELL and ACRU, is higher than that taken from the Gush Tables. This difference in MAR is more pronounced in subcatchments W12C and W12D, where MAP is lowest and subcatchments W12F and W12H, where MAP is highest. Low flow MAR simulated by SHELL and ACRU is generally higher than the Gush estimate, except in the highest MAP catchments - 12F and 12H. In general, the low flow MARs from the three estimation methods are of a similar order of magnitude.

A comparison of the mean annual total SFRs, simulated by SHELL and ACRU with that from the Gush Tables, shows that the total SFRs from SHELL are generally higher than the Gush estimates, falling beyond the upper confidence limit of the Gush estimates. The ACRU total flow reductions fall within the confidence limits of the Gush estimates, close to the lower limit.

In comparing the low flow SFR, the SHELL estimates fall within the confidence bands of the Gush estimates, in the top half of the confidence band, while the ACRU estimates are lower than the lowest confidence limit. Gains in low flows simulated by ACRU are explained in **Section 5.6**.

5.3.3.2 Upper Berg

An area-weighted MAR of 651 mm for the whole Upper Berg catchment was calculated from the MARs taken from the Gush Tables. MARs, estimated by both SHELL and ACRU for the total Upper Berg catchment, are higher than those taken from the Gush Tables, although the ACRU value is similar to the Gush value. An area-weighted low flow MAR of 45 mm for the whole Upper Berg catchment was calculated from the low flow MARs, taken from the Gush Tables. Low flow MAR simulated by SHELL and ACRU is lower than the Gush estimate. The SHELL estimate is much lower, while the ACRU estimate is similar to the Gush value.

The Gush values of mean annual total SFR were area weighted over all three quaternaries in the Upper Berg to produce an upper limit reduction of 9.7 mm per 10% of catchment afforested, and a lower limit of 3.3 mm per 10% of catchment afforested. A comparison of the mean annual total SFRs simulated by SHELL and ACRU with that from the Gush Tables shows that the total SFR from SHELL is higher than the Gush estimate, falling beyond the upper confidence limit of the Gush estimate. The ACRU total flow reduction is lower than the Gush value, but falls within the confidence limits of the Gush estimates.

The Gush values of mean annual low flow SFR were area weighted over all three quaternaries in the Upper Berg to produce an upper limit reduction of 1.1 mm per 10% of catchment afforested, and a lower limit of 0.2 mm per 10% of catchment afforested. In comparing the low flow SFR, the SHELL estimate falls within the confidence bands of the Gush estimate, in the top half of the confidence band, while the ACRU estimate is lower than the lowest confidence limit. Gains in low flows simulated by ACRU are explained in **Section 5.6**.

5.3.3.3 Upper Sabie

An area-weighted MAR of 345 mm for the whole Upper Sabie catchment was calculated from the MARs taken from the Gush Tables. MAR, estimated by both SHELL and ACRU for the total Upper Sabie catchment, is lower than that taken from the Gush Tables. An area-weighted low flow MAR of 24 mm for the whole Upper Sabie catchment was calculated from the low flow MARs taken from the Gush Tables. Low flow MAR, simulated by SHELL and ACRU, is lower than the Gush estimate. The ACRU estimate is much lower, while the SHELL estimate is of the same order of magnitude as the Gush value.

The MAPs in the two tables for the Upper Sabie are different, with the Gush MAP being much higher than the simulation MAPs. The MAP of 873 for the simulations is the actual rainfall used by the ACRU simulations after processing of the input rainfall. This same rainfall was used for the SHELL simulations. This is explained in detail in **Section 4.4.4** of this report

The Gush values of mean annual total SFR were area-weighted over all three quaternaries in the Upper Sabie to produce an upper limit reduction of 12.5 mm per 10% of catchment afforested and a lower limit of 4.7 mm per 10% of catchment afforested. A comparison of the mean annual total SFRs, simulated by SHELL and ACRU with that from the Gush Tables, shows that the total SFR from SHELL is higher than the Gush estimate, falling beyond the upper confidence limit of the Gush estimate. The ACRU total flow reduction falls below the lower confidence limit of the Gush estimates. The gain in total MAR simulated by ACRU is explained in **Section 5.6**.

The Gush values of mean annual low flow SFR were area weighted over all three quaternaries in the Upper Sabie to produce an upper limit reduction of 0.7 mm per 10% of catchment afforested and a lower limit of 0.2 mm per 10% of catchment afforested. In comparing the low flow SFR, the SHELL estimate is higher than the upper confidence limit of the Gush estimate, while the ACRU estimate is lower than the lowest confidence limit.

5.3.3.4 Overview

It was expected that the SFR simulated by ACRU should resemble the Gush estimates, since the Gush estimates had been produced from ACRU runs. It was also expected that the SFR simulated by SHELL should be generally higher than the Gush estimates, since the SHELL simulation has produced higher SFR than the ACRU simulation.

These expectations are met for the total flow reductions for the Mhlatuze and Upper Berg, but not for the Upper Sabie, where the ACRU total flow reduction is lower than the lower confidence limit of the Gush estimate.

The expectation for low flow reductions is met only for the Upper Sabie SHELL simulation, where the low flow estimate falls above the upper bound of the Gush low flow estimate. For the Berg and Mhlatuze, the SHELL low flow estimate falls within the Gush confidence limits. The ACRU low flow estimates for all three catchments fall below the lower Gush limit, with simulated average gains in low flow.

The dissimilarity between the Gush and simulated values may be attributed to the differences in modelling approach between the SHELL and ACRU simulations and the Gush ACRU simulations. The Gush simulations were carried out at quaternary scale, with one parameter value used per quaternary, whereas the current SHELL and ACRU simulations were carried out at finer spatial scales with extensive spatial variation of parameters within each quaternary catchment, particularly for the ACRU configurations.

In this study, ACRU simulations of the Upper Sabie produced lower than expected mean annual SFR for pine. This conclusion is reached from the fact that the Sabie mean annual SFR for this ACRU simulation is below the confidence limit of the Gush values, while for the other catchments the ACRU value falls within the Gush limits. Also, for the Upper Sabie, the range of values within the Gush low flow confidence limits are lower than the SHELL low flow SFR estimate, where, for the other catchments, the SHELL low flow estimates fall within the Gush range of values. **Section 5.3.2** offers reasons for the lowness of the ACRU-simulated pine SFRs.

Table 5-8: Total and Low Flow SFR due to Pine Afforestation Estimated by the Gush Tables for Subcatchments in the Mhlatuze

Quaternary	MAP (mm)	Baseline MAR (mm)	Baseline low flow MAR (mm)	Mean annual total flow reductions (mm)	Mean annual low flow reductions (mm)	Mean annual total flow reductions (mm per 10% catchment afforested)	Mean annual low flow reductions (mm per 10% catchment afforested)	Total flow SFR confidence limit (%SFR)	Total low flow SFR confidence limit (%SFR)
W12A	878	132.8	9.5	64.1	7.5	6.41	0.75	60	75
W12B	935	129.1	9.3	60.8	7.4	6.08	0.74	60	75
W12C	850	82	6.2	39.5	4	3.95	0.4	60	75
W12D	847	80.7	6.1	44.8	5.9	4.48	0.59	60	75
W12F	1283	111.2	5.6	61.4	11.8	6.14	1.18	40	60
W12H	1043	110.8	5.3	47.5	8.6	4.75	0.86	60	75

* MAP from Gush tables

Table 5-9: Total and Low Flow SFR due to Pine Afforestation Estimated by ACRU and SHELL for Subcatchments in the Mhlatuze

Simulated Subcatchment	*MAP (mm)	Baseline MAR (mm)		Baseline low flow MAR (mm)		Mean annual total SFR (mm)		Mean annual low flow reduction (mm)		Mean annual total SFR (mm per 10% of catchment treated)		Mean annual low flow reduction (mm per 10% of catchment treated)	
		SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU
W12A	876	124.9	125.1	6.7	2.7	27.2	7.0	1.5	-0.6	9.0	2.3	0.5	-0.2
W12B	934	150.7	199.2	8.2	9.0	8.6	0.2	0.5	-0.3	10.9	0.3	0.6	-0.3
W12C	848	196.1	161.1	6.6	5.6	34.7	8.5	1.2	0.0	14.1	3.4	0.5	0.0
W12D	847	186.3	175.3	5.0	4.3	2.2	0.7	0.1	0.0	13.5	4.1	0.5	0.1
W12F	1247	300.1	319.6	11.4	14.1	19.2	4.3	0.8	-0.2	21.6	4.9	0.9	-0.3
W12H	1043	298.1	256.9	9.2	7.0	57.5	9.2	1.8	0.2	21.5	3.4	0.7	0.1

* MAP used in simulations

Table 5-10: Total and low flow SFR due to pine afforestation estimated by the Gush Tables for subcatchments in the Upper Berg

Quaternary	*MAP (mm)	Baseline MAR (mm)	Baseline low flow MAR (mm)	Mean annual total flow reductions (mm)	Mean annual low flow reductions (mm)	Mean annual total flow reductions (mm per 10% catchment afforested)	Mean annual low flow reductions (mm per 10% catchment afforested)	Total flow SFR confidence limit (%SFR)	Total low flow SFR confidence limit (%SFR)
G10A	1541	974.7	65.2	76.8	8.1	7.68	0.81	40	60
G10B	1239	704.3	45.8	69.2	6.9	6.92	0.69	40	60
G10C	998	461.5	34.5	57	5.8	5.7	0.58	60	75

* MAP from Gush tables

Table 5-11: Total and Low Flow SFR due to Pine Afforestation Estimated by ACRU and SHELL for the Total Upper Berg Catchment

Simulated Subcatchment	*MAP (mm)	Baseline MAR (mm)		Baseline low flow MAR (mm)		Mean annual total SFR (mm)		Mean annual low flow reduction (mm)		Mean annual total SFR (mm per 10% of catchment treated)		Mean annual low flow reduction (mm per 10% of catchment treated)	
		SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU
Upper Berg	1196	779.9	704.8	13.9	42.8	52.8	6.1	1.0	-0.3	40.8	4.7	0.8	-0.2

* MAP used in simulations

Table 5-12: Total and Low Flow SFR due to Pine Afforestation Estimated by the Gush Tables for Subcatchments in the Upper Sabie

Quaternary	*MAP (mm)	Baseline MAR (mm)	Baseline low flow MAR (mm)	Mean annual total flow reductions (mm)	Mean annual low flow reductions (mm)	Mean annual total flow reductions (mm per 10% catchment afforested)	Mean annual low flow reductions (mm per 10% catchment afforested)	Total flow SFR confidence limit (%SFR)	Total low flow SFR confidence limit (%SFR)
X31A	1233	410.2	30	120.3	8.2	12.03	0.82	40	60
X31B	1248	409.2	28.7	97.7	4.9	9.77	0.49	40	60
X31C	1311	438.6	30.5	111.1	6.6	11.11	0.66	40	60
X31D	937	190.5	11.4	58.4	2	5.84	0.2	60	70
X31E	1254	413.6	29.6	94	5	9.4	0.5	40	60
X31F	1334	494.1	32.4	96.1	4.6	9.61	0.46	40	60
X31G	984	269.9	18.6	69	2.2	6.9	0.22	60	70
X31H	1169	354.2	23.6	83.3	4.3	8.33	0.43	40	60
X31J	897	215.9	14.5	60.5	1.6	6.05	0.16	60	70
X31K	680	94	6.4	33.9	1.3	3.39	0.13	100	140

* MAP from Gush tables

Table 5-13: Total and Low Flow SFR due to Pine Afforestation Estimated by ACRU and SHELL for the total Upper Sabie Catchment

Simulated Subcatchment	*MAP (mm)	Baseline MAR (mm)		Baseline low flow MAR (mm)		Mean annual total SFR (mm)		Mean annual low flow reduction (mm)		Mean annual total SFR (mm per 10% of catchment treated)		Mean annual low flow reduction (mm per 10% of catchment treated)	
		SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU	SHELL	ACRU
Upper Sabie	873	263.3	216.0	17.4	2.6	97.2	-0.4	8.0	-1.2	22.3	-0.1	1.8	-0.3

* MAP used in simulations

5.4 Description of Scenarios Modelled

For each study river system, a number of scenarios were modelled, both in ACRU and SHELL. Every attempt was made to define the scenarios in the same way in the two models, so that the outcome of the models could be compared.

Due to time and resource constraints, it was not possible to run the full set of scenarios for all three study systems. Rather, the Mhlatuze catchment was selected to demonstrate the effects of individual SFR-related land-use changes at various points within the catchment, and the Upper Sabie and Upper Berg catchments were used to demonstrate the effects, at the flow exit point of the study system, of clearing IAPs and commercial afforestation from the current land cover scenario, and afforesting the baseline scenario.

The scenarios simulated and the applicable study systems are summarised in **Table 5-14** and described below. It should be noted that, at present, ACRU can only model one riparian land-use cell at a time in a catchment. Mixed riparian land-use is represented by area weighting the parameters of the different land uses within each riparian subcatchment in the ACRU Model configuration (Hayes, 2003).

Modelling periods used, comprise 40 years as follows:

Upper Berg:	1952 to 1992
Upper Sabie:	1956 to 1996
Mhlatuze:	1954 to 1994

Modelling periods of 40 years were selected as the longest practical simulation period, given the time required to run the ACRU configurations.

Table 5-14: Summary of Scenarios Simulated for the Study Systems

Scenario	Abbreviation	Simulated for Upper Berg	Simulated for Upper Sabie	Simulated for Mhlatuze
Baseline	nat	√	√	√
Current day	cur	√	√	√
Current day with forestry cleared	cfo	√	√	n/a
Current day with IAPs cleared	cav	√	n/a*	n/a
Upland tall trees	utt	n/a	n/a	√
Upland medium trees	umt	n/a	n/a	√
Upland tall shrubs	uts	n/a	n/a	√
Pine afforestation	pin	√	√	√
Eucalyptus afforestation	euc	n/a	n/a	√
Riparian tall trees	rtt	n/a	n/a	√
Riparian medium trees	rmt	n/a	n/a	√
Riparian tall shrubs	rts	n/a	n/a	√

*The area covered by IAPs in the Upper Sabie catchment is negligible so the cav scenario is not applicable

5.4.1 Baseline Scenario

The baseline scenario, also sometimes referred to as the "natural" scenario in this document, represents the "natural" land cover as determined by SHELL. In SHELL, the following land and water uses are eliminated from the current scenario to provide the natural scenario:

- Irrigation and farm dams;
- Afforestation;
- Alien vegetation;
- Dryland sugarcane;
- Large reservoirs and bulk water abstractions;
- Water transfers into and out of the catchment; and
- Return flows / waste discharges.

Normally in ACRU modelling, the natural scenario is defined as the scenario which contains only Acocks land cover, however, because this study aims to compare the outputs from ACRU and SHELL, an attempt was made to create in ACRU, the same baseline found in SHELL. Hence, in the ACRU baseline, all land and water uses except the seven mentioned in bulleted points above, were left in the model. The seven excluded land and water uses were replaced with the relevant Acocks land cover. The residual land uses in the baseline scenario consist mainly of all dry land cultivation (except dryland sugarcane) and occasionally small urban areas.

5.4.2 Current Scenario

The current scenario consists of the current (mid-1990s) mix of land cover and land and water use in the catchment.

5.4.3 Current Scenario with Forestry Cleared

In this scenario, the area covered by commercial forestry in the current scenario, is replaced with the relevant Acocks vegetation.

5.4.4 Current Scenario with IAPs Cleared

In this scenario, the area covered by IAPs in the current scenario, is replaced with the relevant Acocks vegetation. This scenario cannot be run for the Upper Sabie as the condensed area of IAPs in the catchment is negligible, as presented in **Table 4-1**.

5.4.5 Upland Alien Invasion Scenarios

The upland invasion scenarios (upland tall trees, upland medium trees and upland tall shrubs) were created by replacing a portion of the natural area in the baseline scenario with an area of upland alien vegetation equal to the *invadable upland area* of the catchment. In this study, the invadable area for each subcatchment was defined as the current area not covered by man-made influences, i.e., the area not covered by irrigation, urbanisation, dryland cultivation, reservoirs or forestry.

5.4.6 Riparian Alien Plant Invasion Scenarios

For these scenarios (riparian tall trees, riparian medium trees and riparian tall shrubs), the complete riparian area in the baseline scenario is replaced with alien invasion and the upland is left in the baseline state.

5.4.7 Commercial Afforestation Scenarios

The commercial afforestation scenarios (pine afforestation or eucalyptus afforestation) were created by replacing a portion of the upland area in the baseline scenario with an area of commercial afforestation equal to the current area of afforestation in the catchment. In this scenario, the residual upland is left in the baseline condition.

5.5 Comparison of Baseline MAR and Flow Produced by the Models

Since the simulated flows related to the calibration and verification of SHELL and ACRU differ from each other (see **Section 5.2**), it follows that the baseline flows should also differ from each other. This can be seen in **Table 5-15**, which compares the incremental MAR produced by the different models for each study system.

On average, the difference in simulated baseline MAR between the models is greater for low flows. On average, flows simulated by ACRU are lower than those simulated by SHELL, except for the Upper Berg, where low flow simulated by ACRU is much higher than that simulated by SHELL. This is borne out by the cumulative exceedence frequency plots of the baseline flows in **Figure 5-11**, **Figure 5-12**, and **Figure 5-13**.

The differences in baseline MAR produced by ACRU and SHELL imply that SFR estimated by ACRU cannot be compared meaningfully with SFR estimated by SHELL, in absolute (mm) terms, but a comparison on the basis of percentage of MAR should be meaningful. The rest of this report will focus on comparing the SFR outcomes of scenarios, via ACRU with the SFR outcomes of scenarios, via SHELL.

Table 5-15: Baseline MAR Produced by SHELL and ACRU for the Study Systems

Catchment	Subcatchment name / number	Baseline MAR (mm)			Baseline Low Flow MAR (mm)			Standard Deviation in monthly runoff (mm)		
		SHELL	ACRU	%DIFF (ACRU - SHELL)	SHELL	ACRU	%DIFF (ACRU - SHELL)	SHELL	ACRU	%DIFF (ACRU - SHELL)
Upper Berg (total catchment)	G1H020	780	705	-10	14	43	207	73	48	-34
Upper Sabie (total catchment)	30	263	216	-18	17	3	-85	29	34	16
Mhlatuze (total catchment)	W12H	259	223	-14	8.1	5.6	-32	37.5	36.6	-2
Mhlatuze (incremental catchments)	w12A	125	125	0	6.7	2.7	-59	17.8	16.7	-6
	W12B	151	199	32	8.2	9.0	10	23.4	26.2	12
	W12C	196	161	-18	6.6	5.6	-15	28.1	23.3	-17
	W12D	186	175	-6	5.0	4.3	-14	31.0	26.5	-14
	W12E	311	300	-4	8.4	11.5	36	43.6	38.5	-12
	W12F	300	320	7	11.4	14.1	23	51.4	33.8	-34
	W12G	201	173	-14	5.5	2.3	-58	34.7	30.8	-11
	W12H	298	257	-14	9.2	7.0	-24	41.6	41.7	0

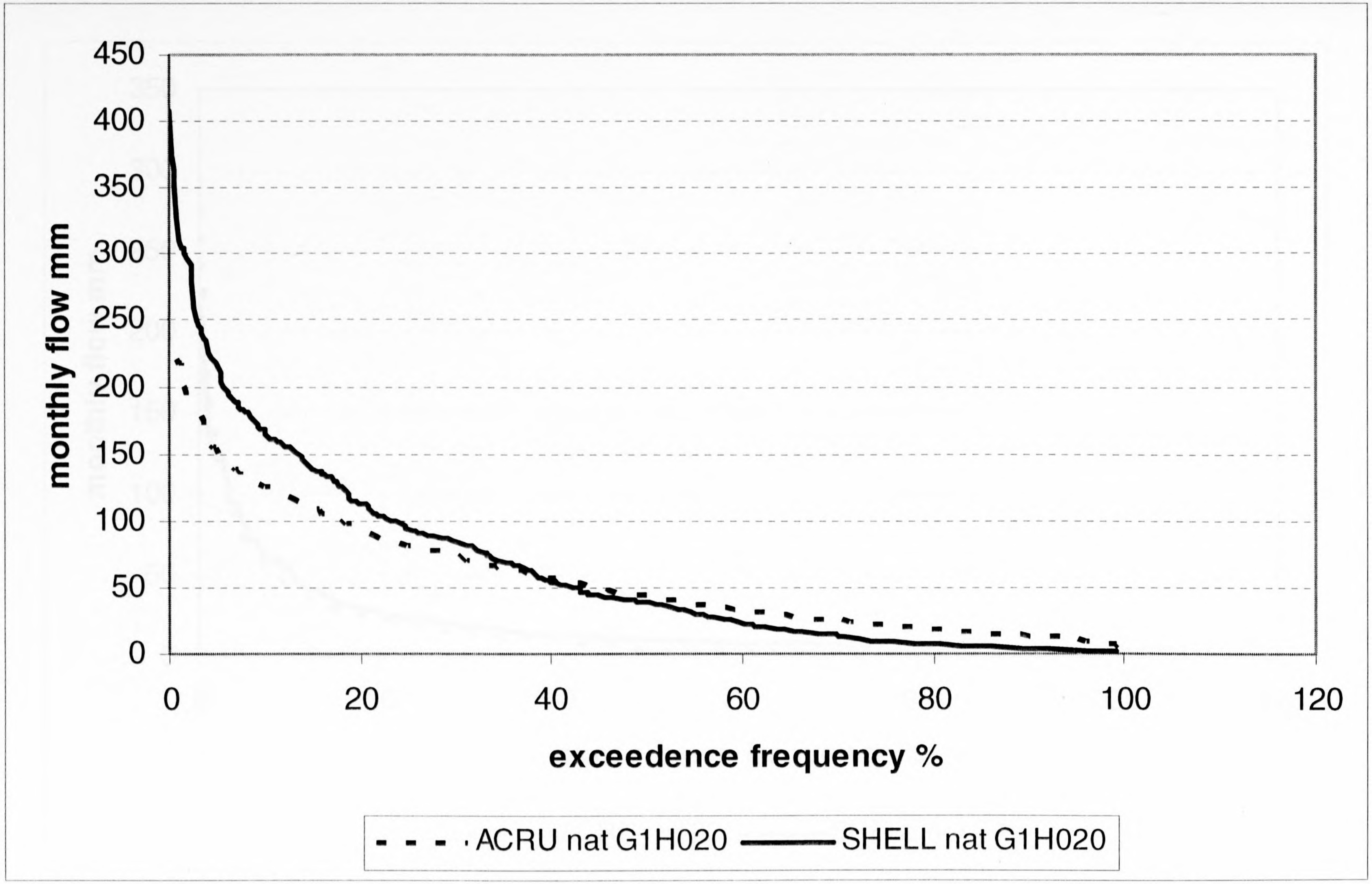


Figure 5-11: Cumulative Exceedence Frequency Plot of Baseline Monthly Flows Produced by SHELL and ACRU for the Total Upper Berg Catchment

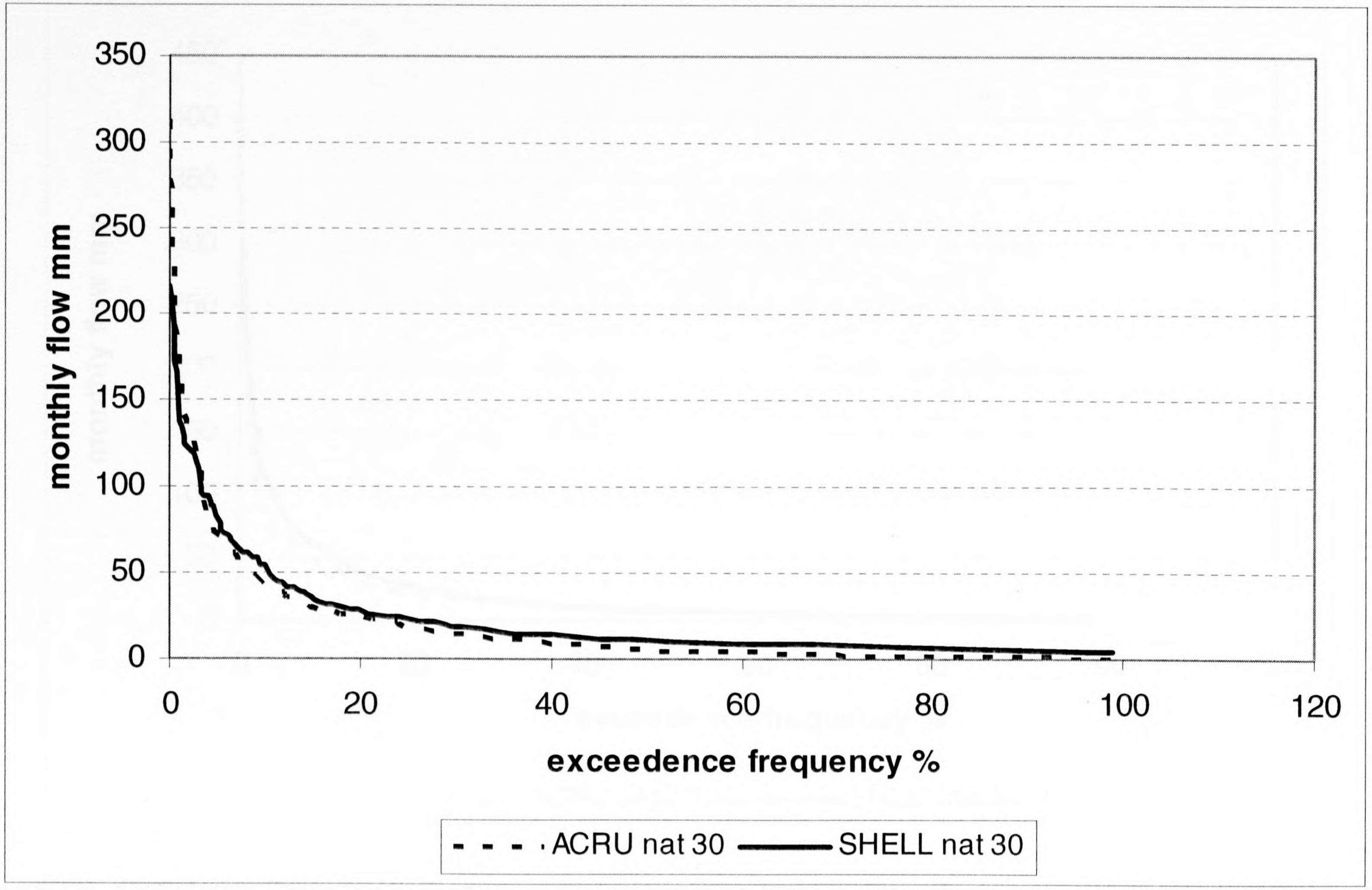


Figure 5-12: Cumulative Exceedence Frequency Plot of Baseline Monthly Flows Produced by SHELL and ACRU for the Total Upper Sabie Catchment

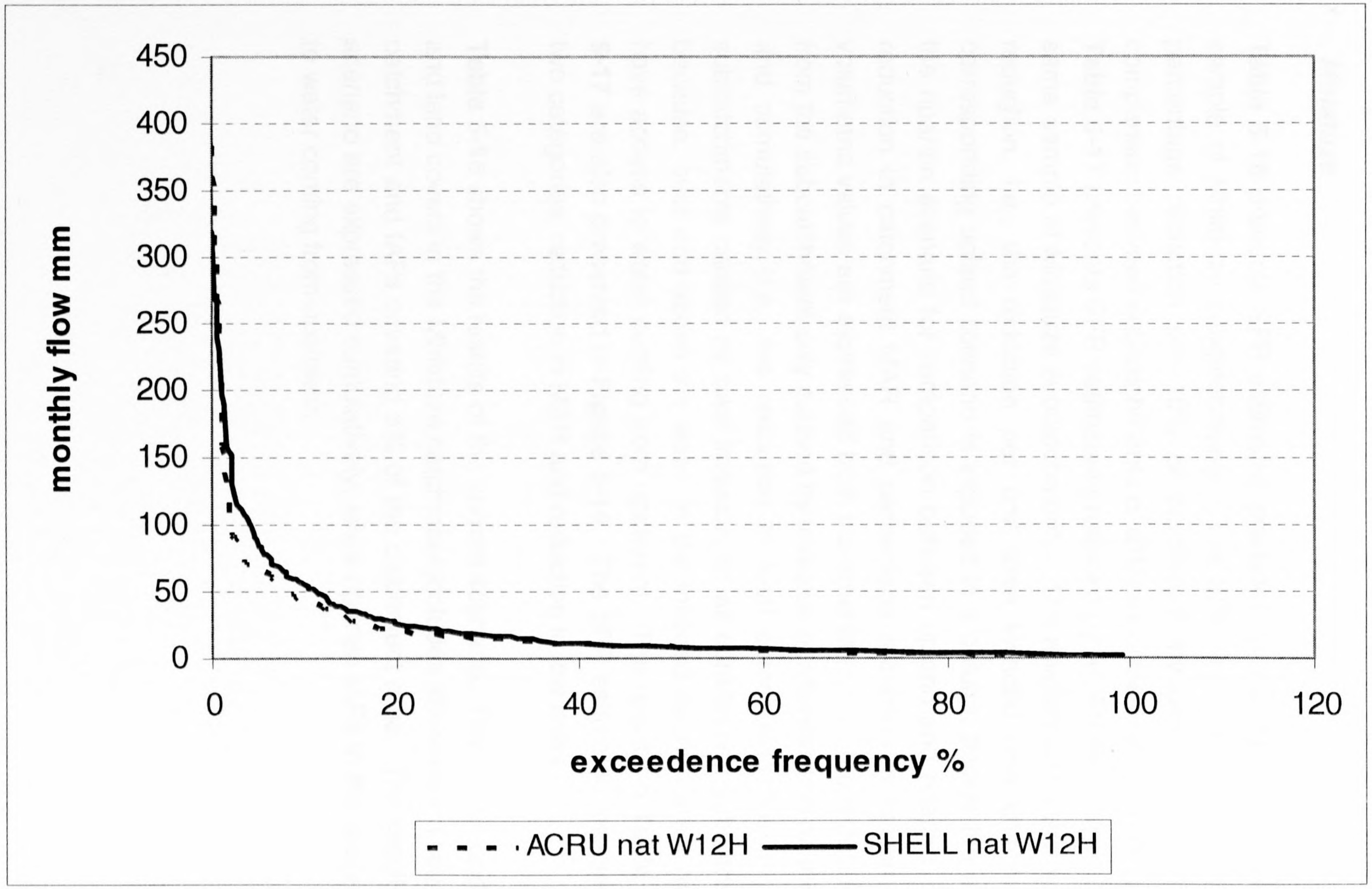


Figure 5-13: **Cumulative Exceedence Frequency Plot of Baseline Monthly Flow Produced by SHELL and ACRU for the Total Mhlatuze Catchment**

5.6 Streamflow Reduction Estimates Produced by ACRU

This section examines and discusses SFR estimates produced by ACRU for the three study systems.

5.6.1 Mhlatuze

Table 5-16 presents SFR estimates produced by ACRU for upland scenarios for a sample of Mhlatuze subcatchments. The SFR is expressed as both absolute and percentage reduction per 10% of catchment invaded or afforested to allow for comparison between subcatchments of different sizes and different levels of invasion. **Table 5-17** presents SFR estimates produced by ACRU for riparian scenarios for the same sample of Mhlatuze subcatchments. The riparian SFRs are expressed as unit reduction, i.e., the reduction per unit area invaded (the unit reduction for the corresponding upland scenario is included in a column beside the unit reduction for the riparian scenario for comparison between upland and riparian SFR), volumetric reduction in catchment MAR and percentage reduction in catchment MAR. The volumetric values are expressed both incrementally, i.e., the reduction in total runoff from the subcatchment only caused by invasion or afforestation on the subcatchment, and cumulatively, i.e., the reduction in total contributing flow from all upstream subcatchments caused by total invasion on all contributing subcatchments. This is because, over and above the water in the invaded riparian area, riparian invasions have access to water coming from upstream. The results in **Table 5-16** and **Table 5-17** are also presented in **Figure 5-14**. The SFR estimates are discussed below in two categories, reduction in MAR and reduction in low flows.

Table 5-18 shows the results of the current scenario. The mix of land and water uses and land covers in the Mhlatuze catchment includes afforestation covering 31% of the catchment and IAPs covering 5% of the catchment area. The results for the current scenario are expressed cumulatively, since riparian IAPs in the scenario have access to water coming from upstream.

Table 5-16: Summary of SFR Estimates Produced by ACRU for the Mhlatuze Upland Scenarios

Scenario	Subcatchment	Baseline MAR (mm)	Baseline low flow MAR (mm)	Reduction per 10% of catchment treated			
				Reduction in baseline MAR (mm)	Reduction in baseline low flow MAR (mm)	Reduction in baseline MAR (%)	Reduction in baseline low flow MAR (%)
INCREMENTAL RUNOFF							
upland tall trees	W12D	175.3	4.3	6.6	0.3	3.7	7.9
	W12E	299.6	11.5	11.9	0.7	4.0	6.5
	W12F	319.6	14.1	14.6	0.5	4.6	3.8
	W12G	172.8	2.3	5.3	0.2	3.1	6.7
upland medium trees	W12D	175.3	4.3	2.3	0.2	1.3	4.2
	W12E	299.6	11.5	4.8	0.4	1.6	3.3
	W12F	319.6	14.1	5.8	0.5	1.8	3.3
	W12G	172.8	2.3	1.7	0.1	1.0	4.1
upland tall shrubs	W12D	175.3	4.3	4.1	0.2	2.4	4.5
	W12E	299.6	11.5	8.4	0.5	2.8	4.5
	W12F	319.6	14.1	10.6	0.4	3.3	2.9
	W12G	172.8	2.3	3.2	0.1	1.8	4.2
commercial pine	W12D	175.3	4.3	4.1	0.1	2.3	2.8
	W12E	No forestry					
	W12F	319.6	14.1	4.9	-0.3	1.5	-1.8
	W12G	No forestry					
commercial eucalyptus	W12D	175.3	4.3	8.5	0.1	4.8	1.8
	W12E	No forestry					
	W12F	319.6	14.1	16.8	0.6	5.2	4.0
	W12G	No forestry					

Table 5-17: Summary of SFR Estimates Produced by ACRU for the Mhlatuze Riparian Scenarios

Scenario	Subcatchment Grouping		Total Flow					Low Flow				
	Incremental	Cumulative	Baseline Catchment MAR (10^6m^3)	Unit reduction: Riparian strip MAR (mm)	Unit reduction: Equivalent Upland MAR(mm)	Reduction: Catchment MAR (10^6m^3)	Reduction: Catchment MAR (%)	Baseline Catchment Low Flow MAR (10^6m^3)	Unit red.: Riparian strip Low Flow MAR(mm)	Unit red.: Equivalent Upland Low Flow MAR(mm)	Reduction: Catchment Low Flow MAR (10^6m^3)	Reduction: Catchment Low Flow MAR (%)
riparian tall trees	W12D		99.4	306.8	65.7	7.6	7.7	2.5	69.2	3.4	1.7	69.7
		W12D+W12C+W12B+W12A	399.5			31.2	7.8	17.0			6.8	39.9
	W12E		73.2	307.4	119.2	2.5	3.4	2.8	61.5	7.4	0.5	17.8
		W12E+W12D+W12C+W12B+W12A	472.7			33.7	7.1	20.1			7.3	36.2
	W12F		53.4	272.6	146.4	1.4	2.7	2.4	81.8	5.4	0.4	18.2
		W12F+W12H+W12G+W12E+W12D+W12C+W12B+W12A	706.2			46.5	6.6	29.0			9.1	31.4
	W12G		55.7	181.7	52.9	2.5	4.5	0.7	26.6	1.5	0.4	49.9
riparian medium trees	W12D		99.4	221.4	22.7	5.5	5.5	2.5	54.5	1.8	1.4	54.9
		W12D+W12C+W12B+W12A	399.5			21.7	5.4	17.0			5.6	33.0
	W12E		73.2	222.3	48.5	1.8	2.5	2.8	58.1	3.7	0.5	16.9
		W12E+W12D+W12C+W12B+W12A	472.7			23.5	5.0	20.1			6.1	30.2
	W12F		53.4	211.0	57.8	1.1	2.1	2.4	35.6	4.6	0.2	7.9
		W12F+W12H+W12G+W12E+W12D+W12C+W12B+W12A	706.2			30.5	4.3	29.0			7.3	25.2
	W12G		55.7	104.6	16.7	1.4	2.6	0.7	21.5	0.9	0.3	40.4
riparian tall	W12D		99.4	299.2	41.3	7.4	7.5	2.5	70.0	2.0	1.7	70.6

Scenario	Subcatchment Grouping		Total Flow					Low Flow				
	Incremental	Cumulative	Baseline Catchment MAR (10^6m^3)	Unit reduction: Riparian strip MAR (mm)	Unit reduction: Equivalent Upland MAR(mm)	Reduction: Catchment MAR (10^6m^3)	Reduction: Catchment MAR (%)	Baseline Catchment Low Flow MAR (10^6m^3)	Unit red.: Riparian strip Low Flow MAR(mm)	Unit red.: Equivalent Upland Low Flow MAR(mm)	Reduction: Catchment Low Flow MAR (10^6m^3)	Reduction: Catchment Low Flow MAR (%)
shrubs		W12D+W12C+W12B+W12A	399.5			30.2	7.6	17.0			6.8	40.2
	W12E		73.2	297.4	83.7	2.4	3.3	2.8	60.7	5.2	0.5	17.6
		W12E+W12D+W12C+W12B+W12A	472.7			32.6	6.9	20.1			7.3	36.4
	W12F		53.4	267.5	106.0	1.4	2.6	2.4	72.8	4.1	0.4	16.2
		W12F+W12H+W12G+W12E+W12D+W12C+W12B+W12A	706.2			44.5	6.3	29.0			9.1	31.5
	W12G		55.7	171.7	31.9	2.4	4.2	0.7	27.3	1.0	0.4	51.2

Table 5-18: Summary of Total Water Use Estimates Produced by ACRU for the Mhlatuze Current Scenario (expressed in terms of cumulative runoff)

Scenario	Subcatchment	Baseline MAR (mm)	Current MAR (mm)	Baseline low flow MAR (mm)	Current low flow MAR (mm)	*Reduction in baseline MAR (%)	*Reduction in baseline low flow MAR (%)
CUMULATIVE RUNOFF							
Current Day	W12D	165.8	63.3	7.0	0.1	61.8	98.9
	W12E	178.1	74.7	7.6	0.5	58.1	93.9
	W12F	194.7	78.8	8.0	0.5	59.5	93.5
	W12G	172.8	161.9	2.3	2.3	6.3	0.0

* Due to all land uses and water uses

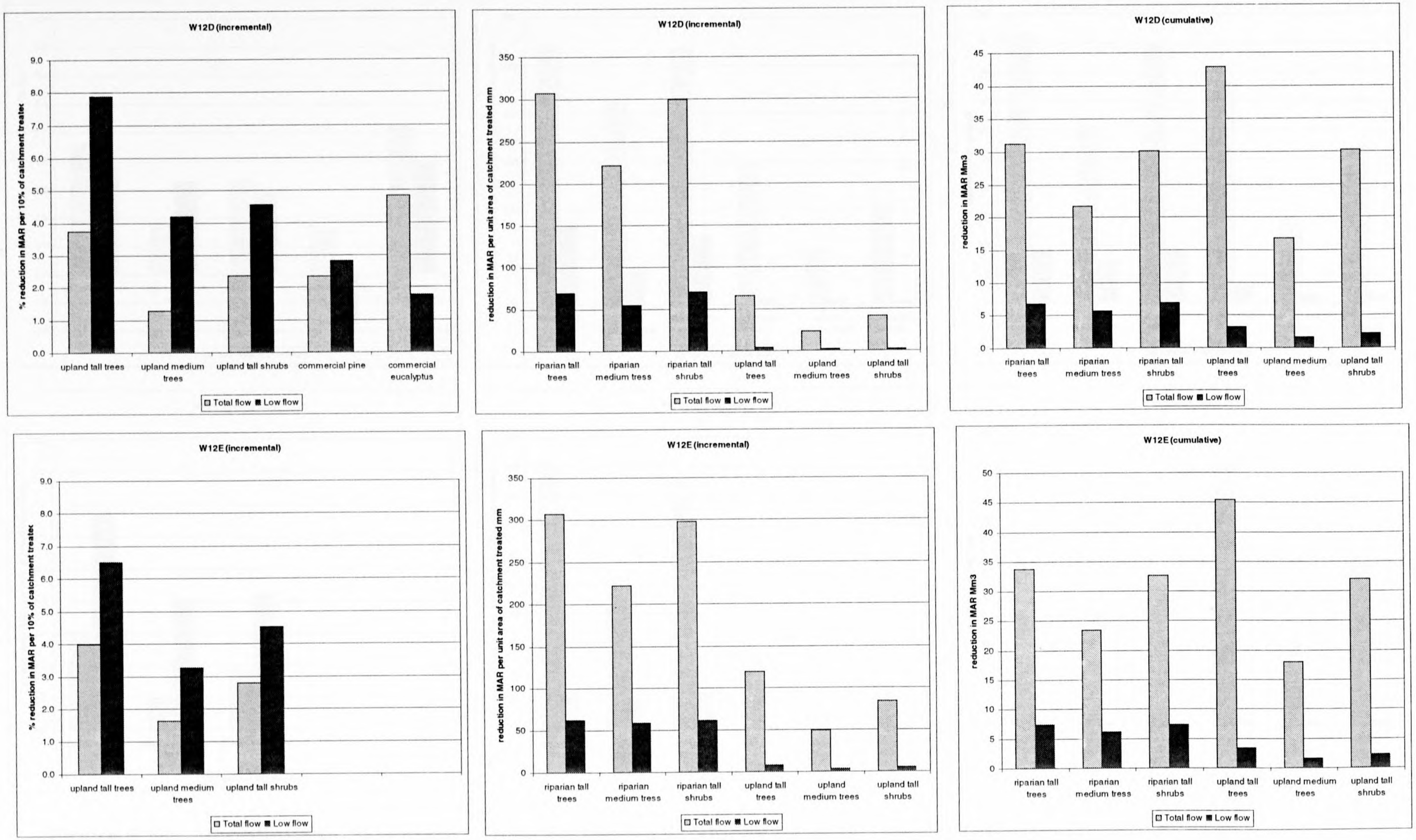


Figure 5-14: Summary of SFR Estimates Produced by ACRU for the Mhlatuze

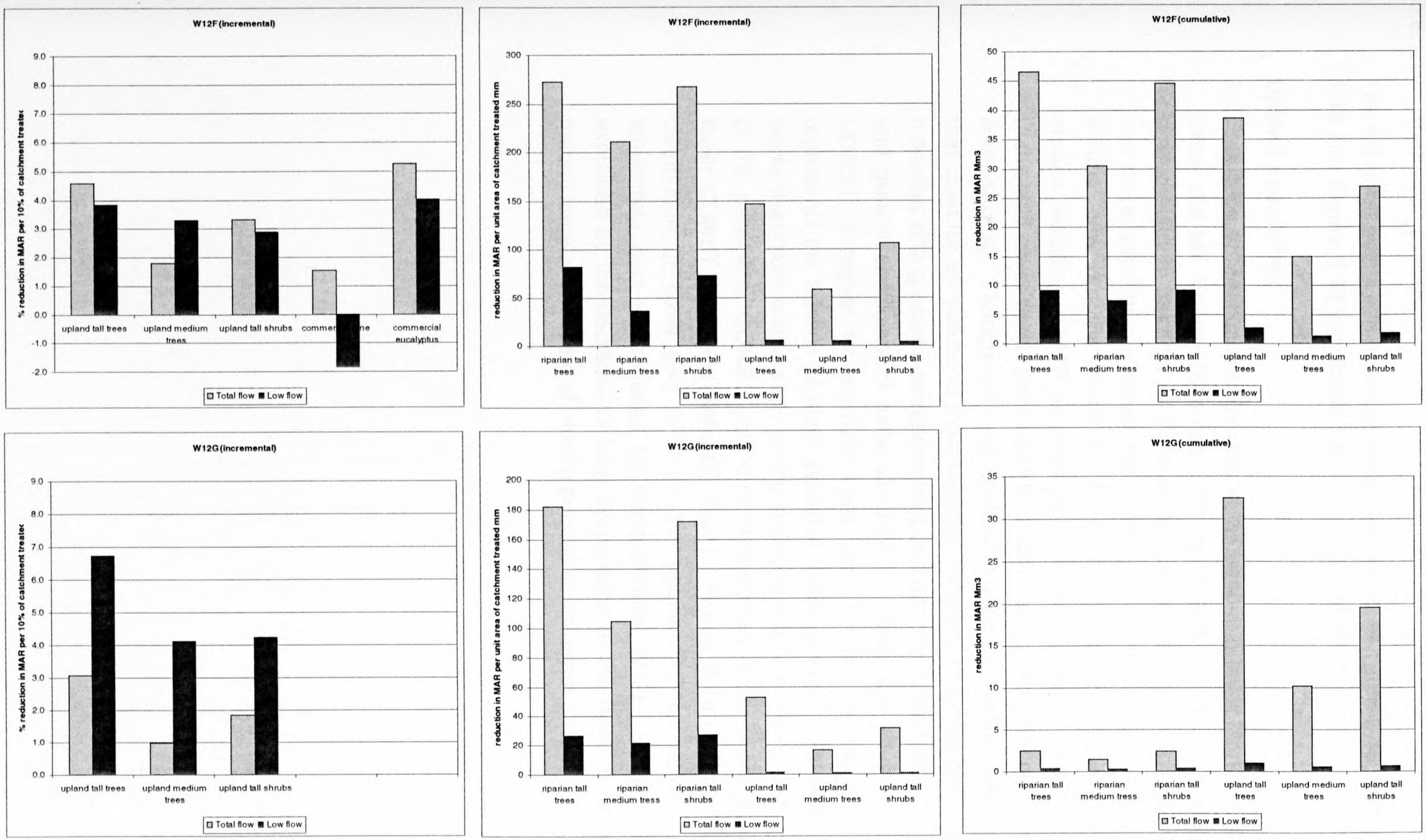


Figure 5.14: (continued) Summary of SFR Estimates Produced by ACRU for the Mhlatuze

5.6.1.1 Reduction in MAR

The following points can be made about the results in **Table 5-16**, **Table 5-17, Table 5-18** and **Figure 5-14** with respect to reduction in MAR:

Upland scenarios:

1. Reduction in MAR caused by upland tall trees is greater than by upland medium trees and tall shrubs; however, SFR by upland tall shrubs is greater than by upland medium trees for all the sample catchments. It is expected that tall trees use more water than medium trees and medium trees use more water than tall shrubs, however, the model results show that tall shrubs in Mhlatuze cause greater reduction in MAR on average than medium trees. This can be attributed to the land cover parameters used to model water use by the plants (presented in **Appendix A**). Though, the crop coefficient used for medium trees is higher than that used for tall shrubs in most months (February to November); tall shrubs are modelled with greater interception loss, greater root colonisation of the B horizon and greater coefficient of initial abstraction. Also, the value of the parameter CONST is higher for medium trees than for tall shrubs. This parameter represents the fraction of plant available water at which total evaporation drops below maximum evaporation during drying of the soil. Plants with higher values of the parameter CONST are more conservative water users than plants with lower CONST (Pike and Schulze, 2001). **Figure 5-15** illustrates the seasonal distribution of flows and SFR for the upland IAP scenarios. An average streamflow gain is simulated for subcatchment W12F in May. This may be explained by the decrease of total evaporation by the trees to below that of the natural vegetation replaced, during periods of soil water stress.

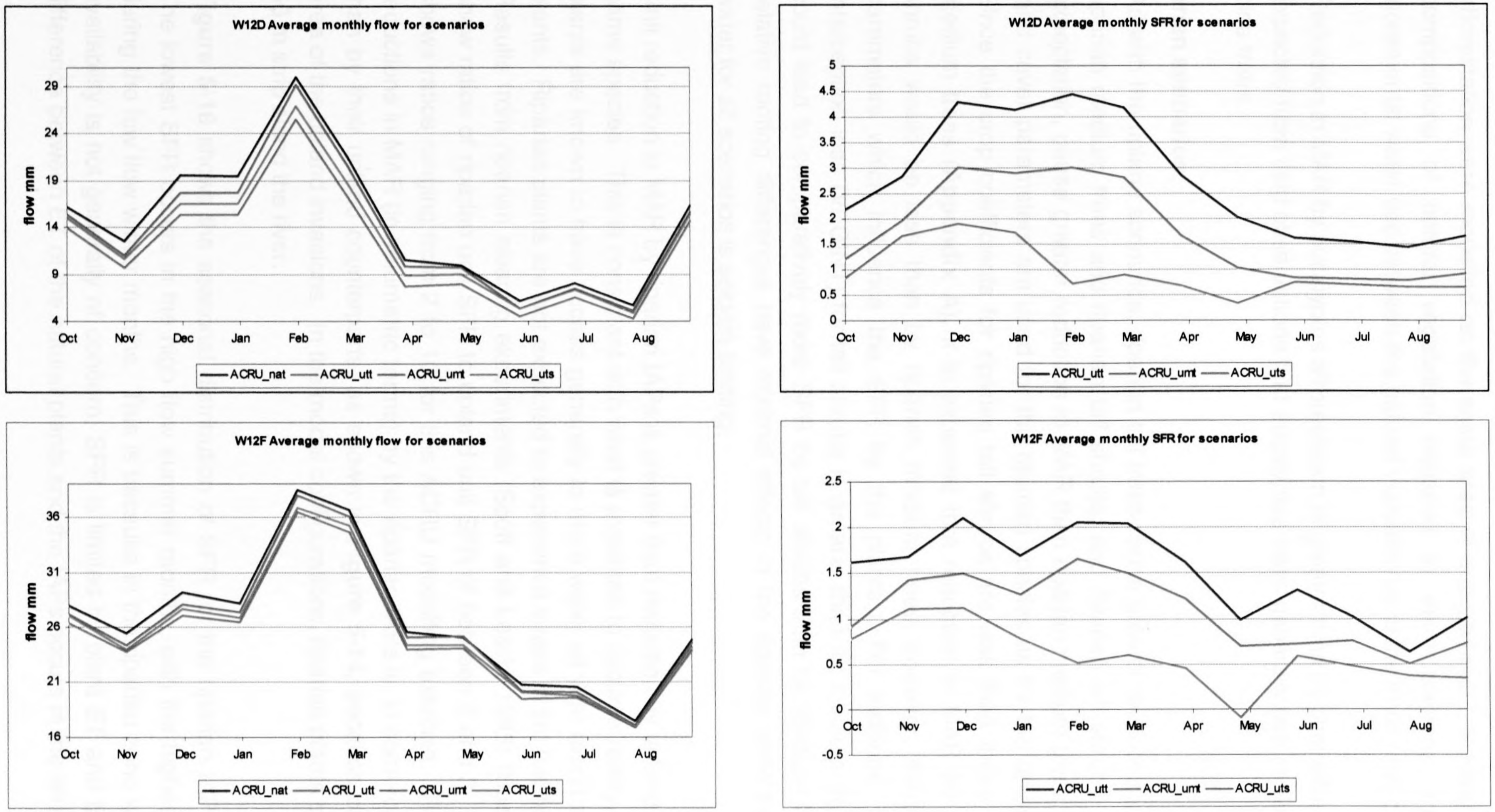


Figure 5-15 Average monthly SFR produced by ACRU for Subcatchments in the Mhlatuze for Upland Scenarios

2. Reduction in MAR estimated for the eucalyptus afforestation scenario is greater than for the tall tree scenario, though eucalyptus land cover parameters are used for tall trees. The difference in results is because different areas of tall trees and eucalyptus afforestation were modelled on the same area of subcatchment, leading to different compositions of natural vegetation replaced in each scenario and different incremental water use between the natural vegetation and the trees replacing it.

3. Reduction in MAR by eucalyptus afforestation is greater than by pine afforestation, as expected from field observations that eucalyptus trees generally use more water than pine trees.

Riparian scenarios:

1. As with the upland scenarios, riparian tall trees cause greater reduction in MAR than riparian medium trees and riparian tall shrubs, and riparian tall shrubs, contrary to expectation, cause greater reduction in MAR than riparian medium trees. The same land cover parameters are used for the riparian species as for the upland species. Since the crop coefficients for riparian tall shrubs are less than those for riparian medium trees (**Appendix A**), it is expected that reduction in MAR by riparian tall shrubs would be less than by riparian medium trees; however, there are other parameters which influence the SFR by the plants. For instance, the canopy interception loss (VEGINT) for tall shrubs is greater than for medium trees and this could lead to comparatively more SFR by tall shrubs than by medium trees. Also relative rooting differences have minimal effects in the riparian zone because soil water for all scenarios is seldom limiting.

2. Unit reduction in MAR by riparian IAPs is greater than reduction by upland IAPs of the same species. This is consistent with what is expected to occur in reality, as riparian plants are known to have access generally to more water all year round than upland plants. Riparian plants are not expected to experience stress in the low flow months. Results from riparian clearing experiments (Scott and Lesch, 1995) (**Section 2.2.2)** show ratios of riparian unit SFR to upland unit SFR of between 2 and 3. **Table 5-17** shows ratios ranging from 2 to 10 for this ACRU modelling exercise. The absolute reductions in MAR (in volumetric terms) by the riparian IAPs is, in some cases, lower than by their upland counterparts, as shown in **Figure 5-14**, because of the larger area of the upland invasions. In the model configurations, riparian plants cover only a 60 m strip along the river.

3. **Figure 5-16** shows the seasonal distribution of SFR for the riparian IAP scenarios. The lowest SFR occurs in the high flow summer months, with the highest occurring during the low flow winter months. This is because in the riparian zone where water availability is not generally of concern, SFR is limited by plant ET and the greatest difference between ET of the natural plants and the IAPs occurs in the winter. This is

because in winter, many natural plants lose their leaves and stop transpiring, whereas many IAPs retain their leaves and continue to transpire. This trend in transpiration is apparent in the plant crop coefficients presented in **Appendix A**. Also, **Appendix A** shows that there are several months where the crop coefficient of tall shrubs is greater than that of the natural vegetation (bushveld and grassveld), however, the results for riparian tall shrubs do not display streamflow gains in these months. This may also be explained by the fact that there are other parameters which influence the SFR caused by the plants. A sensitivity analysis of the various parameters, which influence SFR, is beyond the scope of this study.

Figure 5-16: Average Monthly SFR Produced by ACRU for Subcatchments in Mhlatuze for Riparian IAP Scenarios

Current Scenario:

Table 5-18 shows that the reduction in baseline MAR (caused by all current day water uses, including afforestation and IAPs) over the whole Mhlatuze catchment (at the end of subcatchment W12F; refer to **Figure 4-3**) is 59.5%. Subcatchment W12G has a low reduction in MAR compared to the other subcatchments. An examination of the land use in W12G (an upstream subcatchment) reveals that 59% of the subcatchment (most of the subcatchment) is covered in natural vegetation and there is no commercial afforestation in the subcatchment. This explains why the current day total water use is lower than in the rest of the catchment.

5.6.1.2 Reduction in Low Flows

The following points can be made about the results in **Table 5-16**, **Table 5-17, Table 5-18** and **Figure 5-14**, with respect to reduction in low flow MAR:

Upland scenarios:

1. As with total MAR, reduction in low flow MAR is greater for tall trees than for medium trees and tall shrubs, but reduction in low flow MAR is anomalously greater for tall shrubs than for medium trees. However, subcatchment W12F results are more as expected in that reduction in low flow SFR by medium trees is greater than by tall shrubs. This may be because W12F is wetter than the other subcatchments, with a higher MAP and baseline MAR simulated by ACRU. In such a wetter catchment, the medium trees are less likely to experience stress during the dry season and total evaporation is less likely to fall below that of tall shrubs (See point 1 in **Section 5.6.1.1**).

2. In subcatchment W12D, the average reduction in low flow MAR for pine afforestation is greater than for eucalyptus afforestation, whereas in subcatchment W12F, a gain in low flow SFR is simulated for pine afforestation. Looking at the results of the pine afforestation scenario for the complete catchment, including subcatchments which are not in the selected sample for discussion, gains in low flow due to pine afforestation is a common outcome. This is evident in **Table 5-19** which shows positive average low flow SFR for only subcatchments W12D and W12H. The difference in response between low flow gain and low flow reduction may be due to differences in parameters among the subcatchments, including the composition of natural vegetation replaced by the pine trees, and soil properties.

Table 5-19: **Mean Annual Low Flow SFR due to Pine and Eucalyptus Afforestation Estimated by ACRU for Subcatchments in the Mhlatuze**

subc	% reduction in low flow MAR per 10% of catchment treated with pine	% reduction in low flow MAR per 10% of catchment treated with eucalyptus
W12A	-7.0	12.5
W12B	-3.6	5.4
W12C	-0.2	8.6
W12D	2.8	1.8
W12F	-1.8	4.0
W12H	1.0	9.6

The gains in low flow streamflow, displayed by most of the subcatchments, is due to the decrease of total evaporation by the pine trees below maximum evaporation during drying of the soil. This drop in total evaporation by plants is governed by the parameter CONST, as described Section **5.6.1.1**. As shown in **Appendix A**, CONST for pine trees is relatively high (0.9). This can lead to water use by pines being lower than that of the natural vegetation being replaced during periods of the dry season. **Figure 5-17** presents plots of monthly time series of flow produced by ACRU for upland scenarios. **Figure 5-17** shows that in ACRU streamflow gains after afforestation or invasion by IAPs are possible at various times during the year due to exact types of model coefficient changes affected when changing from baseline or natural to IAP or afforestation conditions. **Figure 5-17** also shows that the streamflow gains in subcatchment W12F are more severe than in subcatchment W12G, though W12F is a wetter subcatchment than W12G (refer to **Table 5-15**) and is covered by lower water-using baseline vegetation than W12G (the dominant natural land cover is grassveld in W12F and bushveld in W12G (refer to **Appendix A**)). This may be because the soil in W12F has a higher plant available water content (PAW) on average, than the soil in W12G, therefore, total evaporation of plants in W12F drops below maximum evaporation earlier (when the soil is wetter) than in W12G. Values of average PAW for the two subcatchments are shown in **Table 5-20**.

Table 5-19 shows that on average reduction in low flow caused by eucalyptus afforestation is higher than by pine afforestation. This is expected from field observations of greater water use generally of eucalyptus trees than pine trees (Scott *et al*, 2000).

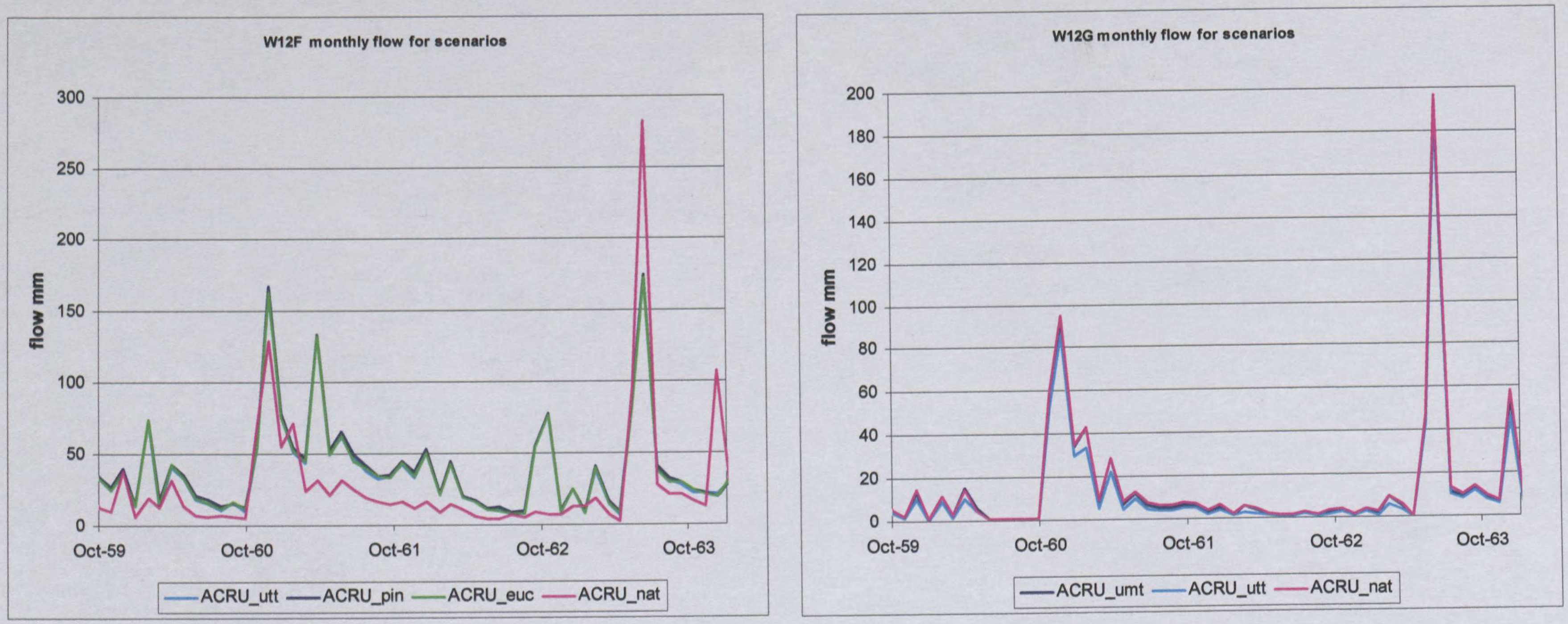


Figure 5-17: Monthly Time Series of Flow Produced by ACRU for Upland Scenarios in Subcatchments W12F and W12G in the Mhlatuze

Table 5-20: Values of Plant Available Water Capacity of Soils in Subcatchments W12F and W12G in the Mhlatuze

Subcatchment	PAW (A horizon) (m.m^{-1})	PAW2 (B horizon) (m.m^{-1})
W12F	0.09	0.09
W12G	0.08	0.08

Riparian scenarios:

It should be noted that riparian invasions in the simulations cover a 60 m strip along the river as explained in **Section 5.4.6**.

1. As may be expected, reduction in low flow MAR by riparian tall trees is greater than by riparian medium trees, however, reduction in MAR by riparian tall shrubs is greater than by both riparian medium trees and tall trees. Whereas absolute reductions in MAR by riparian IAPs can be less than for upland IAPs, because of the large difference in area invaded, absolute reductions in low flow MAR by riparian IAPs tend to be greater than by upland IAPs, despite the much smaller areas of riparian IAPs. This can probably be attributed to the availability of water to riparian plants even in the low flow season and the smaller likelihood of riparian plants being soil water stressed in the low flow season.

   The riparian scenarios do not appear to result in the low flow streamflow gains exhibited by the upland scenarios. This is because riparian plants are less likely to experience soil water stress and total evaporation by the IAPs is less likely to fall below maximum evaporation, as described in **Section 5.6.1.2. Figure 5-18** depicts part of the time series produced for the natural scenario and riparian scenarios for subcatchments W12F and W12G. These are cumulative (because the riparian IAPs have access to upstream throughflows and upstream streamflows) as opposed to incremental time series.

   Current Scenario:

   Table 5-18 shows that the reduction in baseline low flow MAR (caused by all current day water uses, including afforestation and IAPs) over the whole Mhlatuze catchment (at the end of subcatchment W12F) is 93.5%. Subcatchment W12G has negligible reduction in low flow MAR. This can be explained by the composition of land uses in the subcatchment. Most of the subcatchment, 59% is covered in natural vegetation, all the crop production is dryland and there is no commercial afforestation in the subcatchment.

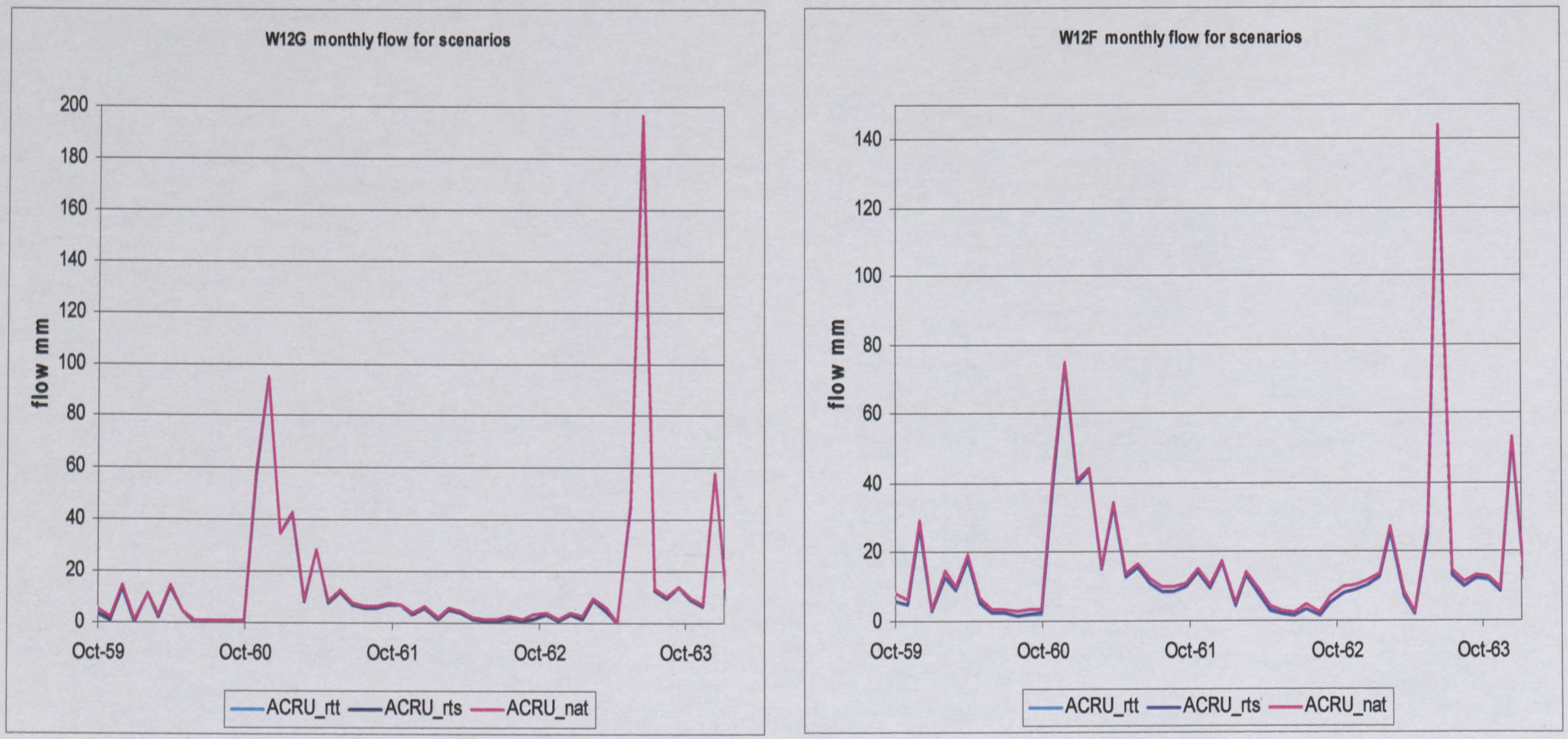


Figure 5-18: Monthly Time Series of Flow Produced by ACRU for Riparian Scenarios in Subcatchments W12F and W12G in Mhlatuze

General observations:

1. On average, percentage reduction in low flow MAR is greater than percentage reduction in total flow MAR. This is consistent with what has been observed in the field (Scott *et al,* 2000) (see **Section 2.2.1**). Exceptions to this trend are: low flow streamflow gains in the pine scenarios; the tall shrub and tall tree scenarios in subcatchment W12F; and the eucalyptus afforestation in subcatchments W12D and W12F. **Table 5-21**, which compares total and low flow MAR reduction for all the Mhlatuze subcatchments for the eucalyptus afforestation scenario, shows that the subcatchments with average proportional low flow reductions greater than average proportional total flow reductions are the exception for this scenario.

Table 5-21: Average Reductions in Total and Low Flow SFR Produced by ACRU for Subcatchments in Mhlatuze

subc	% reduction in total MAR per 10% of catchment treated with eucalyptus	% reduction in low flow MAR per 10% of catchment treated with eucalyptus
W12A	6.5	12.5
W12B	3.3	5.4
W12C	5.6	8.6
W12D	4.8	1.8
W12F	5.2	4.0
W12H	5.2	9.6

2. When the trends in SFR are examined cumulatively, the effects of individual incremental subcatchments appear to be smoothed over and the reductions in MAR follow the general trend of reductions. This is seen in the mean annual low flow SFR for the pine scenario. When examined incrementally, a few subcatchments display an average reduction in low flow due to pine afforestation (rather than the average gain in low flow, which appears to be the general trend for the pine scenario); however, when the cumulative impact on all contributing subcatchments is examined, the general trend, of an average gain in low flow due to pine afforestation, is observed. This is shown in **Table 5-22**, which presents the incremental and cumulative average annual low flow reductions for subcatchments where pine afforestation was modelled.

Table 5-22 Average Incremental and Cumulative Reductions in Low Flow SFR due to Pine Produced by ACRU for Subcatchments in Mhlatuze

Subcatchment		% reduction in low flow MAR per 10% of catchment treated with pine	
Incremental	Cumulative	Incremental	Cumulative
W12A		-7.0	NA
W12B	W12B + W12A	-3.6	-2.6
W12C		-0.2	NA
W12D	W12D + W12C + W12B + W12A	2.8	-2.4
W12F	W12F + W12H + W12G + W12E + W12D + W12C + W12B + W12A	-1.8	-0.5
W12H	W12H + W12G	1.0	NA

The smoothing effect of analysing the results cumulatively is also seen in the comparison of percentage reductions in total and low flow MAR. On some incremental subcatchments, percentage reductions in mean annual low flow due to afforestation or IAPs are anomalously smaller than percentage reductions in MAR; however, when the cumulative impact on all contributing subcatchments is examined, percentage reduction in mean annual low flow is larger than percentage reduction in MAR, as expected.

5.6.2 Upper Berg

Table 5-23 presents results from the ACRU Upper Berg scenarios baseline (nat), current (cur), current with afforestation removed (cfo), current with aliens removed (cav) and commercial pine afforestation scenario (pin). These scenarios are described in **Section 5.4**. The results for the scenarios are expressed as reduction from the natural scenario (for the cur and pin scenarios) and gains (due to clearing) from the current scenario (for the cfo and cav scenarios). **Figure 5-19** compares the flows produced for the different scenarios. The Berg scenarios are analysed at the flow exit point of the total Upper Berg catchment. Commercial afforestation in the current scenario consists of pine and covers 13% of the catchment. IAPs cover 6% of the catchment (condensed area). Of the IAP area, 47% consists of tall trees, predominantly pine, 14% of medium trees, mainly wattle and 39% of tall shrubs, hakea.

It should be noted that the difference in streamflow between the "cur" and "cfo" or "cav" scenarios is not due purely to the clearing of afforestation or the clearing of IAPs, since there are other influences within the scenarios, which might be reflected in the differences in streamflow. For example, abstractions, which may not be satisfied by the current streamflow, may absorb some of the flow liberated by the clearing of the trees. Another example is the modifying impacts of dam storage. These influences are reflected in the difference in results between the "cfo" and "pin" scenarios.

Figure 5-20 shows the seasonal distribution of flows and reductions, and **Figure 5-21** shows a portion of the monthly time series for the natural and current scenarios. The greatest absolute SFR due to afforestation and IAPs occurs in the high flow winter months. Average gains in streamflow due to afforestation and IAPs are produced in some low flow months. The reasons for these gains in streamflow are discussed in **Section 5.6.1.2**. The current scenario displays streamflow gains from the baseline streamflow in the low flow months. This is attributed to irrigation releases from outside the Upper Berg catchment into an upstream catchment of the Upper Berg.

5.6.2.1 Reduction in MAR

The results show that clearing of commercial afforestation from the current land cover scenario is simulated to increase current MAR by 5.7 mm (0.8% of baseline MAR) and clearing of IAPs is simulated to increase current MAR by 2.4 mm (0.3% of baseline MAR).

Streamflow gains from clearing afforestation from the current day land use scenario in the catchment are more per 10% of catchment invaded than streamflow gains from clearing IAPs. This is expected as a large proportion of the IAP area consists of tall shrubs and medium trees and the afforestation consists entirely of tall trees.

Table 5-23 shows that clearing afforestation from the current scenario in the Upper Berg catchment would result in a lesser increase in MAR than clearing the same afforestation from an afforested baseline scenario (5.7 mm and 6.1 mm, respectively). The difference in results between the two scenarios is due to the presence of other water use influences in the "cfo" scenario, as described at the beginning of **Section 5.6.2**. The results show that 0.4 mm (the difference between SFR in the "pin" scenario and water use in the "cfo" scenario) of the water liberated by clearing the commercial afforestation from the Upper Berg current scenario is absorbed by other water uses in the catchment. This is approximately 6.5% of the water liberated by clearing the afforestation.

The gains in SFR from clearing afforestation are lower than expected. **Table 5-6** shows that, from the results of the South African catchment experiments (Scot *et al*, 2000), SFR due to pine afforestation in the winter rainfall region ranges from 21 to 30 mm per 10% of catchment treated, however, the ACRU modelling produces SFR due to pine afforestation of 4.7 mm per 10% of catchment afforested. As described in **Section 5.3.2**, this difference in magnitude between the experimental and simulated results may be due to variations in conditions between the experimental catchment sites and the simulated catchment.

5.6.2.2 Reduction in Low Flows

The increase in low flow MAR from the natural to current scenario (increase of 7.1 mm) is caused by irrigation releases into one of the upstream subcatchments, from Theewaterskloof Dam, which lies outside the Upper Berg catchment.

The results show that clearing the current levels of afforestation and IAPs in the Upper Berg is simulated to create reductions in low flow MAR of 0.3 mm and 0.2 mm respectively, 0,7% and 0,5% of the baseline low flow MAR.

Table 5-23 shows that clearing afforestation from the current scenario in the Upper Berg catchment would result in a reduction in MAR, very similar to the reduction in MAR created by clearing the same afforestation from an afforested baseline scenario, implying that the other water use influences (described at the beginning of **Section 5.6.2)** present in the "cfo" scenario, but not the "pin" scenario, have little effect (on average) on the impact of clearing afforestation on low flows in the Upper Berg. **Figure 5-20** shows a slight variation in the results of the two scenarios in the low flow season, indicating that some of the low flow streamflow gains due to commercial afforestation are absorbed by the other water use influences in the current scenario.

Table 5-23: MAR and SFR and Water Use Estimates Produced by ACRU for the Upper Berg

Scenario	*Determination of water use or SFR	MAR (mm)		Water use or SFR (mm)		Water use or SFR (mm per 10% of catchment treated)		Water use or SFR (% per 10% of catchment treated)	
		Total flow	Low flow	Total flow	Low flow	Total flow	Low flow	Total flow	Low flow
nat		704.8	42.8						
cur	nat - cur	597.6	49.9	107.2	-7.1				
cfo	cfo - cur	603.3	49.6	5.7	-0.3	4.4	-0.2	0.7	-0.5
cav	cav - cur	600.0	49.7	2.4	-0.2	3.8	-0.3	0.6	-0.6
pin	nat - pin	698.7	43.1	6.1	-0.3	4.7	-0.2	0.7	-0.5

* eg current day water use = baseline streamflow-current streamflow (nat-cur)

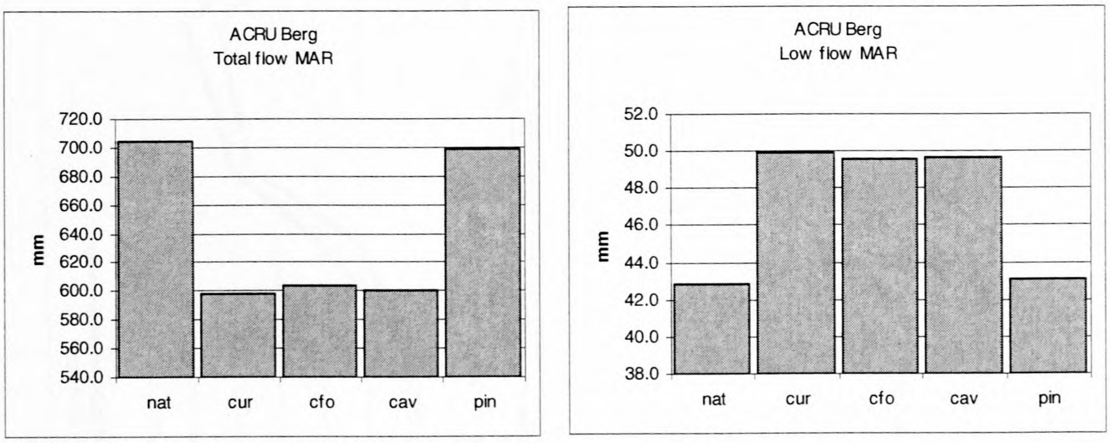
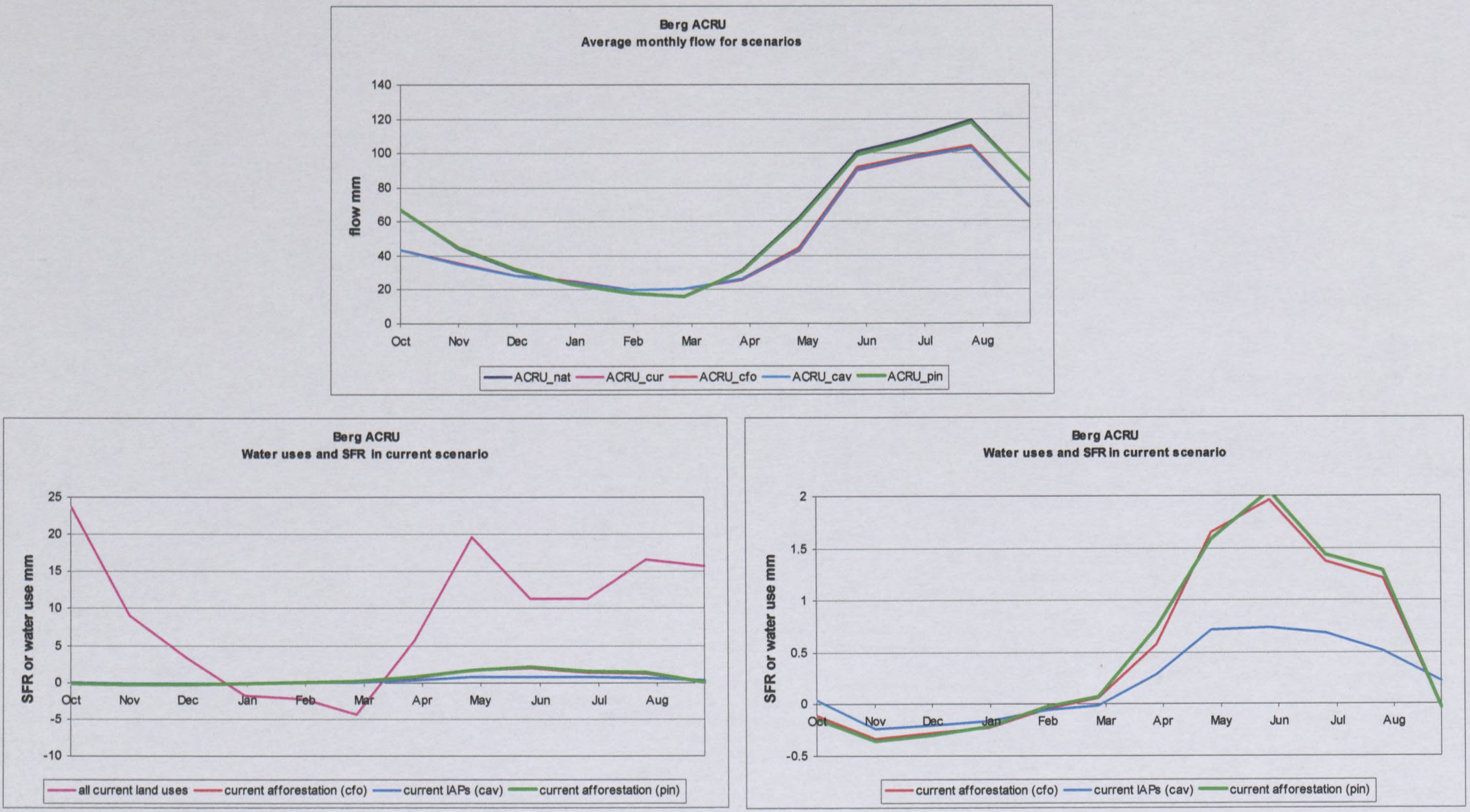


Figure 5-19: MAR Estimates Produced by ACRU for the Upper Berg


Berg ACRU
Average monthly flow for scenarios

Berg ACRU
Water uses and SFR in current scenario

Berg ACRU
Water uses and SFR in current scenario

Figure 5-20: Seasonal Distribution of Flows and Reductions for the Upper Berg ACRU Scenarios

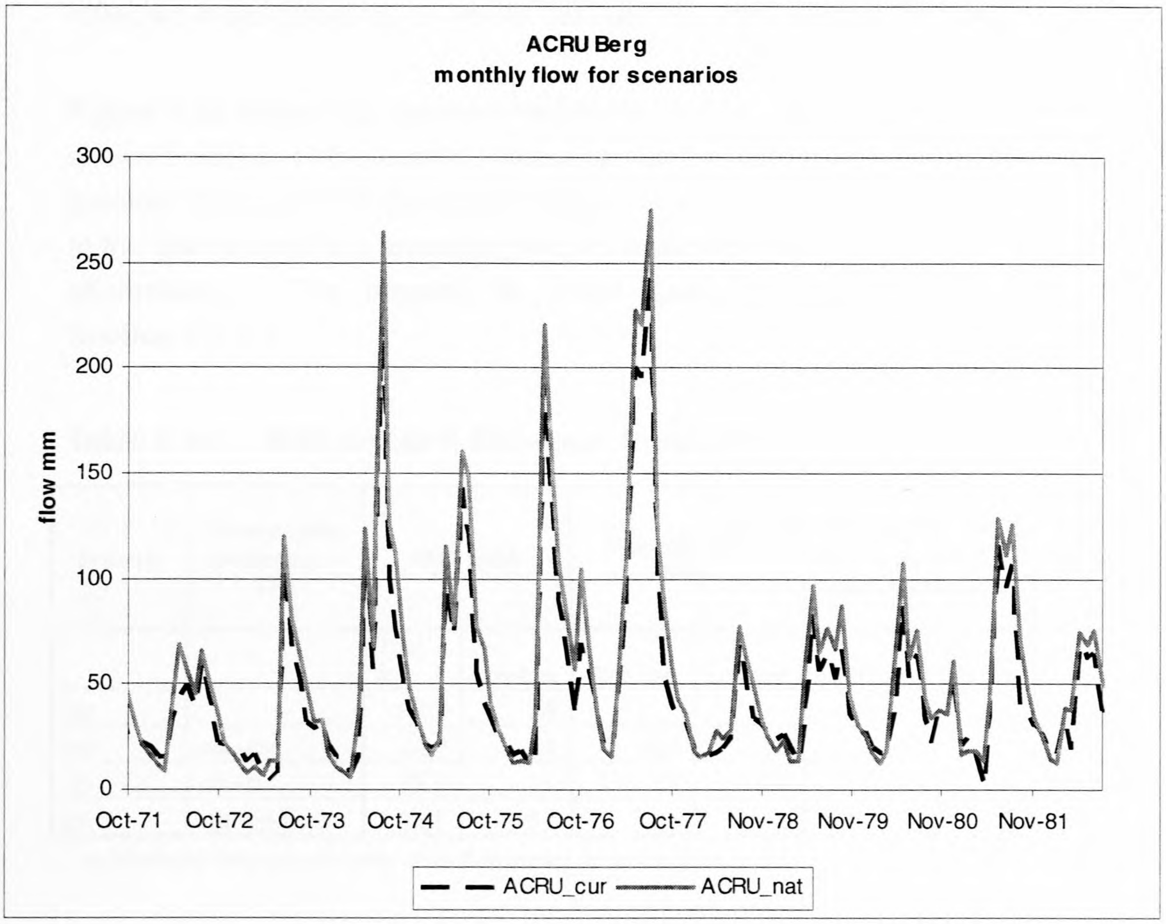


Figure 5-21: Monthly Time Series of Flows for Upper Berg ACRU Scenarios

5.6.3 Upper Sabie

Table 5-24 shows results from the ACRU Sabie scenarios baseline (nat), current (cur), current with afforestation removed (cfo) and commercial afforestation (pin). These scenarios are described in **Section 5.4**. The results for the scenarios are expressed as reduction from the natural scenario (for the cur and pin scenarios) and gains (due to clearing) from the current scenario (for the cfo scenario). **Figure 5-22** compares the flows produced for the different scenarios. The Sabie scenarios are analysed at the flow exit point of the total catchment. Commercial afforestation, predominantly pine, covers 44% of the Upper Sabie catchment. The area covered by IAPs is negligible.

It should be noted that the difference in streamflow between the "cur" and "cfo" scenarios is not due purely to the clearing of afforestation, since there are other influences within the scenarios, which might be reflected in the differences in streamflow. For example, abstractions, which may not be satisfied by the current streamflow, may absorb some of the flow liberated by the clearing of the trees.

Another example is the modifying impacts of dam storage. These influences are reflected in the difference in results between the "cfo" and "pin" scenarios.

Figure 5-22 shows the seasonal distribution of flows and reductions and **Figure 5-23** shows a portion of the monthly timeseries for the natural and current scenarios. The greatest absolute SFR due to afforestation occurs in the high flow summer months. In the low flow months, average gains in streamflow are produced due to commercial afforestation. The reasons for these gains in streamflow are discussed in **Section 5.6.1.2**.

Table 5-24: MAR and SFR Estimates Produced by ACRU for the Upper Sabie

Scenario	*Determination of water use or SFR	MAR (mm)		Water use or SFR (mm)		Water use or SFR (mm per 10% of catchment treated)		Water use or SFR (% per 10% of catchment treated)	
		Total flow	Low flow	Total flow	Low flow	Total flow	Low flow	Total flow	Low flow
nat		216.0	2.6						
cur	nat - cur	130.0	1.5	86.0	1.1				
cfo	cfo - cur	132.9	1.1	2.9	-0.4	0.7	-0.1	0.5	-5.9
pin	nat - pin	216.5	3.7	-0.4	-1.2	-0.1	-0.3	0.0	-10.2

* eg current day water use = baseline streamflow-current streamflow (nat-cur)

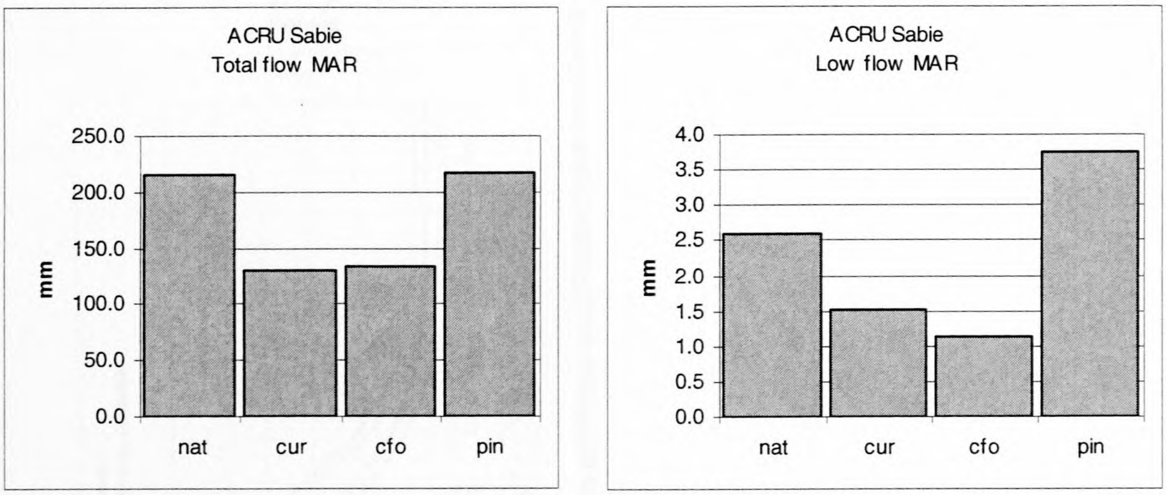


Figure 5-22: MAR Estimates Produced by ACRU for the Upper Sabie

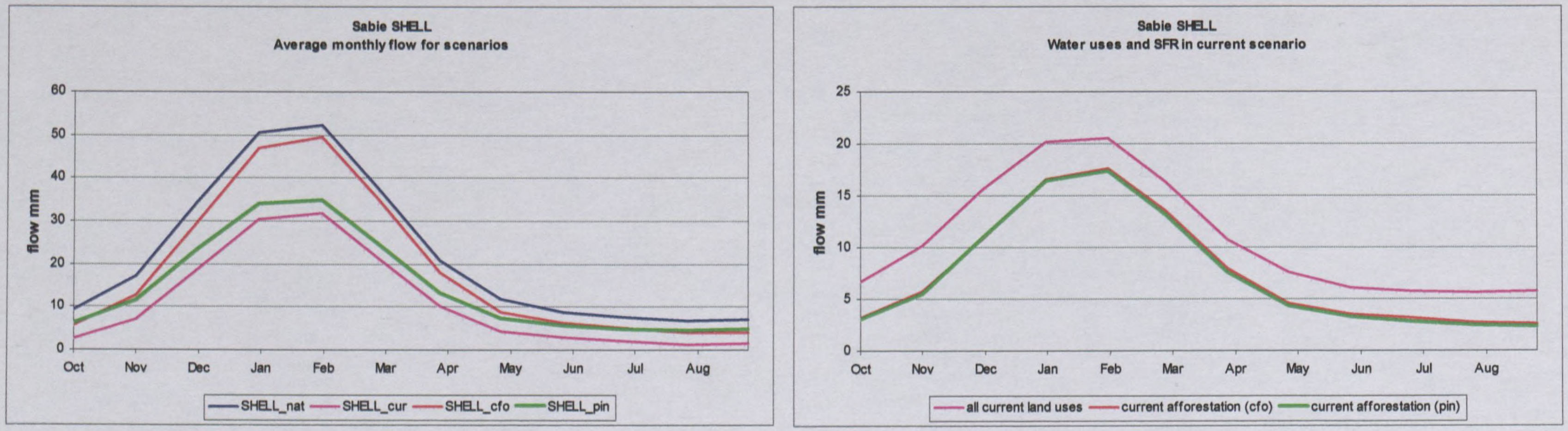


Figure 5-23: Seasonal Distribution of Flows and Reductions for Sabie ACRU Scenarios

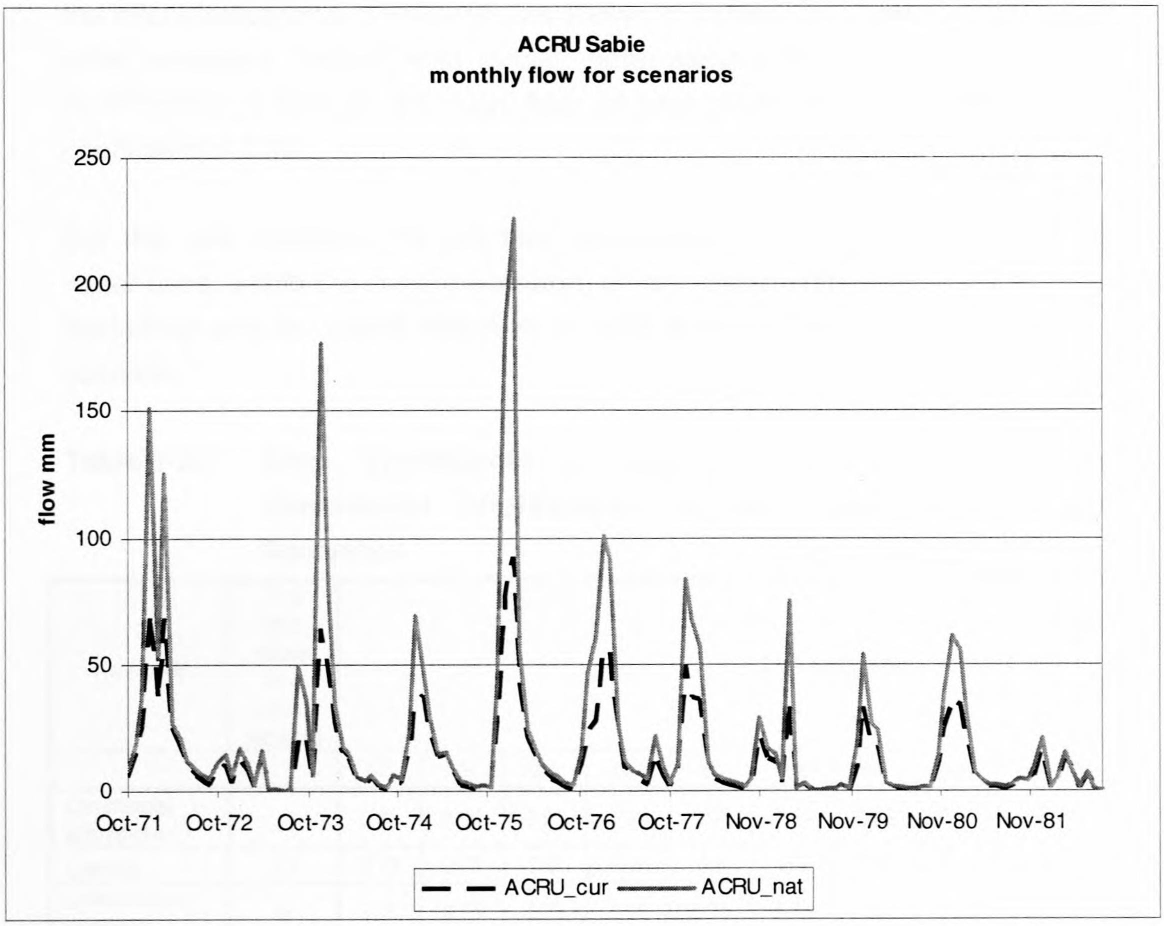


Figure 5-24: Monthly Time Series of Flows for Upper Sabie ACRU Scenarios

5.6.3.1 Reduction in MAR

The results show that clearing of current commercial afforestation from the current land cover scenario is simulated to increase current MAR by 3 mm (1.4% of baseline MAR). The results also show that the same commercial afforestation is simulated to cause a streamflow gain of 0.4 mm when added to the baseline scenario. This difference in results between the two scenarios is due to the presence of other water use influences in the "cfo" scenario, as described at the beginning of **Section 5.6.3.**

The gain in MAR due to afforestation simulated in the "pin" scenario (0.4 mm) is contrary to expectation. **Figure 5-23** shows that, for the "pin" scenario, reductions in streamflow due to afforestation are simulated for the high flow months, whereas streamflow gains are simulated for the low flow months. The high streamflow gains in the low flow months and the larger number of months with streamflow gains than reductions leads to an overall gain in MAR. This small gain in MAR may be explained by the high value of the parameter CONST used for pines (as described in **Section 5.3.2**) and by a comparison of the crop coefficients used for the afforestation and the natural vegetation replaced. In the high flow months, the crop coefficients of the natural vegetation replaced by the afforestation are relatively high compared to the afforestation crop coefficients, as shown in **Table 5-25**. **Table 5-25** shows that the most dominant natural land cover, north-eastern mountain sourveld, has crop coefficients of 0.75 in the high flow months while the afforestation has a crop coefficient of 0.85.

For the “cfo” scenario, the low flow streamflow gains simulated are diminished by water uses, within the current scenario, which absorb some of the stream flow gains, explaining why an overall reduction in MAR due to afforestation is simulated for this scenario.

Table 5-25 Crop Coefficients of Natural Land Covers Replaced by Commercial Afforestation in the Upper Sabie Afforestation Scenarios

Land cover	% of total natural land cover replaced	Crop coefficients											
		oct	nov	dec	jan	feb	mar	apr	may	jun	jul	aug	sep
Commercial afforestation		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Lowveld	0.1	0.75	0.75	0.8	0.8	0.8	0.8	0.65	0.55	0.4	0.4	0.4	0.6
Lowveld sour bushveld	9	0.75	0.75	0.75	0.75	0.75	0.75	0.7	0.65	0.6	0.55	0.55	0.6
North-eastern mountain sourveld	83	0.7	0.7	0.75	0.75	0.75	0.75	0.6	0.5	0.25	0.25	0.25	0.5
Thicket & bushland (etc)	8	0.65	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.5	0.35	0.35	0.55

5.6.3.2 Reduction in Low Flows

The results show that the current level of afforestation in the upper Sabie is simulated to cause gains in low flow MAR of 0.4 mm, about 15% of the baseline low flow MAR. The same afforestation superimposed on a baseline scenario causes gains in streamflow of 1.2 mm. The difference in results is caused by water uses within the current scenario, which absorb some of the streamflow gains caused by the afforestation.

5.7 SFR Estimates Produced by SHELL

This section examines and discusses SFR estimates produced by SHELL for the three study systems.

5.7.1 Mhlatuze

Table 5-26 presents SFR estimates produced by SHELL for upland scenarios for a sample of Mhlatuze subcatchments. The SFR is expressed as both absolute and percentage reduction per 10% of catchment invaded or afforested to allow for comparison between subcatchments of different sizes and different levels of invasion. **Table 5-27** presents SFR estimates produced by SHELL for riparian scenarios for the same sample of Mhlatuze subcatchments. The riparian SFRs are expressed as unit reduction, i.e., the reduction per unit area invaded (the unit reduction for the corresponding upland scenario is included in a column beside the unit reduction for the riparian scenario for comparison between upland and riparian SFR), volumetric reduction in catchment MAR and percentage reduction in catchment MAR. The volumetric values are expressed both incrementally, i.e., the reduction in total runoff from the subcatchment only, caused by invasion or afforestation on the subcatchment, and cumulatively, i.e., the reduction in total contributing flow from all upstream subcatchments caused by total invasion on all contributing subcatchments. This is because, over and above the water in the invaded riparian area, riparian invasions have access to water coming from upstream. The results in **Table 5-26** and **Table 5-27** are also presented in **Figure 5-25**. The SFR estimates are discussed below in two categories, reduction in MAR and reduction in low flows.

Table 5-28 shows the results of the current scenario. The mix of land and water uses and land covers in the Mhlatuze catchment includes afforestation, covering 31% of the catchment, and IAPs, covering 5% of the catchment area. The results for the current scenario are expressed cumulatively, since riparian IAPs in the scenario have access to water coming from upstream.

Table 5-26: Summary of SFR Estimates Produced by SHELL for the Mhlatuze Upland Scenarios

Scenario	Subcatcment	Baseline MAR (mm)	Baseline low flow MAR (mm)	Reduction per 10% of catchment treated			
				Reduction in baseline MAR (mm)	Reduction in baseline low flow MAR (mm)	Reduction in baseline MAR (%)	Reduction in baseline low flow MAR (%)
INCREMENTAL RUNOFF							
upland tall trees	W12D	186.3	5.0	13.2	0.4	7.1	7.8
	W12E	311.1	8.4	22.1	0.7	7.1	7.8
	W12F	300.1	11.4	21.4	0.9	7.1	7.4
	W12G	201.3	5.5	14.3	0.4	7.1	7.8
upland medium trees	W12D	186.3	5.0	10.1	0.3	5.4	6.4
	W12E	311.1	8.4	16.8	0.5	5.4	6.5
	W12F	300.1	11.4	16.3	0.7	5.4	6.1
	W12G	201.3	5.5	10.9	0.3	5.4	6.4
upland tall shrubs	W12D	186.3	5.0	4.0	0.1	2.1	2.9
	W12E	311.1	8.4	6.6	0.2	2.1	2.9
	W12F	300.1	11.4	6.4	0.3	2.1	2.6
	W12G	201.3	5.5	4.3	0.2	2.1	2.8
commercial pine	W12D	186.3	5.0	13.5	0.5	7.3	10.0
	W12E	no forestry					
	W12F	300.1	11.4	21.6	0.9	7.2	7.6
	W12G	no forestry					
commercial eucalyptus	W12D	186.3	5.0	12.3	0.5	6.6	10.0
	W12E	no forestry					
	W12F	300.1	11.4	19.5	0.8	6.5	7.3
	W12G	no forestry					

Table 5-27: Summary of SFR Estimates Produced by SHELL for the Mhlatuze Riparian Scenarios

Scenario	Subcatchment Grouping		Total Flow					Low Flow				
	Incremental	Cumulative	Baseline Catchment MAR (10^6m^3)	Unit reduction : Riparian strip MAR (mm)	Unit reduction: Equivalent Upland MAR(mm)	Reduction: Catchment MAR (10^6m^3)	Reduction: Catchment MAR (%)	Baseline Catchment Low Flow MAR (10^6m^3)	Unit red.: Riparian strip Low Flow MAR(mm)	Unit red.: Equivalent Upland Low Flow MAR(mm)	Reduction: Catchment Low Flow MAR (10^6m^3)	Reduction: Catchment Low Flow MAR (%)
riparian tall trees	W12D		105.6	752.0	132.4	18.7	17.7	2.9	160.0	4.0	4.0	139.2
		W12D+W12C+W12B+ W12A	393.5			78.4	19.9	18.2			17.0	93.3
	W12E		76.0	802.5	221.1	6.5	8.6	2.1	206.0	6.6	1.7	81.1
		W12E+W12D+W12C+ W12B+W12A	469.5			84.9	18.1	21.0			18.6	88.6
	W12F		50.1	810.3	213.7	4.2	8.5	1.9	389.6	8.5	2.0	106.9
		W12F+W12H+W12G+ W12E+W12D+W12C+ W12B+W12A	728.9			126.7	17.4	32.4			27.1	83.5
	W12G		64.9	576.7	143.1	7.9	12.2	1.8	119.2	4.3	1.6	93.1
riparian medium trees	W12D		105.6	525.5	100.7	13.0	12.4	2.9	133.0	3.2	3.3	115.7
		W12D+W12C+W12B+ W12A	393.5			53.8	13.7	18.2			14.8	81.5
	W12E		76.0	547.6	168.1	4.5	5.9	2.1	142.0	5.5	1.2	55.9
		W12E+W12D+W12C+ W12B+W12A	469.5			58.2	12.4	21.0			16.0	75.9
	W12F		50.1	547.6	162.6	2.9	5.7	1.9	202.1	7.0	1.1	55.4
		W12F+W12H+W12G+ W12E+W12D+W12C+ W12B+W12A	728.9			86.7	11.9	32.4			22.3	68.8
	W12G		64.9	335.2	108.8	4.6	7.1	1.8	82.6	3.5	1.1	64.5
riparian	W12D		105.6	227.7	39.7	5.7	5.4	2.9	60.7	1.5	1.5	52.8

Scenario	Subcatchment Grouping		Total Flow					Low Flow				
	Incremental	Cumulative	Baseline Catchment MAR (10^6m^3)	Unit reduction : Riparian strip MAR (mm)	Unit reduction: Equivalent Upland MAR(mm)	Reduction: Catchment MAR (10^6m^3)	Reduction: Catchment MAR (%)	Baseline Catchment Low Flow MAR (10^6m^3)	Unit red.: Riparian strip Low Flow MAR(mm)	Unit red.: Equivalent Upland Low Flow MAR(mm)	Reduction: Catchment Low Flow MAR (10^6m^3)	Reduction: Catchment Low Flow MAR (%)
tall shrubs		W12D+W12C+W12B+ W12A	393.5			20.8	5.3	18.2			5.9	32.5
	W12E		76.0	223.4	66.3	1.8	2.4	2.1	62.2	2.5	0.5	24.5
		W12E+W12D+W12C+ W12B+W12A	469.5			22.6	4.8	21.0			6.4	30.5
	W12F		50.1	220.0	64.1	1.2	2.3	1.9	26.1	2.9	0.1	7.1
		W12F+W12H+W12G+ W12E+W12D+W12C+ W12B+W12A	728.9			32.9	4.5	32.4			8.9	27.4
	W12G		64.9	7.3	42.9	0.1	0.2	1.8	7.3	1.6	0.1	5.7

Table 5-28: Summary of Total Water Use Estimates Produced by SHELL for the Mhlatuze Current Scenario (expressed in terms of cumulative runoff)

Scenario	Subcatchment	Baseline MAR mm	Current MAR mm	Baseline flow MAR mm	Current low flow MAR mm	*Reduction in baseline MAR (%)	*Reduction in baselinene Low flow MAR (%)
CUMMULATIVE RUNOFF							
Current Day	W12D	163.3	88.8	7.5	0.2	45.6	97.0
	W12E	176.9	108.7	7.9	1.3	38.5	84.1
	W12F	200.9	132.7	8.9	2.6	34.0	70.5
	W12G	201.3	192.3	5.5	4.7	4.5	14.7

* Due to all land uses and water uses

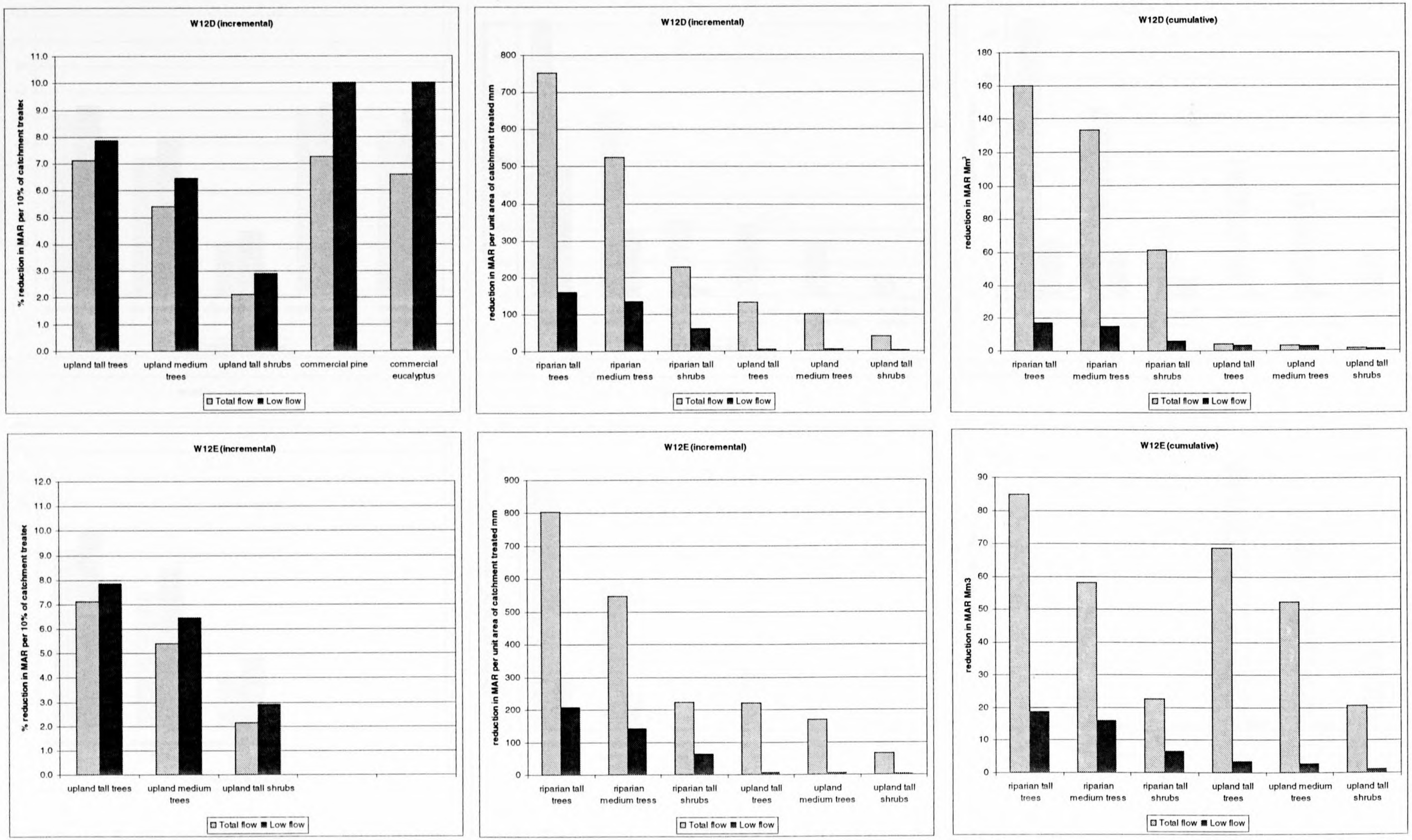


Figure 5-25: Summary of SFR Estimates Produced by SHELL for the Mhlatuze

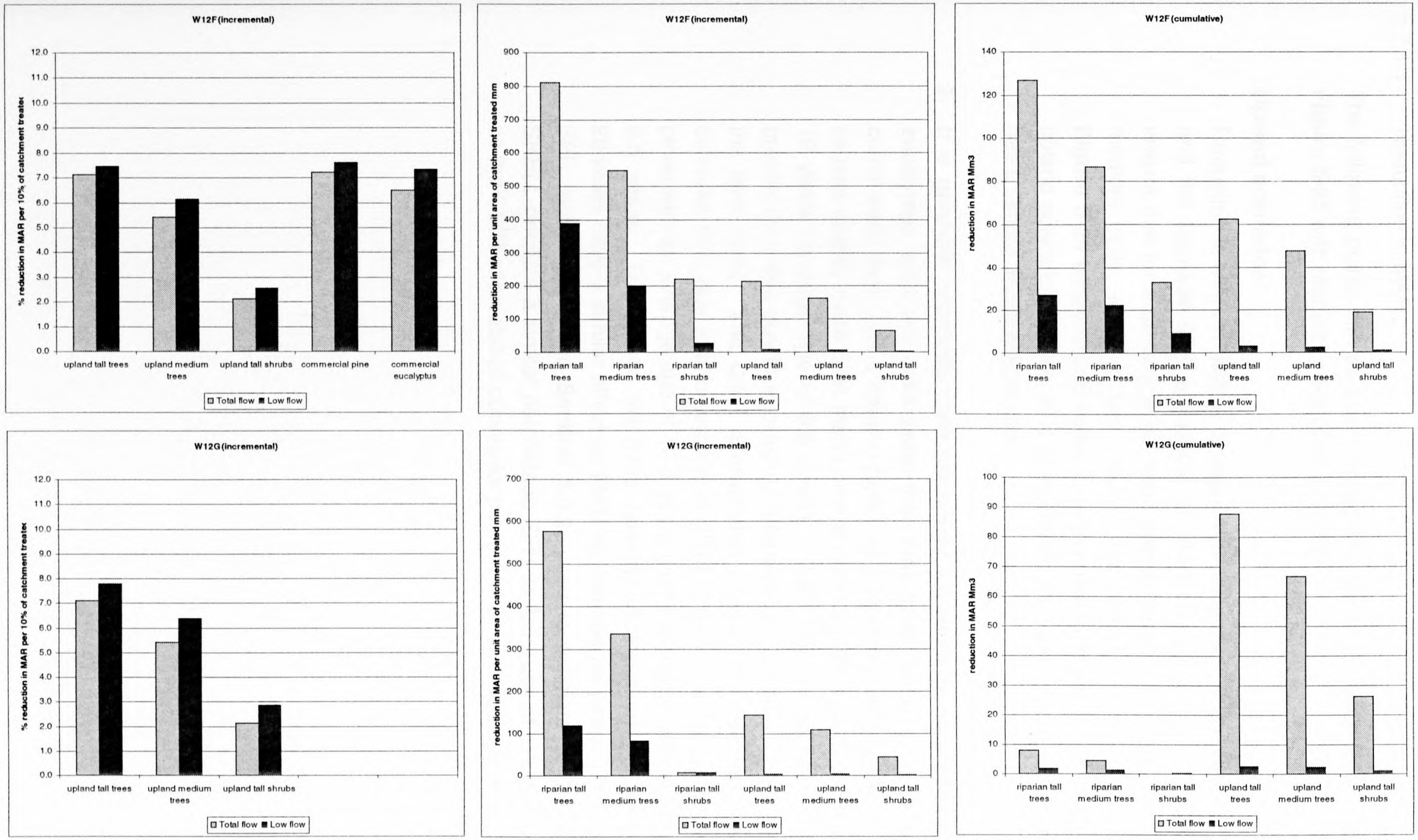


Figure 5-25: (continued) **Summary of SFR Estimates Produced by SHELL for the Mhlatuze**

5.7.1.1 Reduction in MAR

The following points can be made about the results in **Table 5-26, Table 5-27** and **Figure 5-25** with respect to reduction in MAR:

Upland scenarios:

1. Reduction in MAR in SHELL is estimated using the CSIR curves for afforestation and the biomass SFR equations for alien invasions. The fixed CSIR curves ensure that for a given age tall trees always cause more reduction in MAR than medium trees, which in turn cause more reduction in MAR than tall shrubs. **Figure 5-26** below shows some seasonal distributions of flows and SFR for the upland scenarios. Since SFR is estimated as a percentage of natural flow, SFR has a similar distribution to flow.

2. It is generally expected, from catchment experiments (see **Section 2.2.1**) that eucalyptus trees use more water than pine trees; however, in these scenarios, commercial pine, with a rotation period of 20 years (average age of 10.5 years), causes slightly more SFR than commercial eucalyptus, with a rotation period of 12 years (average age of 6.5 years). The SFR, due to pine afforestation, is greater than that due to eucalyptus afforestation, because of the greater age of the pine trees. The CSIR afforestation curves (see **Section 3.3.1**), used to estimate SFR due to afforestation in SHELL, give a higher percentage SFR for pines with an average age of 10.5 years than eucalyptus with an average age of 6.5 years. The upland tall trees (eucalyptus invasion) with average age of 20 years have a similar effect on MAR as commercial pines. The Age-Biomass-SFR relationships (see **Section 3.3.2**) used to estimate SFR due to IAPs in SHELL produce a similar percentage SFR for tall trees of average age 20 years as the CSIR afforestation curves for pines with an average age of 10.5 years.

Figure 5-26: Average Monthly SFR Produced by SHELL for Subcatchments in the Mhlatuze for Upland Scenarios

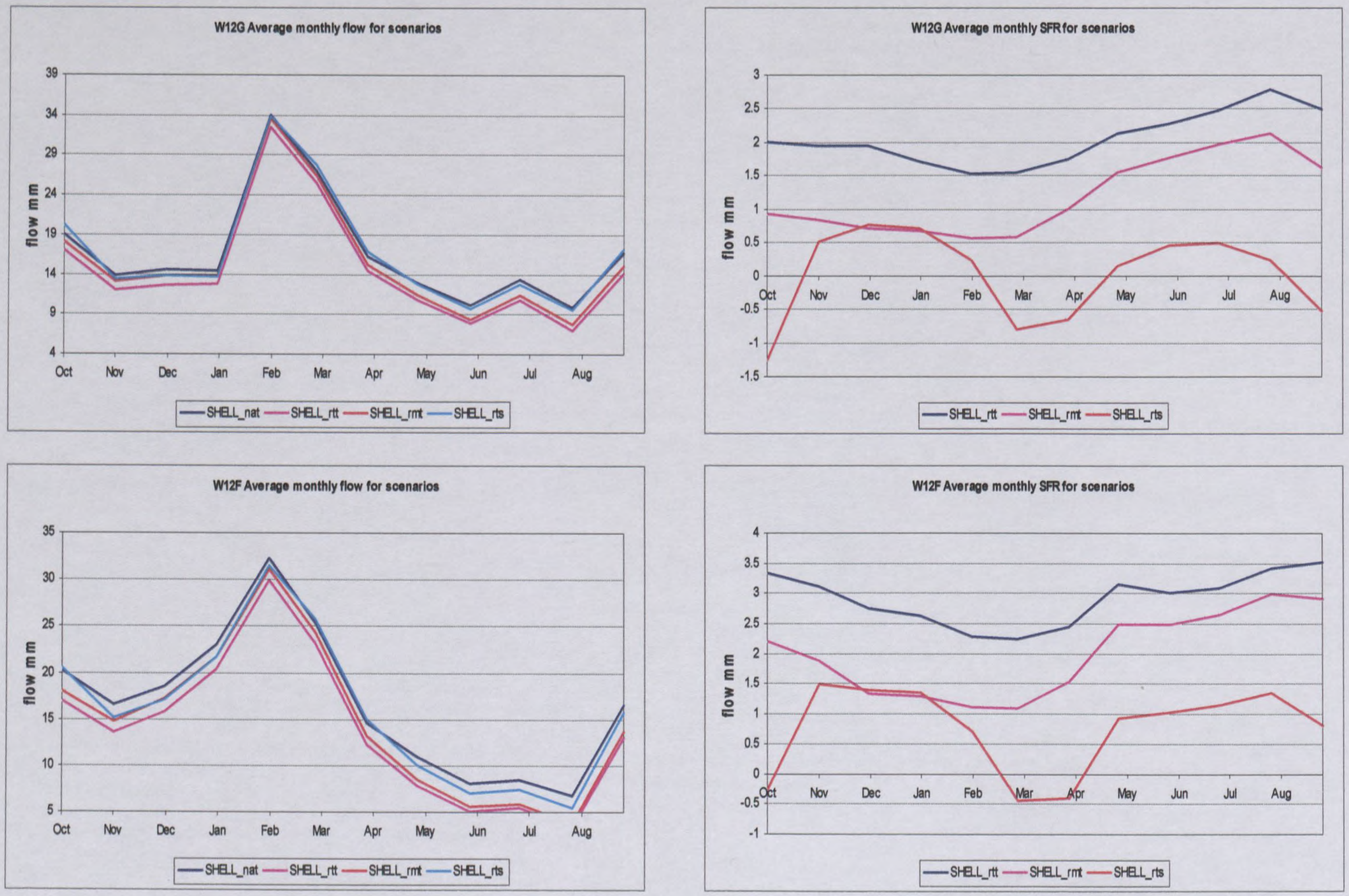
Riparian scenarios:

1. Riparian tall trees cause greater reduction in MAR than riparian medium trees, which in turn cause greater reduction in MAR than riparian tall shrubs. This is because the method used to estimate SFR by riparian IAPs (see **Section 3.3.4**) is based on crop coefficients, and, on average, the crop coefficients used for tall trees are higher than those for medium trees, which are higher than the tall shrub coefficients. The crop coefficients are presented in **Appendix A**.

2. Unit reduction in MAR by riparian IAPs is generally greater than reduction by upland IAPs of the same species. This is consistent with what is expected to occur in reality, as riparian plants are known to have access generally to more water all year round than upland plants. Riparian plants are not expected to experience stress in the low flow months. Results from riparian clearing experiments (Scott and Lesch, 1995). **Section 2.2.2** show ratios of riparian unit SFR to upland unit SFR of between 2 and 3. **Table 5-17** shows ratios ranging from 3 to 6 for this SHELL modelling exercise. Subcatchment W12G is anomalous in that unit upland SFR is greater than unit riparian SFR. This is because riparian SFR estimated, for subcatchment W12G, through the PET method is very low, because the crop coefficients for riparian tall shrubs (**Appendix A**) are similar to (and in some months lower than) those for the dominant natural vegetation (Bushveld) covering the riparian strip of W12G. In comparison, the method for estimating upland SFR is based on generic proportional reduction of the natural runoff and is not flexible in terms of describing the difference in water use between the IAP and the specific subcatchment natural vegetation. For example, the upland SFR curves do not differentiate between SFR caused when water use by the baseline vegetation is less than, or similar to, or greater than, that of the IAP. SFR by riparian trees is estimated through the potential ET method, which assumes that SFR by riparian trees is limited only by their physiology, evaporative demand and the immediate availability of water. In the SHELL configuration, riparian plants are allowed access to all the streamflow from upstream catchments. This can be seen in **Table 5-27**, where mean annual percentage reduction in low flow sometimes exceeds 100%. The absolute reduction in MAR (in volumetric terms) for these subcatchments is greater for riparian trees than upland trees (as seen in **Figure 5-25**) in spite of the sometimes much larger area of upland trees, except for subcatchment W12G, because of the limitations of the upland SFR method, as described above.

3. **Figure 5-27** shows some of the seasonal distributions of SFR for the riparian IAP scenarios. For the tall tree and medium tree categories, the lowest SFR occurs in high flow summer months, with the highest occurring during low flow winter

months. This is because the method used to estimate riparian IAP SFR is based on the difference between crop coefficients of the IAP and those of the natural vegetation being replaced. The greatest difference occurs in the low flow months, when the crop coefficients of the natural vegetation being replaced are lowest. Streamflow gains occur when, (in the case of tall shrubs), the crop coefficient of the natural vegetation is higher than that of the IAP.


W12G Average monthly flow for scenarios

W12G Average monthly SFR for scenarios

W12F Average monthly flow for scenarios

W12F Average monthly SFR for scenarios

Figure 5-27 : Average Monthly SFR Produced by SHELL for Subcatchments in the Mhlatuze for Riparian IAP Scenarios

Current scenario:

Table 5-28 shows that the reduction in baseline MAR (caused by all current day water uses, including afforestation and IAPs) over the whole Mhlatuze catchment (at the end of subcatchment W12F) due to all land and water use is 34%. The reduction in baseline MAR in subcatchment W12G is much lower than in the other subcatchments. This can be explained by the composition of land uses in the catchment. Most of the subcatchment, 59%, is covered by natural vegetation and there is no commercial afforestation in the subcatchment.

5.7.1.2 Reduction in Low Flows

The following points can be made about the results in **Table 5-26**, **Table 5-27**, **Table 5-28** and **Figure 5-25** with respect to reduction in low flow MAR:

Upland scenarios:

1. As with total MAR, the fixed SFR curves ensure that, for a given age, upland tall trees always cause more low flow reduction than upland medium trees, which cause more low flow reduction than upland tall shrubs.

Figure 5-28 shows plots of monthly timeseries of flow produced by SHELL for upland scenarios.

Figure 5-28: Monthly Time Series of Flow Produced by SHELL for Upland Scenarios in Subcatchment W12F in the Mhlatuze

Riparian scenarios:

1. As with the reduction in total MAR, reduction in low flow MAR by riparian tall trees is greater than by riparian medium trees, which in turn is greater than riparian tall shrubs. As shown in **Figure 5-25**, average absolute reductions in low flow MAR by riparian IAPs are generally larger than for upland IAPs, in spite of the larger areas of upland invasions, due to the availability of water to riparian plants even in the low flow season.

Figure 5-29 shows part of the time series produced for the natural scenario and riparian scenarios for subcatchment W12F. These are cumulative as opposed to incremental time series.

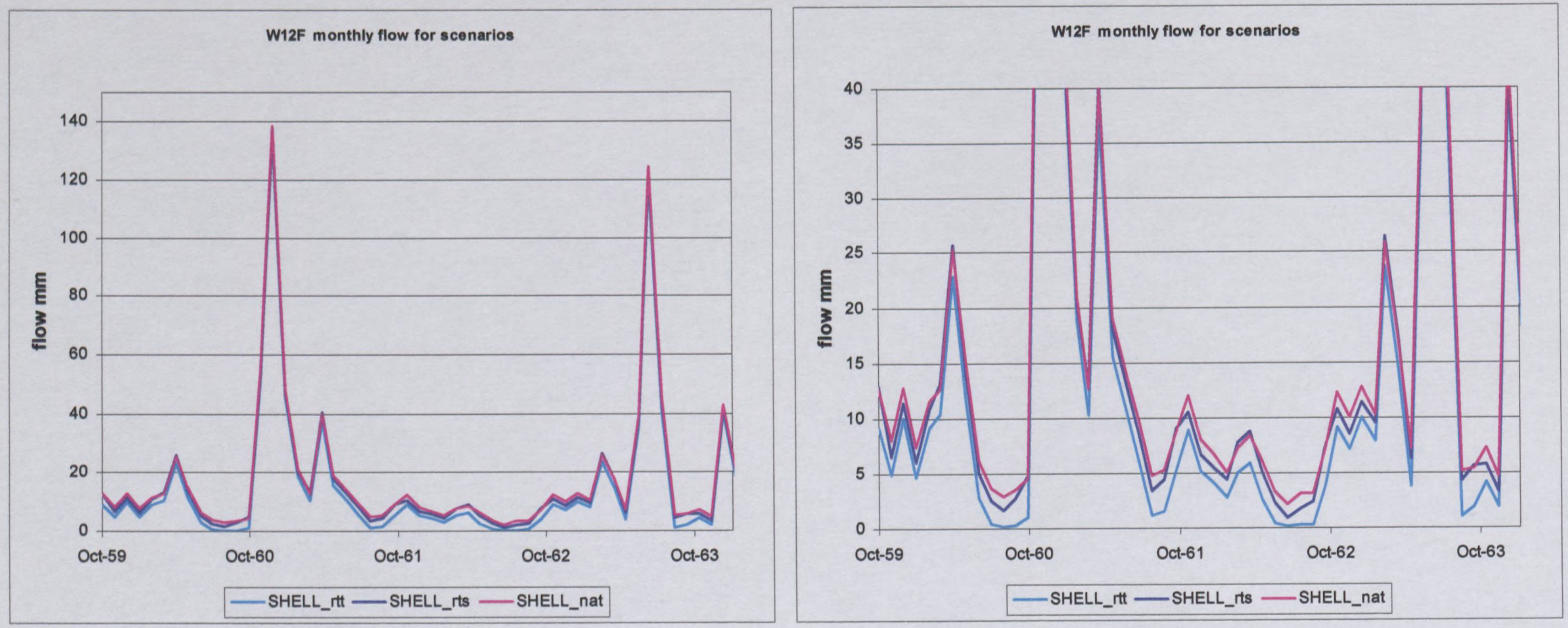


Figure 5-29: Monthly Time Series of Flow Produced by SHELL for Riparian Scenarios in Subcatchment W12F in the Mhlatuze

Current scenario:

Table 5-28 shows that the reduction in baseline low flow MAR (caused by all current day water uses, including afforestation and IAPs) over the whole Mhlatuze catchment (at the end of subcatchment W12F) is 70.5%. The reduction in baseline low flow MAR in subcatchment W12G is much lower than in the other subcatchments. This can be explained by the composition of land uses in the subcatchment. Most of the subcatchment, 59%, is covered by natural vegetation and there is no commercial afforestation in the subcatchment.

General observations:

1. On average, percentage reduction in low flow MAR is greater than percentage reduction in MAR. This is consistent with what has been observed in the field (Scott *et al,* 2000) (see **Section 2.2.1**).

5.7.2 Upper Berg

Table 5-29 presents results from the SHELL Upper Berg scenarios baseline (nat), current (cur), current with afforestation removed (cfo), current with aliens removed (cav) and commercial pine afforestation (pin). These scenarios are described in **Section 5.4.** The results for the scenarios are expressed as reduction from the natural scenario (for the cur and pin scenarios) and gains (due to clearing) from the current scenario (for the cfo and cav scenarios). **Figure 5-30** compares the flows produced for the different scenarios. The Berg scenarios are analysed at the flow exit point of the total Upper Berg catchment.

The reader is reminded that commercial afforestation in the current scenario consists of pine and covers 13% of the catchment. IAPs cover 53%, which is equivalent to a condensed area of 6%. Of the IAP area, 47% consists of tall trees, (predominantly pine), 14% of medium trees (wattle) and 39% of tall shrubs (hakea).

It should be noted that the difference in streamflow between the “cur” and “cfo” or “cav” scenarios is not due purely to the clearing of afforestation or the clearing of IAPs, since there are other influences within the scenarios, which might be reflected in the differences in streamflow. For example, abstractions, which may not be satisfied by the current streamflow, may absorb some of the flow liberated by the clearing of the trees. Another example is the modifying impacts of dam storage. These influences are reflected in the difference in results between the “cfo” and “pin” scenarios.

Table 5-29: Summary of SFR Estimates Produced by SHELL for the Upper Berg

Scenario	*Determination of water use or SFR	MAR (mm)		Water use or SFR (mm)		Water use or SFR (mm per 10% of catchment treated)		Water use or SFR (% per 10% of catchment treated)	
		Total flow	Low flow	Total flow	Low flow	Total flow	Low flow	Total flow	Low flow
nat		779.9	13.9						
cur	nat - cur	666.3	38.3	113.6	-24.4				
cfo	cfo - cur	694.9	38.5	28.6	0.2	22.1	0.2	3.3	0.4
cav	cav - cur	671.7	38.4	5.4	0.1	8.6	0.2	1.3	0.4
pin	nat - pin	727.1	12.9	52.8	1.0	40.8	0.8	5.2	5.7

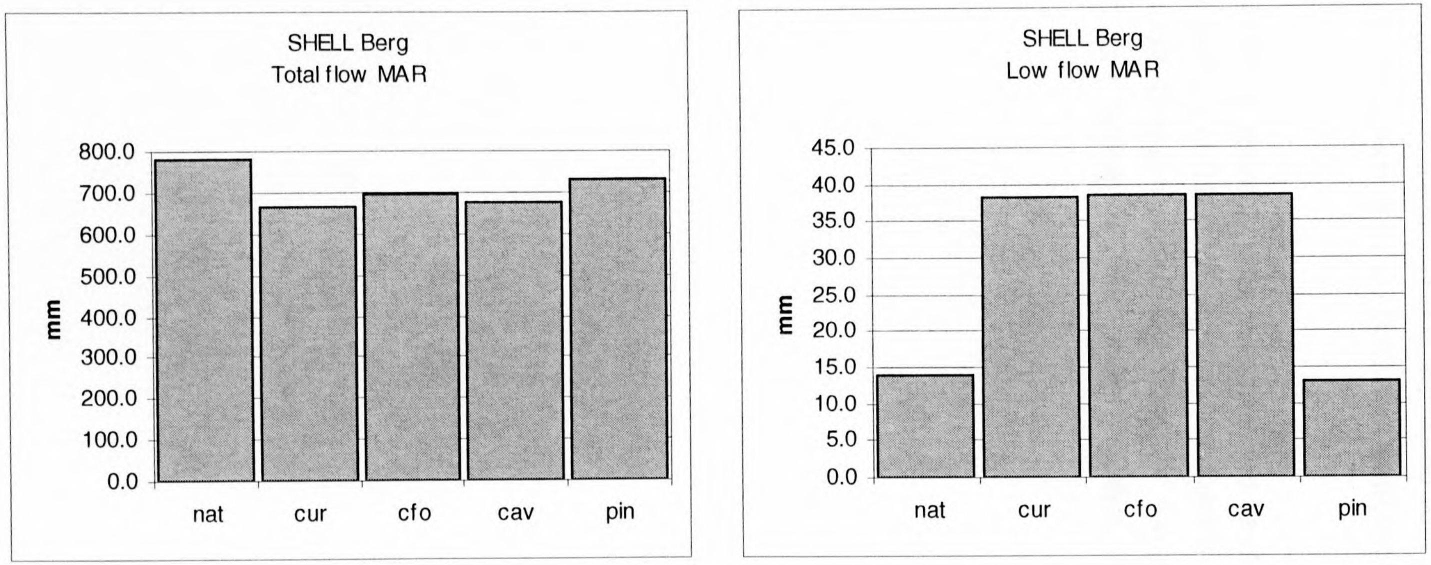


Figure 5-30: Summary of MAR Estimates Produced by SHELL for the Upper Berg

Figure 5-31 shows the seasonal distribution of flows and reductions. The greatest absolute SFR due to afforestation and IAPs occurs in the high flow winter months. This distribution is in keeping with the CSIR curves used to estimate the afforestation and upland IAP SFR. The current scenario displays streamflow gains from the baseline streamflow in the low flow months. This is attributed to irrigation releases from outside the Upper Berg catchment into an upstream catchment of the Upper Berg.

Figure 5-32 shows a portion of the monthly time series for the baseline and current scenarios. The time series pattern of the "cfo" and "cav" scenarios is similar to the current scenario. **Figure 5-32** shows elevated low flows for the current scenario relative to the baseline and "pin" scenarios", due to the irrigation releases into the catchment.

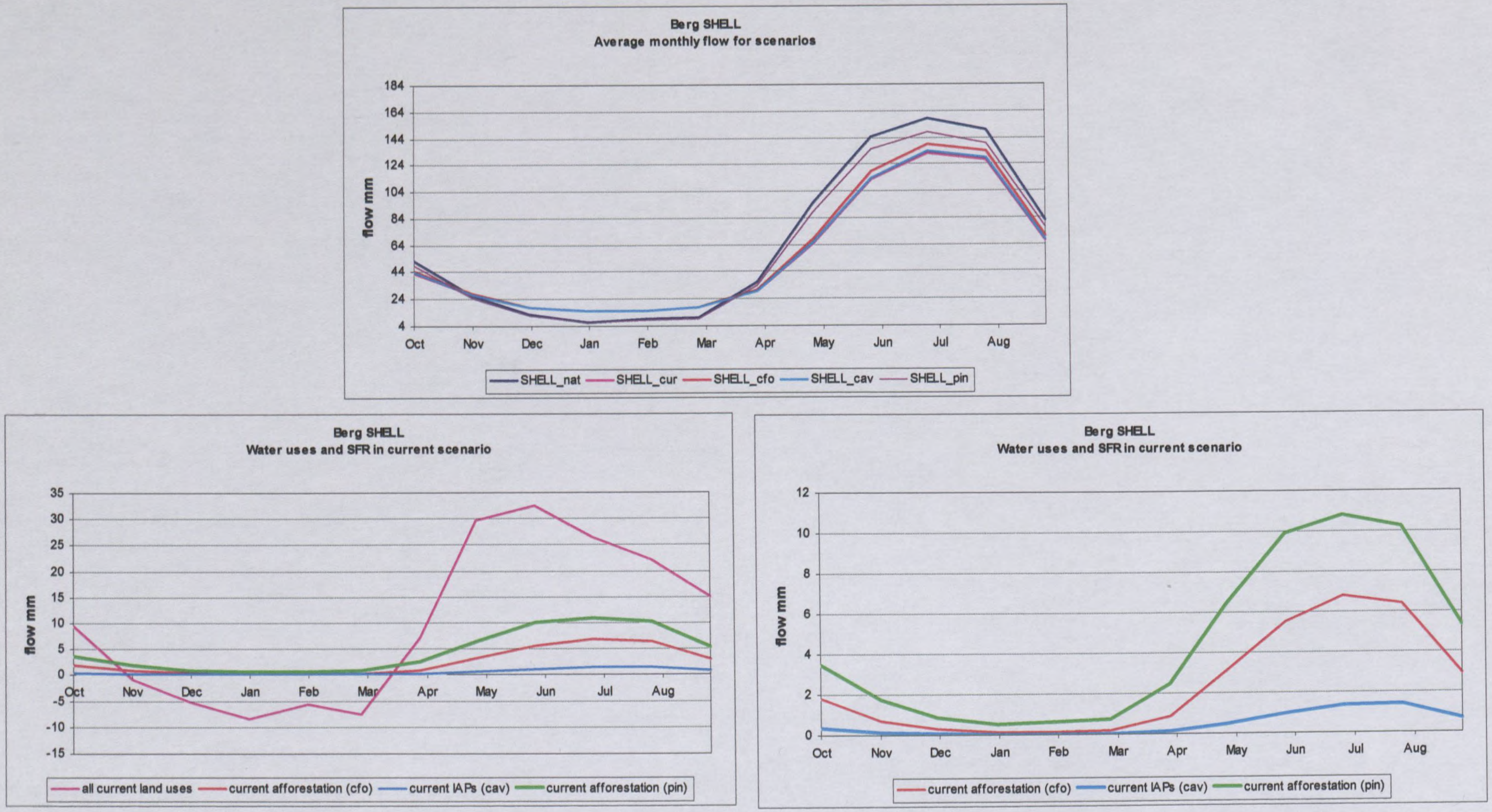


Figure 5-31: Seasonal Distribution of Flows and Reductions for Upper Berg SHELL Scenarios

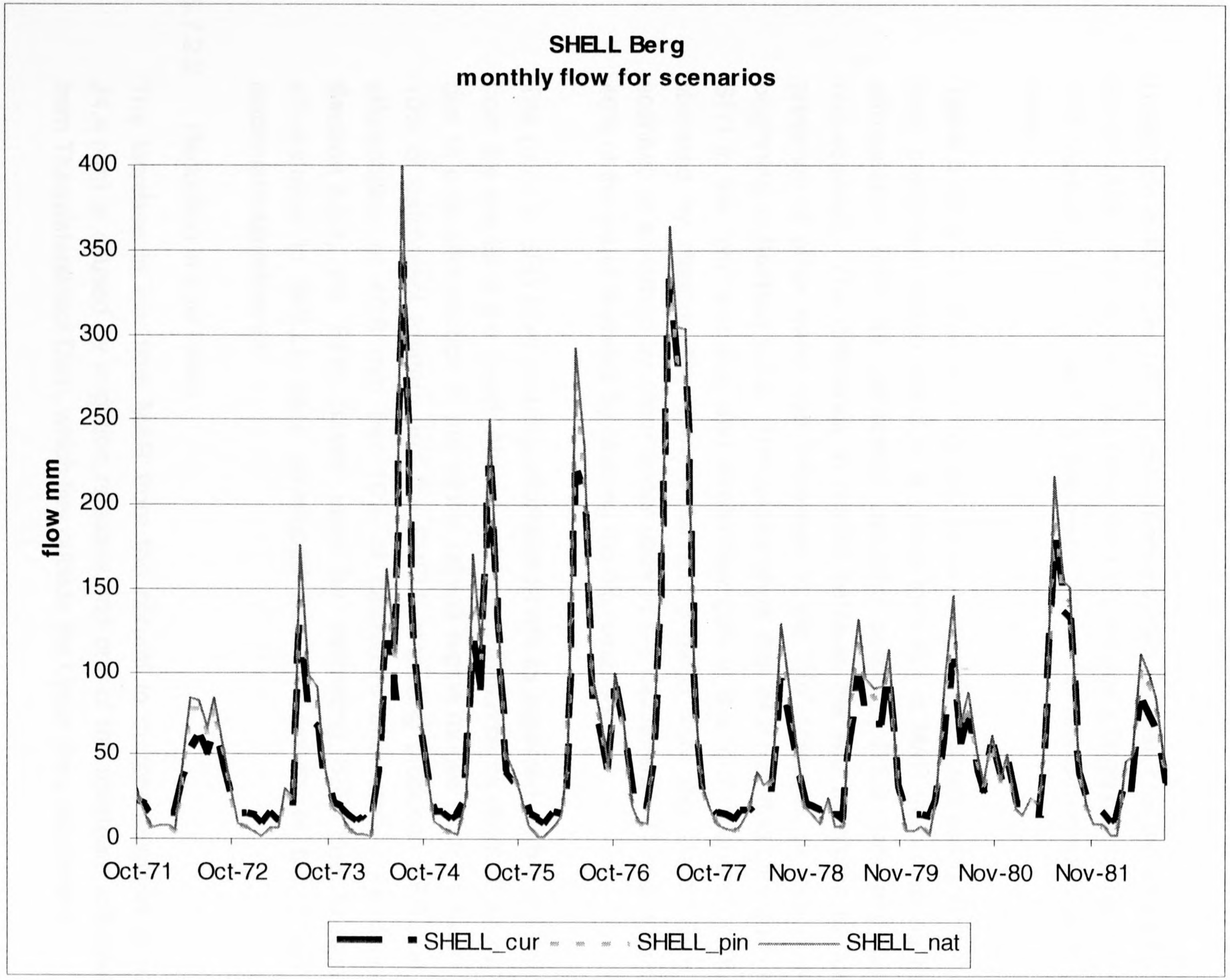


Figure 5-32: Monthly Time Series of Flows for Upper Berg SHELL Scenarios

5.7.2.1 Reduction in MAR

The results show that clearing of current commercial afforestation is simulated to make available 28.6 mm of MAR in the current scenario and clearing of current IAPs from the current scenario is simulated to make 5.4 mm of MAR available. This constitutes 3.6% and 0.7% of baseline MAR, respectively.

Reduction in MAR per 10% of catchment invaded is greater for the afforestation than for the IAPs. This is expected since the IAPs include a large proportion of tall shrubs and medium trees, as well as tall trees, while afforestation consists entirely of tall trees.

Table 5-29 shows that clearing afforestation from the current scenario in the Upper Berg catchment would result in a lesser increase in MAR than clearing the same afforestation from an afforested baseline scenario (28.6 mm and 52.8 mm, respectively). The difference in results between the two scenarios is due to the presence of other water use influences in the "cfo" scenario, as described at the beginning of **Section 5.7.2**. The results show that 24.2 mm (the difference between SFR in the "pin" scenario and streamflow gain in the "cfo" scenario) of the water liberated by clearing the commercial afforestation from the Upper Berg current scenario is absorbed by other water uses in the catchment. This is approximately 46% of the water liberated by clearing the afforestation.

The gains in SFR from clearing afforestation are as expected. **Table 5-6** shows that, from the results of the South African catchment experiments (Scot *et al*, 2000), SFR due to pine afforestation in the winter rainfall region ranges from 21 to 30 mm per 10% of catchment treated, and the SHELL modelling produces SFR due to pine afforestation of 40.8 mm per 10% of catchment afforested. As described in **Section 3.3.1**, the SFR curves used for estimating SFR due to commercial afforestation in SHELL were developed from the results of the South African catchment experiments.

5.7.2.2 Reduction in Low Flows

The increase in low flow MAR from the natural to current scenario (increase of 24.4 mm) is caused by irrigation releases into one of the upstream subcatchments, from Theewaterskloof Dam, which lies outside the Upper Berg catchment.

The results show that clearing the current levels of afforestation and IAPs in the Upper Berg are simulated to create reductions in low flow MAR of 0.2 and 0.1 mm, respectively, 1.4% and 0.7% of the baseline low flow MAR.

Table 5-29 shows that clearing afforestation from the current scenario in the Upper Berg catchment would result in a reduction in MAR greater than the reduction in MAR created by clearing the same afforestation from an afforested baseline scenario. This difference is due to the other water use influences (described at the beginning of **Section 5.7.2)** present in the "cfo" scenario, but not in the "pin" scenario. **Figure 5-31** shows this variation in the results of the two scenarios.

5.7.3 Upper Sabie

Table 5-30 shows results from the SHELL Sabie scenarios natural (nat), current (cur), current with afforestation removed (cfo) and commercial afforestation (pin). These scenarios are described in **Section 5.4**. The results for the scenarios are expressed as reduction from the natural scenario (for the "cur" and "pin" scenarios) and gains (due to clearing) from the current scenario (for the "cfo" scenario). **Figure 5-33** compares the flows produced for the different scenarios. The Sabie scenarios are analysed at the flow exit point of the total catchment.

Commercial afforestation, predominantly pine, covers 44% of the Upper Sabie catchment. The area covered by IAPs is negligible.

It should be noted that the difference in streamflow between the "cur" and "cfo" scenarios is not due purely to the clearing of afforestation, since there are other influences within the scenarios, which might be reflected in the differences in streamflow. For example, abstractions which may not be satisfied by the current streamflow may absorb some of the flow liberated by the clearing of the trees. Another example is the modifying impacts of dam storage. These influences are reflected in the difference in results between the "cfo" and "pin" scenarios.

Table 5-30: Summary of SFR Estimates Produced by SHELL for the Upper Sabie

Scenario	*Determination of water use or SFR	MAR (mm)		Water use or SFR (mm)		Water use or SFR (mm per 10% of catchment treated)		Water use or SFR (% per 10% of catchment treated)	
		Total flow	Low flow	Total flow	Low flow	Total flow	Low flow	Total flow	Low flow
nat		263.3	17.4						
cur	nat - cur	132.8	2.1	130.4	15.3				
cfo	cfo - cur	224.5	9.0	91.7	6.9	21.0	1.6	15.8	74.8
pin	nat - pin	166.1	9.4	97.2	8.0	22.3	1.8	8.5	10.5

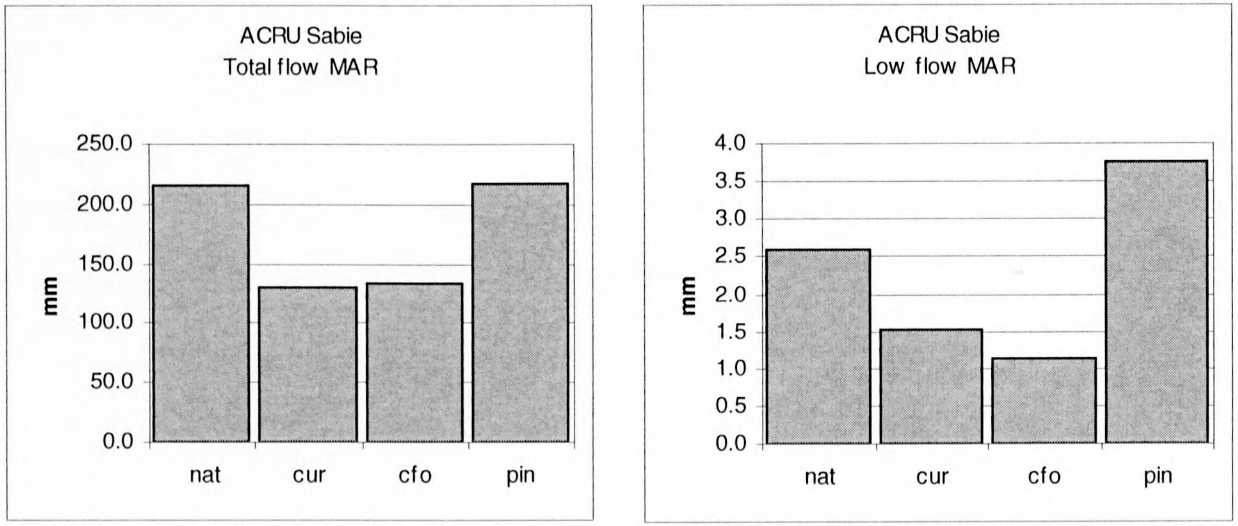


Figure 5-33: Summary of MAR Estimates Produced by SHELL for the Upper Sabie

Figure 5-34 shows the seasonal distribution of flows and reductions and **Figure 5-35** shows a portion of the monthly time series for the natural and current scenarios. The greatest absolute SFR due to afforestation occurs in the high flow summer months. This distribution is in keeping with the CSIR curves used to estimate the afforestation SFR.

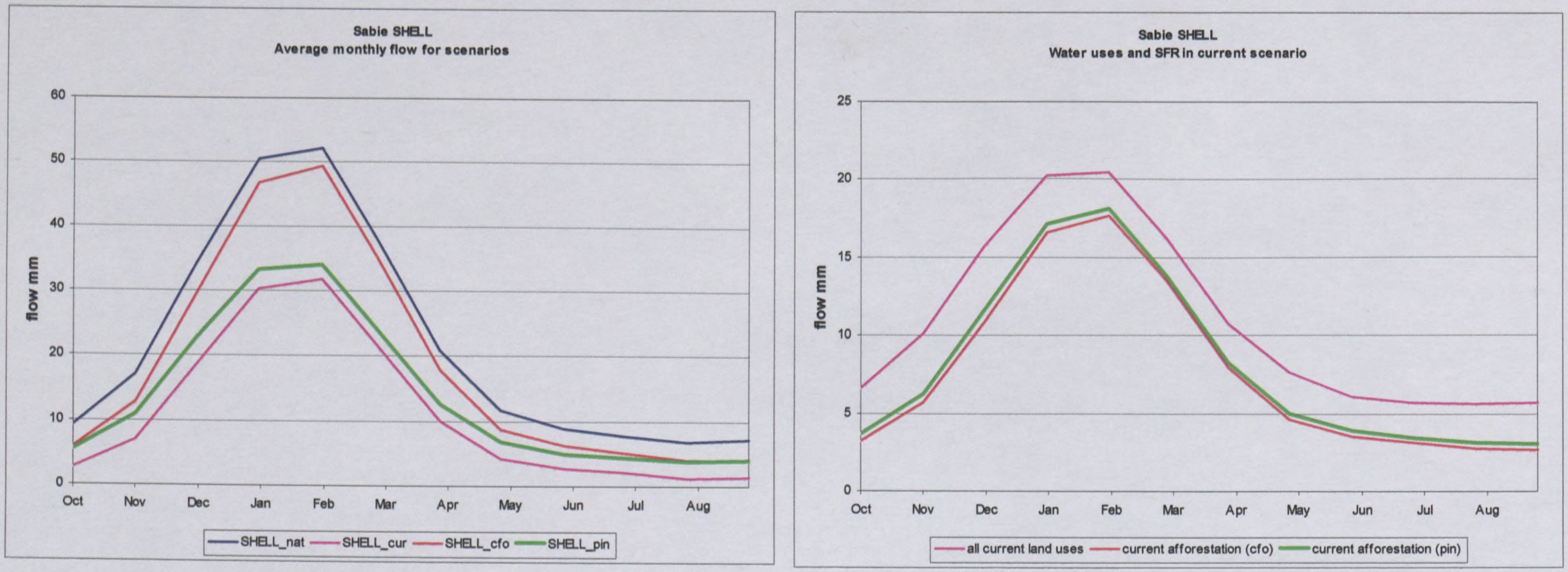


Figure 5-34: Seasonal Distribution of Flows and Reductions for Upper Sabie SHELL Scenarios

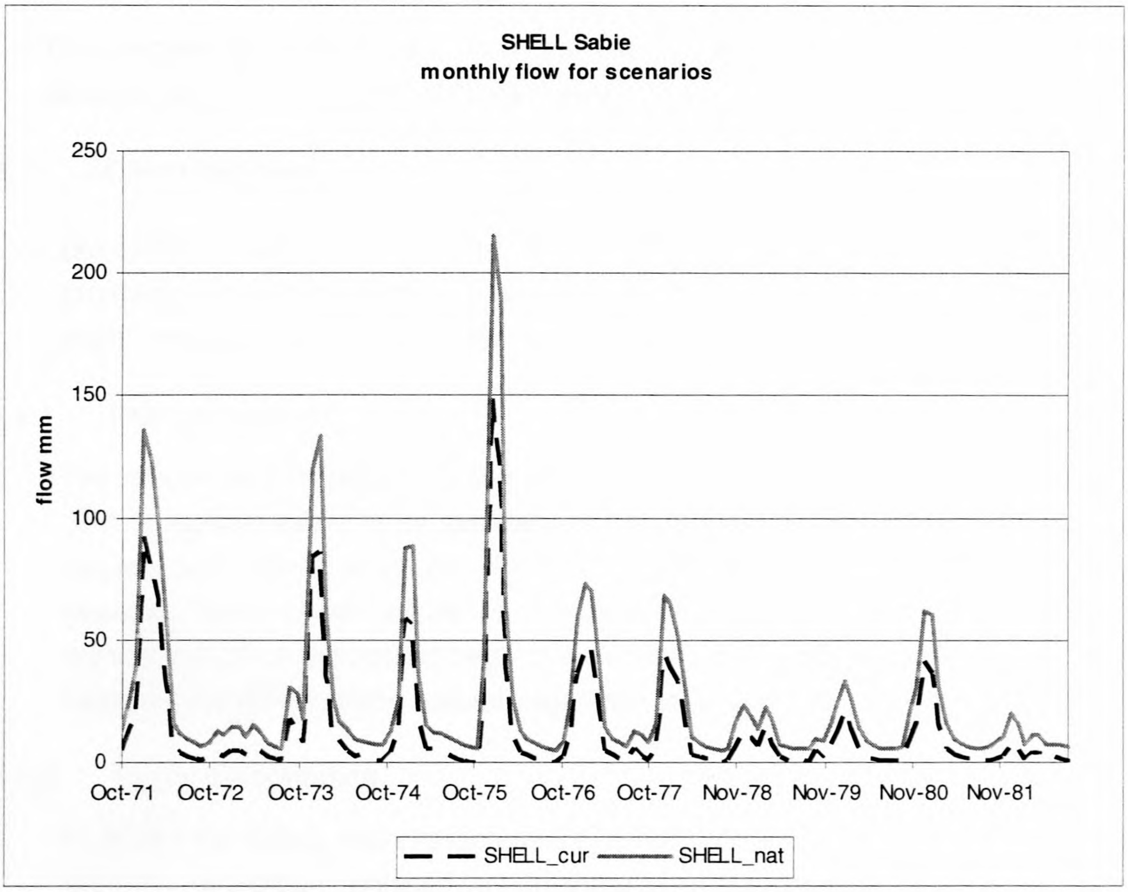


Figure 5-35: Monthly Time Series of Flows for Upper Sabie SHELL Scenarios

5.7.3.1 Reduction in MAR

The results show that clearing of current commercial afforestation from the current land cover scenario is simulated to increase current MAR by 91.7 mm (35% of baseline MAR). The results also show that the same commercial afforestation is simulated to cause SFR of 97.2 mm when added to the baseline scenario. This difference in results between the two scenarios is due to the presence of other water use influences in the "cfo" scenario, as described at the beginning of **Section 5.7.3**. These water use influences have the effect of reducing streamflow gains from clearing current afforestation by 5.5 mm, approximately 6% of SFR, due to current afforestation.

5.7.3.2 Reduction in Low Flows

The results show that the current level of afforestation in the upper Sabie is simulated to cause a reduction in low flow MAR of 6.9 mm, about 40% of the baseline low flow MAR. The same afforestation superimposed on a baseline scenario causes a reduction in low flow of 8mm. The difference in results is caused by water uses within the current scenario, as described at the beginning of **Section 5.7.3**.

5.8 Bio-Climatic Variation

This section describes variations in the results, which are as a result of bio-climatic differences in the subcatchments modelled.

5.8.1 ACRU Modelling

Bio-climatic variations discussed in this section, as affecting the outcome of ACRU modelling, include the type of rainfall region, the predominant types of baseline and exotic vegetation in the catchment and the MAP ("wetness") of the catchment.

5.8.1.1 Rainfall Region

The rainfall region determines the seasonal distribution of SFR. The highest absolute SFR by upland exotic trees generally occurs in the high flow months during the rainy season and lowest absolute SFR occurs in the low flow months during the dry season. The opposite is true for riparian IAPs where the highest SFR occurs in the dry season when the natural vegetation is less active and the difference in water use between the IAPs and the natural vegetation is greatest.

5.8.1.2 Types of Vegetation

In ACRU modelling, the characteristics of both the SFR-causing vegetation and the baseline vegetation replaced are important, as the model is physically based and estimates SFR via the difference in water use by the two vegetation scenarios.

Baseline vegetation:

Predominant natural vegetation varies across regions and also within catchments. Within the Mhlatuze, the vegetation varies between grassveld and bushveld, in the Upper Berg, the dominant natural vegetation at the top of the catchment is macchia and at the lower reaches, coastal rhenosterveld. The Upper Sabie has a greater variety of natural vegetation, including lowveld and indigenous forest.

The difference in water use between the natural vegetation included in the ACRU configuration of the Berg and IAPs or commercial afforestation is potentially greater than for the natural vegetation in the Mhlatuze configuration, which is in turn potentially greater than in the Sabie configuration. This is gathered from the crop coefficients of the natural vegetation (**Appendix A**) and could explain why the percentage reduction in SFR per 10% of catchment afforested is much lower for the Upper Sabie, as shown in **Table 5-31**. The negative low flow reductions (flow increases) are explained in **Section 5.6.1.2** and **Section 5.6.3.1**. In **Section 5.6.3.1**, the small gain in total MAR for the Sabie pine scenario is explained by comparing the crop coefficients of the pine trees with those of the natural vegetation replaced.

Table 5-31: Comparison of SFR Estimated by ACRU for the Study Systems

Catchment	Species	Vegetation replaced	Reduction in MAR per 10% of catchment afforested (%)	Reduction in low flow MAR per 10% of catchment afforested (%)
Mhlatuze	pine	grassveld, bushveld	1.4	-0.5
Berg	pine	macchia, coastal rhenosterveld	0.7	-0.5
Sabie	pine	includes forest and woodland and thicket and bushland	-0.05	-10.2

5.8.1.3 Mean Annual Precipitation (MAP)

The subcatchments, modelled in the Mhlatuze catchment, were used to investigate a relationship between MAP and SFR within the Mhlatuze catchment. The MAP of the subcatchments range from 830 to 1 250 mm. **Figure 5-36** suggests a decrease in percentage low flow SFR with increasing MAP, from the "utt", "uts" and "umt" scenarios. The variation in total annual SFR appears to be less variable with MAP, also judging from the upland IAP graphs.

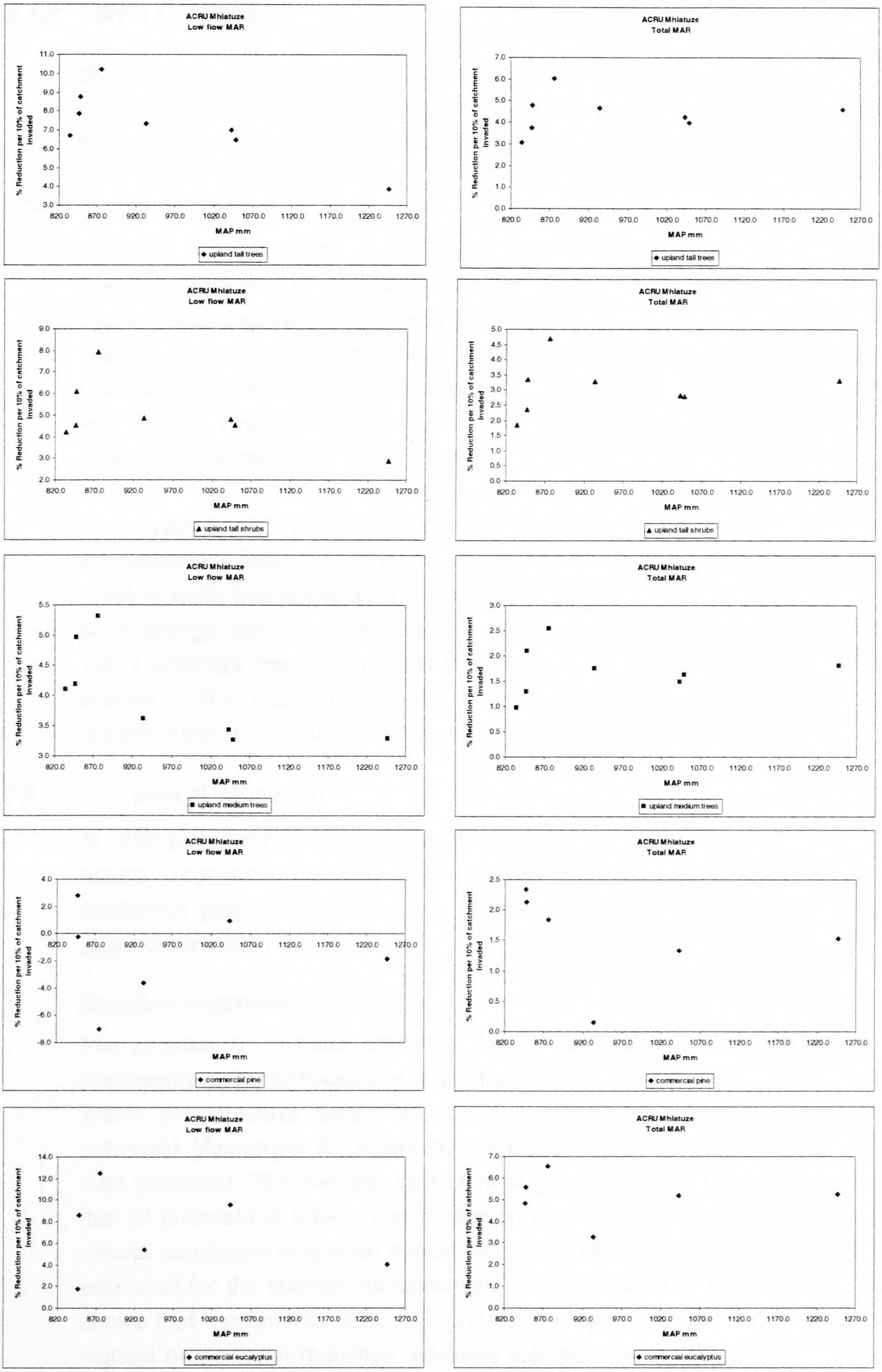


Figure 5-36: Plots of % SFR against MAP (mm) for ACRU Mhlatuze Scenarios

5.8.2 SHELL Modelling

Bio-climatic variations, discussed in this section as affecting the outcome of SHELL modelling, include the type of rainfall region, the predominant types of vegetation in the catchment and the MAP of the catchment.

5.8.2.1 Rainfall Region

In SHELL modelling, the rainfall region affects the seasonality of upland SFR, as absolute SFR series, estimated from the CSIR curves, takes the same general monthly shape as the natural flow, high in the rainy season and low in the dry season. Rainfall region also affects the seasonality of riparian SFR estimated with the potential ET method, as the greatest difference in potential ET between alien trees and natural vegetation occurs in the dry season. The potential ET method is described in **Section 3.3.4** of this report.

The proportional reduction obtained from the CSIR curves for commercial afforestation is also affected by the rainfall region. In winter rainfall areas, where the greatest water availability does not occur at the same time as the greatest amounts of solar energy, growth conditions are described as sub-optimal (Scott and Smith, 1997), whereas growth conditions in summer rainfall areas are generally defined as optimal. The sub-optimal curve for afforestation produces lower proportional reduction than the optimal curve for the same age of trees.

5.8.2.2 Types of Vegetation

In SHELL modelling, the characteristics of both the SFR-causing vegetation and the natural vegetation replaced are important. The characteristics of the natural vegetation play a direct role only in estimating riparian SFR with the potential evapotranspiration method.

Baseline vegetation:

The potential ET method estimates riparian SFR based on the difference in crop coefficients of the SFR-causing vegetation and the natural vegetation being replaced. Within the Mhlatuze catchment, the natural vegetation types are bushveld and grassveld (**Appendix A**), where bushveld has higher crop coefficients on average than grassveld. The average coefficient of grassveld over 12 months is 0.45, while that of bushveld is 0.64. The proportion of each land cover type making up the natural vegetation in riparian subcatchments in Mhlatuze was compared to the SFR estimated for the riparian subcatchment. This is shown in **Table 5-32**. **Table 5-32** shows that catchments 12D, 12E and 12F, which have 100% grassveld, have the highest proportional reduction, whereas subcatchments 12C and 12G, which have the highest proportion of bushveld, have the lowest proportional reductions.

Table 5-32: Comparison of SFR Estimated by SHELL for Riparian Tall Trees (Potential ET method) for Subcatchments in the Mhlatuze

	Proportion of riparian subcatchment natural vegetation %		Reduction in MAR per 10% of catchment afforested	Reduction in low flow MAR per 10% of catchment afforested
	Bushveld	Grassveld		
12B	13	87	0.8	3.0
12C	34	66	0.3	2.3
12D	0	100	1.9	9.0
12E	0	100	5.9	28.9
12F	0	100	12.0	57.9
12G	69	31	0.3	2.2

5.8.2.3 Mean Annual Precipitation (MAP)

The subcatchments modelled in the Mhlatuze catchment were used to investigate a relationship between MAP and SFR within the Mhlatuze catchment. The MAP of the subcatchments range from 830 to 1 250 mm. Subcatchment MAP and SFR are plotted in **Figure 5-37**. Ignoring the outliers (which may mean that there are other stronger influences than MAP affecting the SFR in these subcatchments), proportional SFR appears fairly constant with increasing MAP. This is expected, as SFR for these scenarios is estimated using the CSIR curves, which are not directly related to MAP.

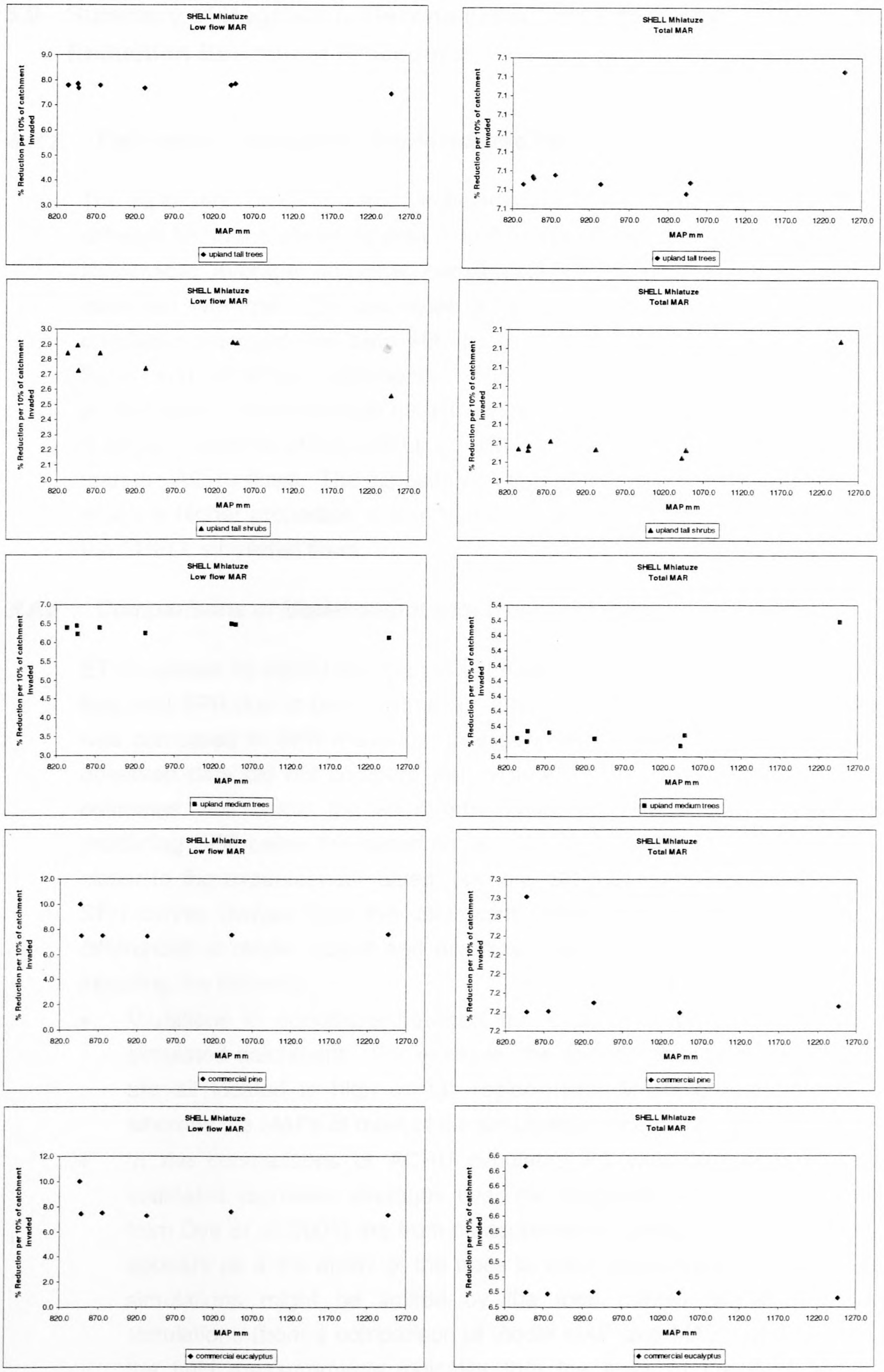


Figure 5-37: Plots of % SFR against MAP (mm) for SHELL Mhlatuze Scenarios

5.9 Summary of Upgrading, Reconciliation and Integration of Streamflow Reduction Estimation Procedures

5.9.1 Calibration, Verification and Simulated Natural Flows

The calibration of SHELL and verification of ACRU for the study systems produced different fits to the observed data from the two models, though both models achieved reasonable average seasonal correspondence of high and low flows with the observed averages. The calibration of SHELL was heavily influenced by patching of unreliable observed flow data with the simulated SHELL results, particularly for the Sabie and Mhlatuze catchments. The SHELL configuration of the Upper Berg produced comparatively high natural low flows compared to the ACRU configuration. A larger proportion of the SHELL simulated flows for the Berg consisted of low flows than the ACRU flows. The opposite was true for the Sabie and Mhlatuze catchments, where a higher proportion of the ACRU simulated flows consisted of low flows than the SHELL simulated flows.

5.9.2 Comparisons of Model output with Observed Data

ET simulated by ACRU for riparian tall trees was compared to ET measured in the field and SFR due to pine commercial afforestation simulated by ACRU and SHELL was compared to SFR measured in experimental catchments. The simulated and observed data did not compare well, with ACRU producing long-term average ET estimates well below the short-term measured values and SHELL and ACRU producing SFR below the experimental values. The SHELL pine SFR values were closer to the experimental values, because SHELL SFR determination is based on SFR curves derived from the catchment experiments. It was concluded that the differences in model output and measured data are due to a number of reasons, including the following:

- Variations in conditions between the experimental catchment sites and the simulated catchment. For example, the experimental afforestation catchments are all located in high rainfall regions with MAPs greater than 1 100 mm, whereas the MAPs of most of the simulated subcatchments are below 1 100 mm.
- In the comparisons of ACRU simulated ET with measured ET, the ACRU estimates represent averages over the long-term (40 years), whereas values from Dye *et al* (2001) are from measurements conducted over one year. Also, it appears as if the ability of the trees to meet evaporative demand in the ACRU simulations might be limited by the total rainfall available to the model simulations (from a comparison of model MAP and MAE), whereas the ET from the field measurements indicates that the trees in the field had access to sufficient water to meet evaporative demand.

5.9.3 Comparison of Model Output with Commercial Afforestation SFR Tables used by DWAF ("Gush Tables")

SFR due to pine afforestation, simulated by ACRU and SHELL, was compared to SFR indicated by the Gush Tables for the three study catchments.

The outcomes of the comparison for the Mhlatuze and Upper Berg catchments were similar in that:

- the total annual SFR for SHELL was higher than the upper confidence limit of the Gush value.
- the annual low flow SFR for SHELL fell within the confidence bands of the Gush estimate.
- the total annual SFR for ACRU fell within the confidence bands of the Gush estimate.
- the annual low flow SFR for ACRU was lower than the lower limit of the Gush value.

The comparison for the Sabie catchment yielded similar outcomes to the Berg and Mhlatuze catchments for total annual SFR for SHELL and annual low flow SFR for ACRU. The Sabie comparison differed from that for the other two catchments in that:

- the annual low flow SFR estimate for SHELL was higher than the upper limit of the Gush estimate.
- the total annual SFR for ACRU fell below the lower limit of the Gush estimate.

These differences in the outcome of the Sabie comparisons point to the fact that ACRU simulates lower than expected SFR due to pine in the Sabie catchment.

5.9.4 Assessment of SFR Produced by ACRU and SHELL

SFR simulated by SHELL for the Mhlatuze, Upper Berg and Upper Sabie catchments was assessed in terms of reductions in total MAR and reductions in low flow MAR.

5.9.4.1 ACRU Modelling

ACRU modelling of the scenarios produced some *unexpected* results as follows:

- Tall shrubs, which intuitively can be expected to cause little SFR, cause greater reduction in total MAR than medium trees in both the upland and riparian situations in the Mhlatuze catchment. Riparian tall shrubs also cause slightly more reduction in low flow MAR than Riparian tall trees in the Mhlatuze.
- Different proportional reductions in MAR and low flow MAR were estimated for the same tall tree species in the same subcatchment, because the different areas under trees considered resulted in different compositions of natural vegetation replaced.

- Gains in low flow MAR are simulated for the replacement of natural vegetation with pine trees. This is because when pine trees experience water stress in the dry season, total evaporation by the trees drops well below maximum evaporation. This leads to water use by pines being lower than that of the natural vegetation being replaced, during periods of the dry season. The subcatchment soil properties can influence the severity of the low flow gains in SFR. In the Upper Sabie, a small gain in baseline total MAR due to pine afforestation was simulated. This was attributed to a combination of the early dropping of total evaporation by pine trees below maximum evaporation during dry periods and the relatively high crop coefficients of the natural vegetation in the Upper Sabie.

Expected outcomes of the ACRU modelling include the following:

- Proportional reduction in MAR by tall trees is greater than by medium trees and tall shrubs in both the upland and riparian situations.
- Proportional reduction in MAR and low flow MAR by riparian IAPs is greater than for upland IAPs.
- The seasonal distribution of upland SFR follows the same trend as natural runoff with highest absolute SFR in the high flow season and lowest absolute SFR in the low flow season. The seasonal distribution of riparian SFR is the opposite, with highest absolute SFR in the low flow season and lowest absolute SFR in the high flow season.
- Percentage reduction in low flow MAR is generally higher than percentage reduction in total MAR.
- There appears to be a lessening of tributary effects in subcatchments, which lie further downstream in the catchment. Some trends in SFR, observed at the upstream catchments, are not observed at the mouth of the total catchment.
- In some cases, the average absolute total reductions of SFR (at the catchment outflow point) caused by riparian plants are less than by upland plants since upland plants cover much larger areas, however, the average absolute low flow reductions by riparian plants tends to be similar to that for upland plants.

5.9.4.2 SHELL Modelling

Generally, the results produced by the SHELL modelling were as expected from the input data used to produce them. These include:

- Reduction in total and low flow MAR in the upland situation is greater for tall trees than for medium trees and greater for medium trees than for tall shrubs.
- The comparative effect of pine afforestation and eucalyptus afforestation depends on the rotation chosen for the trees for use with the CSIR curves.
- Riparian tall trees cause a greater reduction in total and low flow MAR than riparian medium trees, which in turn, cause greater reductions than riparian tall shrubs. This outcome depends on the crop coefficients used to estimate the SFR.

- Riparian IAPs cause greater proportional reduction in total and low flow MAR than upland IAPs.
- The seasonal distribution of upland SFR follows the same trend as natural runoff with highest SFR in the high flow season and lowest SFR in the low flow season. The seasonal distribution of riparian SFR is the opposite, with highest SFR in the low flow season and lowest SFR in the high flow season.
- Percentage reduction in low flow MAR is generally higher than percentage reduction in total MAR, all else being the same.
- In some instances, the average absolute total reductions of SFR (at the catchment outflow point) caused by riparian plants are less than upland plants, since upland plants cover much larger areas, however, in most instances the average absolute low flow reductions by riparian plants are greater than for upland plants.

5.9.4.3 Interpreting the Effects of Bio-climatic Variations

The effects of bio-climatic variations on the results of the SFR modelling with ACRU and SHELL raised the following insights:

- The rainfall region, whether winter or summer rainfall, affects the seasonal distribution of SFR produced and also affects the growth condition of afforestation for use with the CSIR curve.
- The types of natural vegetation and IAPs dominant in the region determine the difference in water use between the IAPs or afforestation and the natural vegetation they replace. This has a large influence on SFR.
- There appears to be a relationship between upland SFR, modelled by both ACRU and SHELL, and subcatchment MAP.

5.10 Conclusions

5.10.1 Comparison of Flows Simulated by ACRU and SHELL

A necessary requirement to achieve comparable simulated flows in ACRU and SHELL is a reliable observed flow record to calibrate the monthly Pitman catchment model inside SHELL, since this is the only means of producing a SHELL configuration, which is representative of the catchment. Even with a reliable flow record, the results produced by ACRU and SHELL can be very different, as seen in the case of the Upper Berg where the observed flow record is fairly complete. Since ACRU does not rely on calibration against observed flow to achieve an ACRU configuration, which is representative of the catchment, reliable input data influencing the various hydrological processes in the catchment is required.

5.10.2 ***Comparisons of Model Output with Observed Data***

Comparison of simulated and measured ET and SFR data is not always useful in obtaining an indication of model performance in SFR estimation as there is still very little data available for the varied site conditions applicable in South Africa. Such comparisons may be used to gauge if results are within an expected range, as with comparisons of SFR produced by the CSIR curves and results of the catchment experiments from which the CSIR curves are derived.

5.10.3 ***Comparison of Model Output with Commercial Afforestation SFR Tables used by DWAF ("Gush Tables")***

The Gush Tables are used as a tool in the DWAF licensing process for afforestation.

In general, total annual SFR simulated by SHELL is higher than that indicated by the Gush Tables, whereas annual low flow SFR simulated by SHELL is similar to that indicated by the Gush Tables.

In general, total annual SFR simulated by ACRU is similar to that indicated by the Gush Tables, whereas annual low flow SFR simulated by ACRU is lower than that indicated by the Gush Tables.

Since the Sabie comparison with the Gush Tables showed that total annual SFR estimated by ACRU is lower than the Gush value and that the Gush value for annual low flow SFR is lower than the SHELL estimate, it is concluded that ACRU simulation of the Upper Sabie produces lower than expected SFR.

5.10.4 ***Comparison of SFR Produced by ACRU and SHELL***

Proportional SFR produced by the ACRU Model is generally less than that produced by the SHELL Model, as can be seen in all the categories of results presented in this section.

5.10.5 ***Predictability of SFR Produced by ACRU and SHELL***

The output produced by SHELL is predictable in that the modeller knows what to expect, based on the values of the input variables used. All the outcomes of the SFR modelling with SHELL are easily linked to the input variables. The output produced by ACRU, on the other hand, is less predictable as it is based on the representation of a number of different physical processes and is very sensitive to the choices of ACRU consumptive use-controlling coefficients for the baseline vegetation. Some results obtained from the ACRU modelling are contrary to what is expected intuitively from the vegetation types.

6 AN ASSESSMENT OF STREAMFLOW REDUCTION IMPACTS ON YIELD-RELIABILITY CHARACTERISTICS

6.1 Introduction

The impact of SFR on the yield of a river system is of interest to water resources managers and practitioners. A few studies on this type of SFR impact have been done to date. Among these, is the study by Le Maitre and Görgens (2003), which aimed to produce "first approximations of the impacts of invasions by alien plants on the assurance of supply from typical dams in typical catchments (the Upper Mgeni, Sonderend, Upper Wilge and Sabie-Sand Systems) in the form of a limited budget, short-term study for the Water Research Commission (WRC). The study was conducted at quaternary catchment scale, used WR90-sourced naturalised flows and compared the IAP-SFR impacts on yield for a total catchment and for individual quaternary subcatchments within the catchment. The study used the CSIR curve-based SHELL methodology for SFR estimation and the SHELL reservoir simulation module to determine yield. The study found that the magnitude of the reduction in yield differed among river systems and that reduction in yield at the quaternary catchment scale may be different to the impact on the entire river system. An important conclusion from the study was that it was feasible to estimate the potential impacts of SFR on water yields in South African river systems for which reliable databases on alien vegetation invasion exist (Le Maitre and Görgens, 2003).

This chapter looks at the impact on yield of the flow sequences of SFR produced by SHELL and ACRU and compares the two sets of yield impacts.

6.2 River System Model used in this Project

The river system model used in this project is the WRYM. "WRYM is "designed to assess the long term yield capabilities of a system for a given operating policy. It is used to analyse systems at constant development levels, i.e., the system components and the system demands remain constant throughout the full simulation period." (DWA, 1987).

Inputs required for WRYM for the purposes of this study (not the complete list of possible input) consist of the following (DWA, 1987):

- Naturalised flows (flow produced from the baseline scenario).
- Precipitation and evaporation associated with reservoirs (this was taken as the same as precipitation over the subcatchment, containing the reservoir).

- Diffuse irrigation and afforestation demand sequences for particular subcatchments.
- Reservoir storage and releases (including hypothetical dams).
- Specified monthly demands (these are the SFR sequences, of either IAPs or forestry, output from ACRU and SHELL).

6.3 System Modelling

Each scenario in each catchment was modelled for a 40-year period. Through trial and error, this was found to be the longest practical time-period for the study, considering the time necessary to run the ACRU scenarios. The Upper Berg was modelled from 1952 to 1992, the Upper Sabie from 1956 to 1996 and the Mhlatuze from 1954 to 1994.

For each catchment, and for the flow sequences from each model, a fully developed catchment system was configured with a 1 MAR hypothetical dam situated at the bottom of the catchment.

In the Mhlatuze catchment, the spatial variation of impacts on yield was also investigated at various points within the catchment, so 1 MAR hypothetical dams were additionally set up at the two furthest upstream subcatchments within the Mhlatuze catchment. The two subcatchments chosen had comparatively high and low MAPs, respectively. For the scenarios, at the three hypothetical dams, the following yield characteristics were determined:

- Firm yield: the annual volume of water, which can be supplied from the reservoir or river without failure for the given flow sequence.
- 1 in 5-year failure yield: the annual volume of water, which can be supplied by the reservoir or river with a 20% annual probability of failure (or 80% annual reliability of supply) for the given flow sequence.

These yields were determined for the following two sites of interest:

- reservoir yield (“Res yield”); and
- run-of-river yield (“ROR yield”).

6.3.1 Upper Berg

The system model used in this study was adapted from the system model used for the annual operation of the Western Cape system, as updated after the Skuifraam Dam Feasibility Study. The original model was provided by Ninham Shand. The hypothetical yield dam was located at the end of subcatchment h20cd (at gauge G1h020) (see **Figure 4-2**, which shows a map of the subcatchments) to determine yield effects at the flow exit point of the catchment.

6.3.2 Upper Sabie

As no existing system model configuration for the Upper Sabie was available from other studies, a configuration was set up for this study. The hypothetical yield dam was located at the end of subcatchment 30 (see **Figure 4-3**, which shows a map of the subcatchments) to determine yield effects at the flow exit point of the catchment.

6.3.3 Mhlatuze

The system model used in this study was adapted from the system model used for the Mhlatuze Operating Rules and Future Phasing Study. The original model was provided by DWAF.

Three hypothetical dams, each of 1 MAR full supply capacity, were set up for the Mhlatuze investigations. The dams were located (see **Figure 4-4,** which shows a map of the subcatchments):

- at the end of subcatchment W12G, to determine yield at a lower MAP (834 mm) subcatchment upstream in the catchment.
- at the upstream end of subcatchment W12F, which contributes 40% of the runoff from W12F, to determine yield at a higher MAP (1 247 mm) subcatchment upstream in the catchment.
- at the end of subcatchment W12F to estimate yield at the bottom of the total catchment.

6.4 The Quantification of SFR Impacts on Yield Reliability Characteristics

This section describes the outcome of the yield modelling for the study river systems. The impacts on baseline yield by the various scenarios described in **Section 5.4** are compared to the impacts on natural MAR of the scenarios. The comparison is done, using the ratio of percentage reduction in yield to percentage reduction in MAR.

6.4.1 Mhlatuze

Table 6-1 summarises the baseline yield estimates at the three points in the Mhlatuze catchment. There is no run-of-river firm yield in the upstream catchments for both ACRU and SHELL flow sequences, meaning that there are one or more zero flow months in the baseline sequence for the upstream catchments.

Table 6-2 summarises the comparison of impacts of SFR on MAR and yield for the Mhlatuze catchments. **Figure 6-1** shows these results graphically.

Table 6-1: Baseline Yield Estimates for the Mhlatuze

	Yield from ACRU flow sequences Mm^3/a						Yield from SHELL flow sequences Mm^3/a					
	High MAP Top catchment		Low MAP Top catchment		Total catchment		High MAP Top catchment		Low MAP Top catchment		Total catchment	
Yield assurance	Res yield	ROR yield	Res yield	ROR yield	Res yield	ROR yield	Res yield	ROR yield	Res yield	ROR yield	Res yield	ROR yield
Firm yield	9	0	29	0	405	5	8	0	35	1	427	46
1:5 year failure	15	2	35	2	477	70	11	2	49	3	479	78
Baseline MAR Mm^3/a	21		56		706		20		65		729	

Table 6-2: Summary of Yield Modelling Results for the Mhlatuze (NA indicates zero baseline yield estimate) (See Section 5.4 for description of scenarios)

Configuration	Scenario	Yield assurance	ACRU FLOW SEQUENCES					SHELL FLOW SEQUENCES				
			% Reduction in			Ratio of % reductions		% Reduction in			Ratio of % reductions	
			Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR	Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR
HIGH MAP	Current day	Firm yield	93.1	95.6	NA	1.0	NA	26.8	74.5	100.0	2.8	3.7+
		1:5 year failure	93.1	95.9	100.0	1.0	1.1	26.8	51.4	100.0	1.9	3.7+
	Upland tall trees	Firm yield	5.5	6.7	NA	1.2	NA	8.6	19.5	100.0	2.3	11.6+

Configuration	Scenario	Yield assurance	ACRU FLOW SEQUENCES					SHELL FLOW SEQUENCES				
			% Reduction in			Ratio of % reductions		% Reduction in			Ratio of % reductions	
			Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR	Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR
		1:5 year failure	5.5	3.2	42.9	0.6	7.8	8.6	11.1	99.5	1.3	11.6
	Upland medium trees	Firm yield	2.2	4.9	NA	2.2	NA	6.6	15.7	100.0	2.4	15.2+
		1:5 year failure	2.2	6.5	52.2	2.9	23.7	6.6	9.2	99.0	1.4	15.0
	Upland tall shrubs	Firm yield	4.0	5.2	NA	1.3	NA	2.6	7.0	100.0	2.7	38.5+
		1:5 year failure	4.0	-4.5	36.0	-1.1	9.0	2.6	5.5	55.1	2.1	21.2
	Pines	Firm yield	1.4	4.3	NA	3.0	NA	6.4	15.3	100.0	2.4	15.6+
		1:5 year failure	1.4	7.1	23.6	5.0	16.9	6.4	9.1	99.0	1.4	15.5
	Eucalypts	Firm yield	4.7	5.1	NA	1.1	NA	5.8	14.0	100.0	2.4	17.2+
		1:5 year failure	4.7	-1.3	29.8	-0.3	6.3	5.8	8.4	99.0	1.4	17.1
	Riparian tall trees	Firm yield	2.7	6.3	NA	2.4	NA	8.5	21.3	100.0	2.5	11.8+
		1:5 year failure	2.7	13.8	59.6	5.2	22.5	8.5	14.6	96.1	1.7	11.3
	Riparian medium trees	Firm yield	2.1	5.1	NA	2.5	NA	5.7	14.4	100.0	2.5	17.5+
		1:5 year failure	2.1	-5.6	11.8	-2.7	5.7	5.7	10.2	68.8	1.8	12.0

Configuration	Scenario	Yield assurance	ACRU FLOW SEQUENCES					SHELL FLOW SEQUENCES				
			% Reduction in			Ratio of % reductions		% Reduction in			Ratio of % reductions	
			Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR	Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR
	Riparian tall shrubs	Firm yield	2.6	6.6	NA	2.5	NA	2.3	6.0	50.0	2.6	21.7
		1:5 year failure	2.6	-10.2	39.1	-3.9	14.9	2.3	4.1	29.8	1.8	12.9
LOW MAP	Current day	Firm yield	6.3	-5.9	NA	-0.9	NA	4.5	1.1	24.6	0.2	5.5
		1:5 year failure	6.3	-1.9	100.0	-0.3	15.9	4.5	1.2	8.4	0.3	1.9
	Upland tall trees	Firm yield	18.8	15.8	NA	0.8	NA	43.6	23.7	100.0	0.5	2.3+
		1:5 year failure	18.8	16.9	60.8	0.9	3.2	43.6	29.9	100.0	0.7	2.3+
	Upland medium trees	Firm yield	5.9	5.8	NA	1.0	NA	33.2	17.1	100.0	0.5	3.0+
		1:5 year failure	5.9	3.8	41.2	0.6	7.0	33.2	28.0	100.0	0.8	3.0+
	Upland tall shrubs	Firm yield	11.3	8.1	NA	0.7	NA	13.1	8.3	100.0	0.6	7.6+
		1:5 year failure	11.3	6.7	39.2	0.6	3.5	13.1	15.6	100.0	1.2	7.6+
	Pines (NA)	Firm yield		0.0	NA	NA	NA		0.0	0.0	NA	NA
		1:5 year failure		0.0	0.0	NA	NA		0.0	0.0	NA	NA
	Eucalypts (NA)	Firm yield		0.0	NA	NA	NA		0.0	0.0	NA	NA

Configuration	Scenario	Yield assurance	ACRU FLOW SEQUENCES					SHELL FLOW SEQUENCES				
			% Reduction in			Ratio of % reductions		% Reduction in			Ratio of % reductions	
			Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR	Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR
		1:5 year failure		0.0	0.0	NA	NA		0.0	0.0	NA	NA
	Riparian tall trees	Firm yield	4.5	4.8	NA	1.1	NA	12.2	19.3	100.0	1.6	8.2+
		1:5 year failure	4.5	5.0	99.7	1.1	22.2	12.2	15.9	100.0	1.3	8.2+
	Riparian medium trees	Firm yield	2.6	4.0	NA	1.5	NA	7.1	12.1	100.0	1.7	14.1+
		1:5 year failure	2.6	2.9	99.7	1.1	38.4	7.1	9.8	100.0	1.4	14.1+
	Riparian tall shrubs	Firm yield	4.2	4.8	NA	1.1	NA	0.1	3.0	100.0	29.6	981.2+
		1:5 year failure	4.2	4.6	99.7	1.1	23.7	0.1	2.1	64.0	21.0	628.0
TOTAL CATCHMNET	Current day	Firm yield	59.5	39.2	32.7	0.7	0.5	39.5	35.30	82.40	0.89	2.08
		1:5 year failure	59.5	40.1	94.6	0.7	1.6	39.5	34.19	85.90	0.86	2.17
	Upland tall trees	Firm yield	19.8	19.7	21.0	1.0	1.1	31.1	20.9	59.2	0.7	1.9
		1:5 year failure	19.8	14.5	36.1	0.7	1.8	31.1	16.6	63.1	0.5	2.0
	Upland medium trees	Firm yield	7.7	10.0	3.8	1.3	0.5	23.7	18.3	59.2	0.8	2.5
		1:5 year failure	7.7	8.0	29.9	1.0	3.9	23.7	15.3	60.5	0.6	2.6

Configuration	Scenario	Yield assurance	ACRU FLOW SEQUENCES					SHELL FLOW SEQUENCES				
			% Reduction in			Ratio of % reductions		% Reduction in			Ratio of % reductions	
			Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR	Baseline MAR	Res Yield	ROR Yield	Res Yield / MAR	ROR Yield / MAR
	Upland tall shrubs	Firm yield	13.8	15.1	21.0	1.1	1.5	9.3	11.0	56.8	1.2	6.1
		1:5 year failure	13.8	10.9	29.9	0.8	2.2	9.3	9.0	40.2	1.0	4.3
	Pines	Firm yield	2.1	3.5	0.0	1.7	0.0	10.2	12.8	56.6	1.3	5.5
		1:5 year failure	2.1	2.8	3.2	1.4	1.5	10.2	10.3	42.3	1.0	4.1
	Eucalypts	Firm yield	7.3	7.3	21.0	1.0	2.9	9.2	12.1	56.0	1.3	6.1
		1:5 year failure	7.3	6.5	19.4	0.9	2.6	9.2	9.8	40.5	1.1	4.4
	Riparian tall trees	Firm yield	6.6	10.0	24.8	1.5	3.8	31.1	24.5	68.9	0.8	2.2
		1:5 year failure	6.6	8.7	48.1	1.3	7.3	31.1	21.2	76.2	0.7	2.4
	Riparian medium trees	Firm yield	4.3	6.6	21.0	1.5	4.9	11.9	17.2	68.9	1.4	5.8
		1:5 year failure	4.3	5.9	42.4	1.4	9.9	11.9	15.8	75.4	1.3	6.3
	Riparian tall shrubs	Firm yield	6.3	9.7	24.8	1.5	3.9	4.5	8.4	68.2	1.9	15.1
		1:5 year failure	6.3	8.6	47.4	1.4	7.5	4.5	7.8	58.3	1.7	12.9

+ indicates that the ratio could be greater than the figure presented in the table

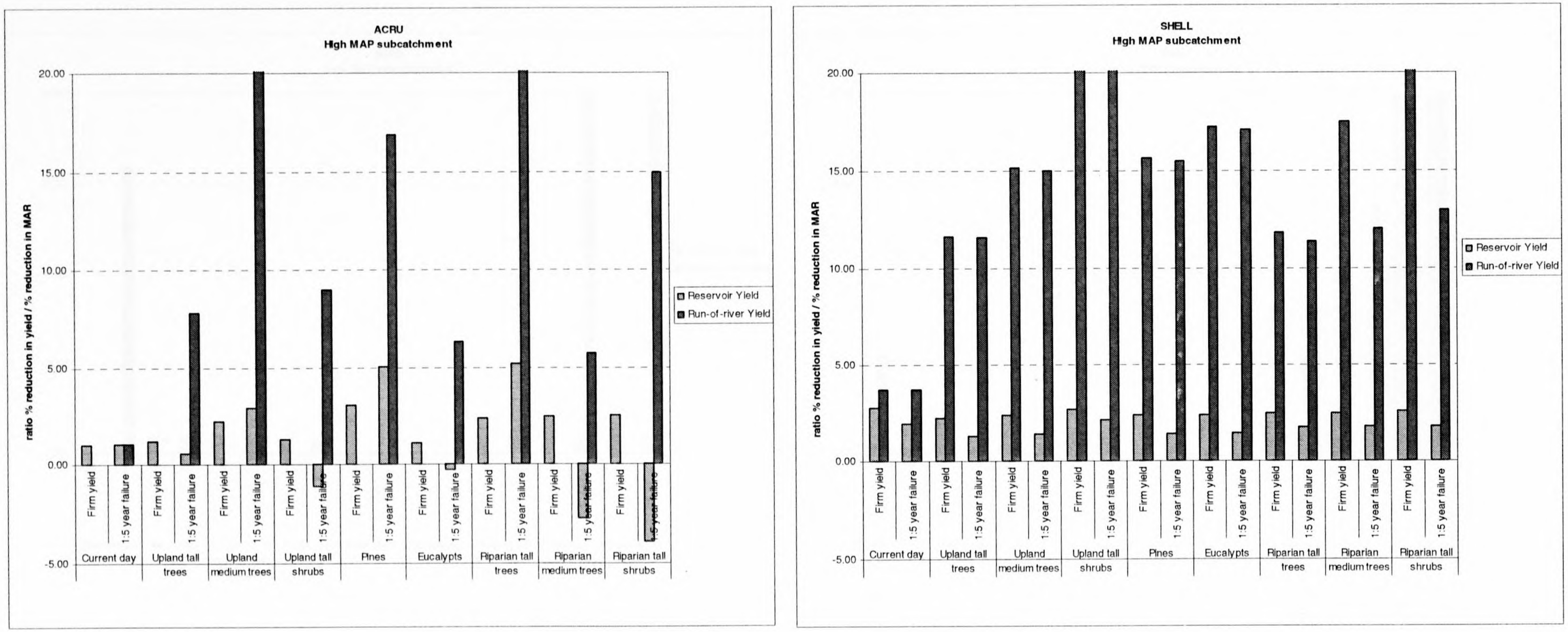


Figure 6-1: Summary of Yield Modelling Results for the Mhlatuze

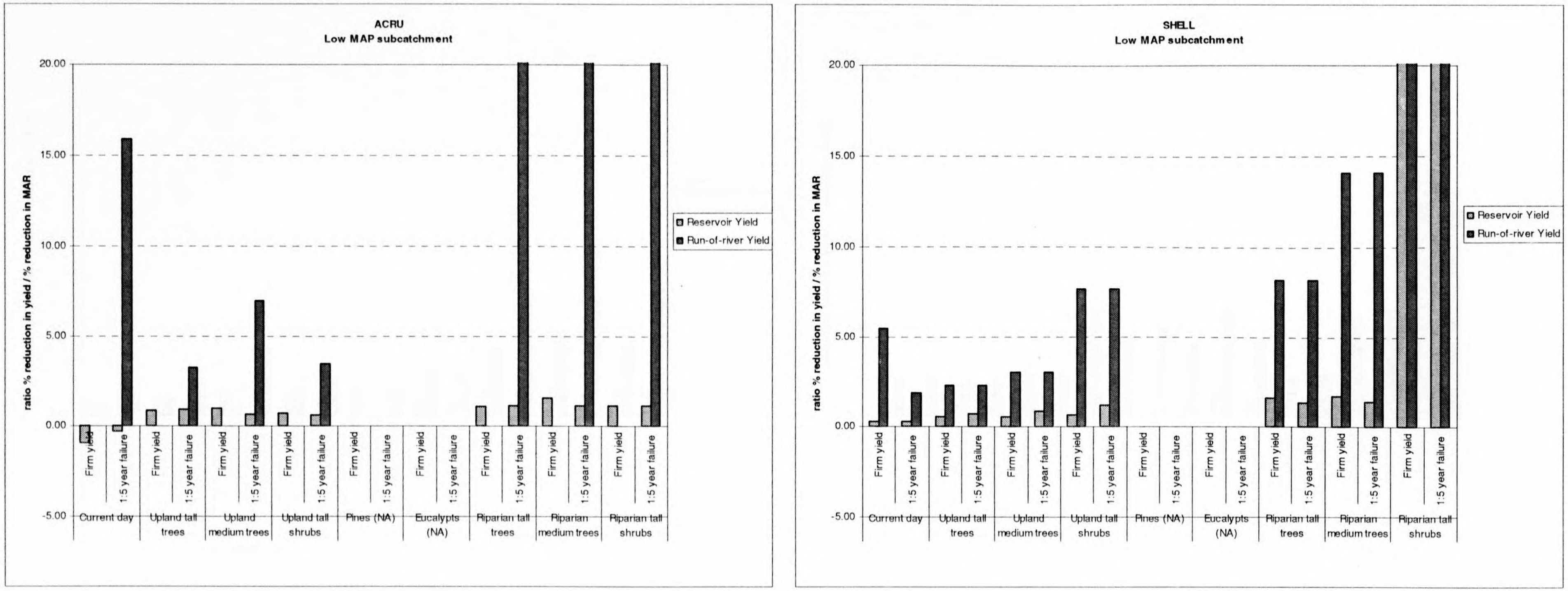


Figure 6-1: (continued) Summary of Yield Modelling Results for the Mhlatuze

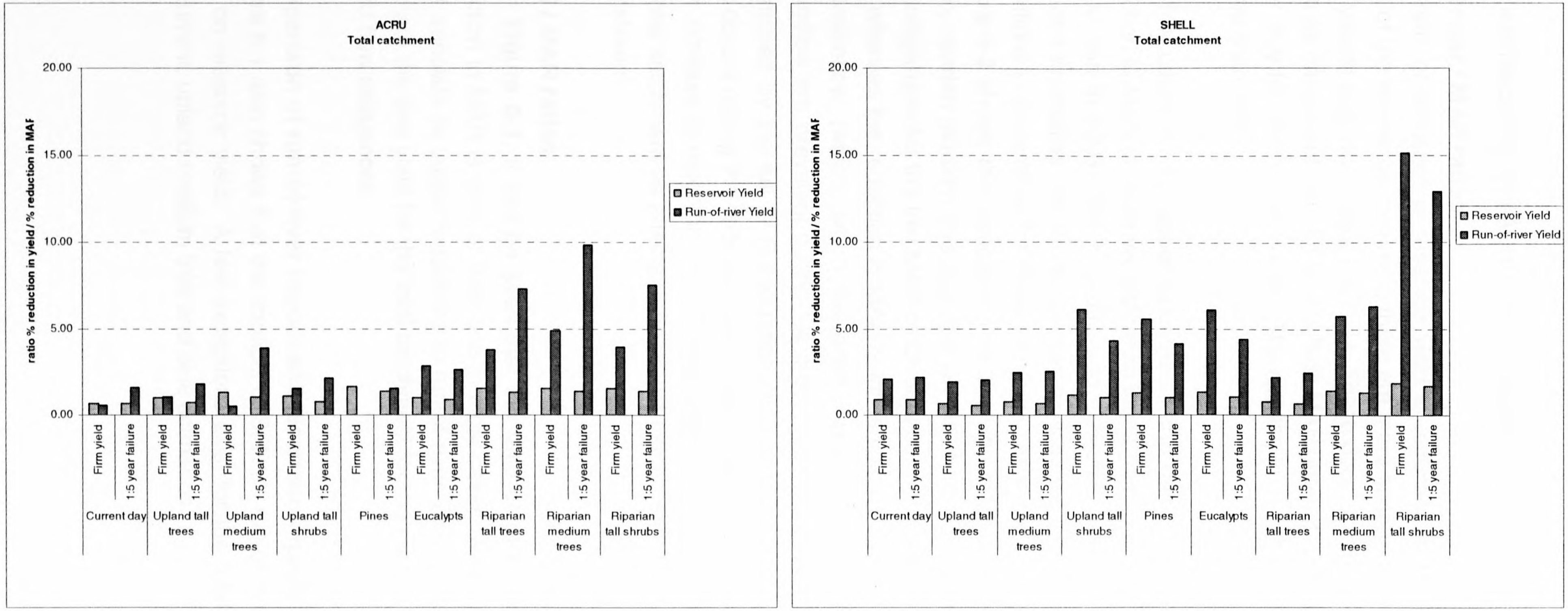


Figure 6-1: (continued) Summary of Yield Modelling Results for the Mhlatuze

6.4.1.1 Yield Modelling with ACRU Flow Sequences

Reservoir / MAR ratios:

The ratio of reduction in reservoir yield to reduction in MAR is greater than one for most of the scenarios, however, there are more scenarios (than in the case of run-of-river yields) with ratios less than one. These occur for the low MAP upper catchment and total catchment, but not for the high MAP upper catchment. Ratios less than one occur only for upland land uses. The riparian land uses all have ratios of magnitude greater than one.

In a few cases for the upper catchments, the ratio of reduction in reservoir yield to reduction in MAR is negative, indicating that a gain in reservoir yield is simulated from a reduction in MAR. This is contrary to expectation. In an attempt to explain these apparent anomalies, the monthly reservoir volumes were compared with the monthly reductions in streamflow for these scenarios, as shown in **Figure 6-2** and **Figure 6-3**. **Figure 6-2** shows the comparison for the high MAP catchment eucalypt, upland tall shrub, riparian medium tree and riparian tall shrub scenarios, and **Figure 6-3** shows the comparison for the low MAP catchment current scenario. The comparisons show that, whereas the reduction in MAR is influenced by alternating gains and reductions in streamflow (which, when averaged, result in a reduction in MAR), gains in streamflow are prevalent during the critical periods. Whereas the impact on MAR is determined by the full SFR sequence, the impact on yield is heavily dependent on what occurs during the critical period. This explains why a reduction in MAR can lead to an increase in reservoir yield. These gains in reservoir yield are not simulated for the total catchment as effects at upstream catchments are usually attenuated further downstream.

ROR / MAR ratios:

From **Figure 6-1**, it can be seen that the ratio of reduction in run-of-river yield to reduction in MAR is greater than one in most cases, which means that reductions in MAR translate to larger reductions in run-of-river yield. The only exceptions to this trend are the firm yield for the total catchment for the current and upland medium tree ACRU flow sequences.

Comparison of run-of-river impact and reservoir impact:

Figure 6-1 also shows that the impacts of SFR on run-of-river yield tend to be higher than on reservoir yield. A few exceptions exist for the total catchment firm yield for the current, upland medium tree and pine scenarios.

Comparison of upland catchment and total catchment cases:

The ratio of reduction in yield to reduction in MAR is generally lower for the total catchment than for the upstream catchments. This trend is, however, not clearly defined for the reservoir yields in the low MAP catchment,

Comparison of 1:5-year yield and firm yield cases:

For most of the ACRU scenarios, the impact of SFR on the run-of-river 1:5-year yield is greater than on the run-of-river firm yield, whereas the opposite is generally true for the impacts on reservoir yield. Exceptions to this lie mostly in the high MAP catchment, where no clear trend in the relationship between reservoir 1:5-year and reservoir firm yield can be discerned.

6.4.1.2 Yield Modelling with SHELL Flow Sequences

Reservoir / MAR ratios:

The ratio of reduction in reservoir yield to reduction in MAR is greater than one for most of the scenarios. Ratios less than one occur, mostly for upland land covers, in the low MAP upper catchment and the total catchment, but not in the high MAP upper catchment.

ROR / MAR ratios:

From **Figure 6-1**, it can be seen that the ratio of reduction in run-of-river yield to reduction in MAR is greater than one in all cases, which means that reductions in MAR translate to larger reductions in run-of-river yield.

Comparison of run-of- river impact and reservoir impact:

Figure 6-1 also shows that the impacts of SFR on run-of-river yield are higher than on reservoir yield for all the scenarios.

Comparison of upland catchment and total catchment cases:

The ratio of reduction in yield to reduction in MAR is generally lower for the total catchment than for the upstream catchments.

Comparison of 1:5-year yield and firm yield cases:

For most of the SHELL scenarios, the impact of SFR on the run-of-river 1:5-year yield is equal to or less than on the run-of-river firm yield. The same can be said for the impacts on reservoir yield, with exceptions for the upland IAP scenarios in the low MAP catchment.

6.4.1.3 Comparison of Impacts on Yield for ACRU and SHELL Flow Sequences.

Yield / MAR ratios:

On average, impacts of SFR on MAR translate to a larger impact on yield for both ACRU and SHELL flow sequences. No exceptions to this are found for the high MAP catchment.

For SHELL flow sequences, the impact on run-of-river yield is greater than the impact on MAR for all scenarios, whereas for the ACRU flow sequences, some scenarios display a lesser impact on run-of-river yield than MAR for the total catchment. As could be expected, the larger total catchment, with a wider variety of influences, shows less impact on yield than the smaller upstream catchments.

Gains in yield occur in some of the upper ACRU catchments. These might be attributed to gains in low flows, which occur during the critical period in some of the ACRU flow sequences. These gains in yield do not occur in the SHELL scenarios.

In general, corresponding scenarios for SHELL and ACRU display ratios of impact on reservoir yield to impact on MAR smaller than one.

Comparison of run-of- river impact and reservoir impact:

The impacts of SFR on run of-river-yield are higher than on reservoir yield for all the SHELL scenarios, whereas a few exceptions exist for the total catchment ACRU scenarios. As could be expected, impacts on run-of-river yield are greater than on reservoir yield, as the attenuating effects of storage do not exist in the run-of-river situation.

Comparison of upland catchment and total catchment cases:

The ratio of reduction in yield to reduction in MAR is generally lower for the total catchment than for the upstream catchments. More exceptions exist in the low MAP catchment ACRU scenarios than in the other scenarios. As could be expected, the larger total catchment with a wider variety of influences shows less impact on yield than the smaller upstream catchments.

Comparison of 1:5-year yield and firm yield cases:

For the run-of-river case, 1:5-year yield impacts tend to be greater than firm yield impacts for ACRU flow sequences, whereas the opposite tends to be true for SHELL flow sequences. The same comparison for reservoir yield shows that for SHELL, the

1:5-year yield impacts tend to be less than impacts on firm yield, but the ACRU results do not show a clear trend.

Comparison of upland and riparian scenarios:

Impacts on yield for the riparian scenarios appear to be greater than in the upland scenarios, for both ACRU and SHELL flow sequences for the low MAP and total catchments. This trend is less clear for the high MAP catchment.

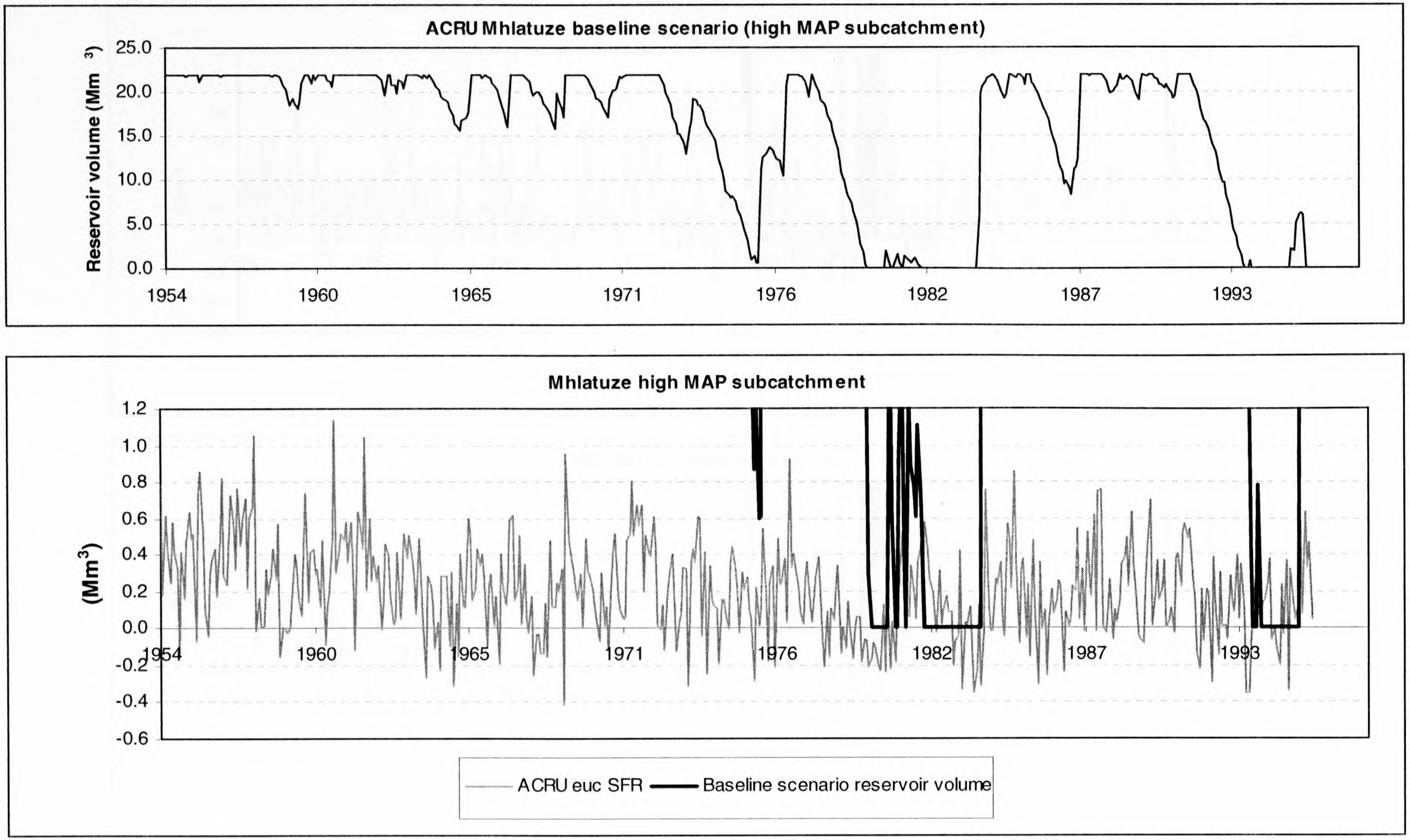


Figure 6-2: Comparison of Yield Reservoir Volume for the ACRU 1 in 5 year Baseline Scenario and SFR for ACRU Scenarios for the High MAP Mhlatuze Catchment

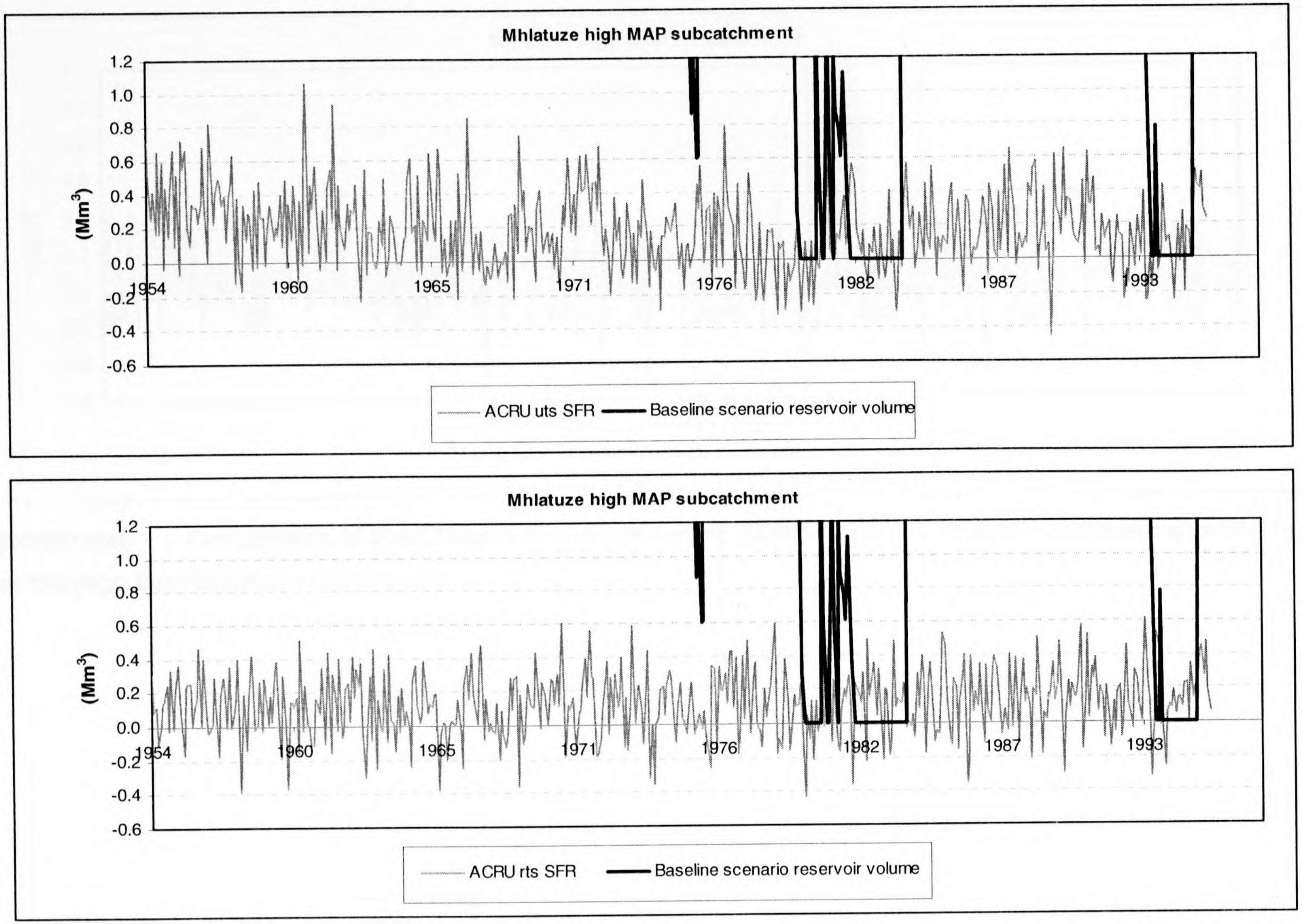


Figure 6-2: (continued) **Comparison of Yield Reservoir Volume for the ACRU 1 in 5 year Baseline Scenario and SFR for ACRU Scenarios for the High MAP Mhlatuze Catchment**

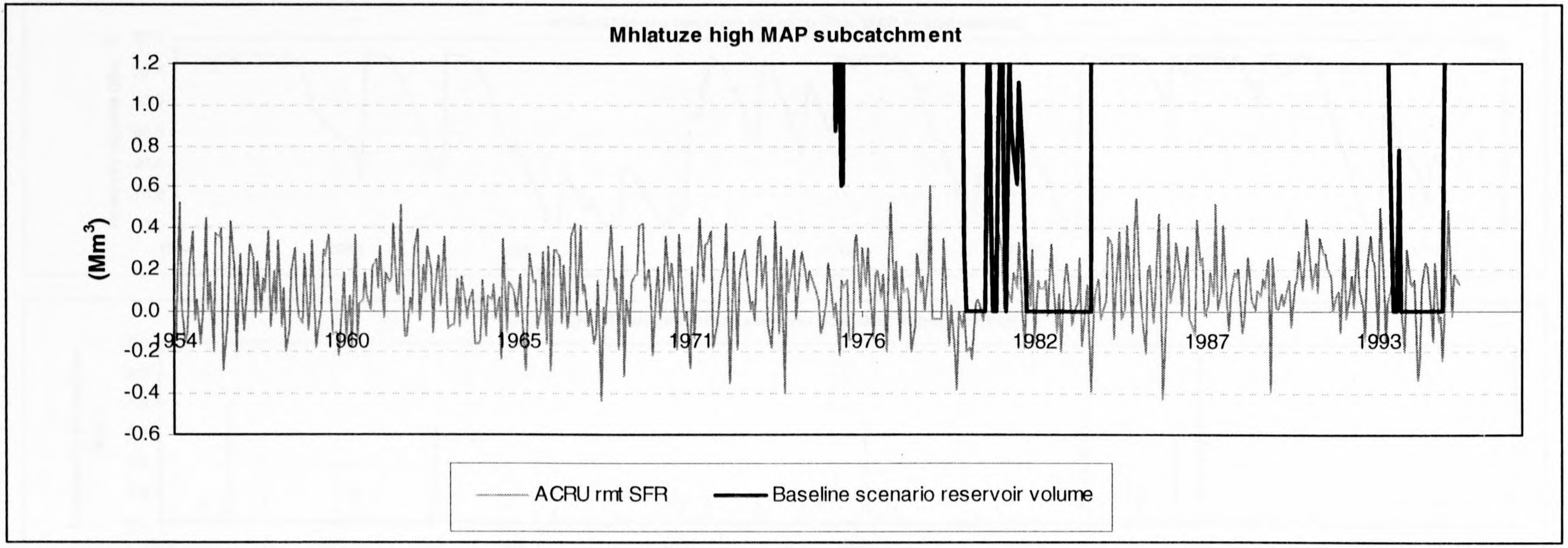


Figure 6-2: (continued) **Comparison of Yield Reservoir Volume for the ACRU 1 in 5 year Baseline Scenario and SFR for ACRU Scenarios for the High MAP Mhlatuze Catchment**

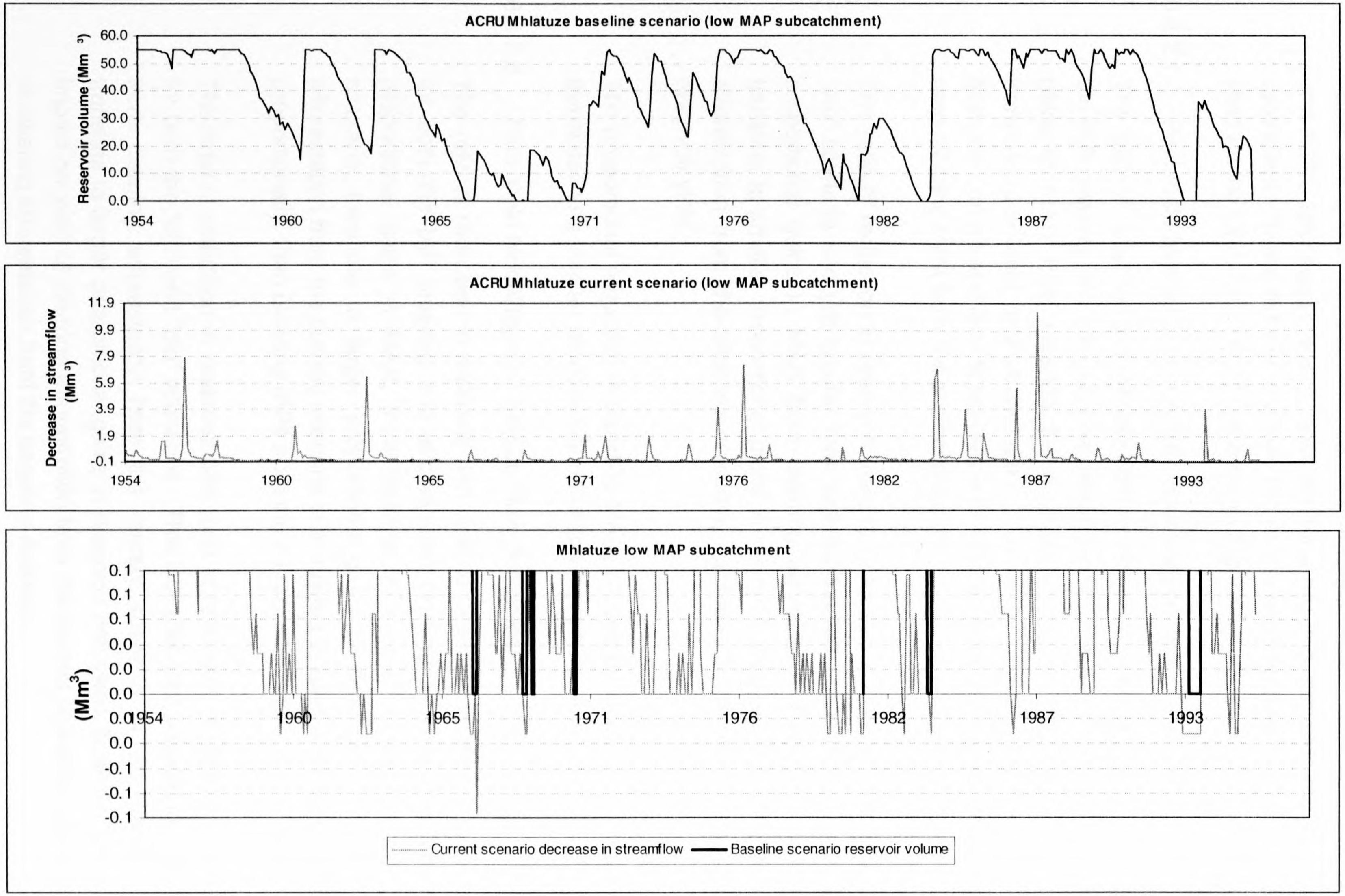


Figure 6-3: **Comparison of Yield Reservoir Volume for the ACRU 1 in 5 year Baseline Scenario and Decrease in Baseline Streamflow for the ACRU Current Scenario for the Low MAP Mhlatuze Catchment**

6.4.2 Upper Berg

Table 6-3 shows the baseline yield estimates produced for the Upper Berg SHELL and ACRU flow sequences. These are for a hypothetical dam at the end of the total catchment. **Table 6-4** summarises the comparison of impacts of SFR on MAR and yield for the total Upper Berg catchment. **Figure 6-4** shows these results graphically.

6.4.2.1 Firm Yield Modelling with ACRU Flow Sequences

The ratio of reduction in reservoir yield to reduction in MAR is less than one for both the IAP clearing and afforestation clearing scenarios, which means that proportional gains in MAR from clearing these vegetation types from the current scenario, translate to smaller proportional gains in reservoir firm yield. Clearing afforestation from the current scenario is simulated to have a larger impact on yield, proportionally, than clearing IAPs from the current scenario.

The ratio of reduction in reservoir yield to reduction in MAR is less than one for the "cfo" scenario and yet greater than one for the "pin" scenario. This indicates that proportional gains in MAR from clearing afforestation from the current scenario, translate to smaller proportional gains in reservoir yield, whereas clearing the same afforestation from the baseline scenario, translates to greater proportional gains in reservoir yield.

The proportional reduction in baseline MAR, caused by all the current day land uses, translates to a smaller proportional reduction in reservoir firm yield.

6.4.2.2 Firm Yield Modelling with SHELL Flow Sequences

The ratio of reduction in reservoir firm yield to reduction in MAR is greater than one for both the IAP clearing and afforestation clearing scenarios, which means that proportional gains in MAR, from clearing IAPs or afforestation from the current scenario, translate to larger proportional gains in reservoir firm yield. Clearing afforestation from the current scenario is simulated to have a smaller impact on yield, proportionally, than clearing IAPs from the current scenario.

The ratio of reduction in reservoir firm yield to reduction in MAR is greater than one for both the "cfo" and "pin" scenarios. This indicates that proportional gains in MAR, from clearing afforestation from the current scenario or the baseline scenario, translate to larger proportional gains in reservoir firm yield, however, the proportional impact on yield of clearing afforestation from the current scenario is greater than that of clearing afforestation from the baseline scenario.

The proportional reduction in baseline MAR, caused by all the current day land uses, translates to a larger proportional reduction in reservoir firm yield.

6.4.2.3 Comparison of Impacts on Yield for ACRU and SHELL Flow Sequences

The ratio of reduction in firm yield to reduction in MAR for SHELL flow sequences is larger than that for ACRU flow sequences for all the scenarios. Whereas all the SHELL ratios are greater than one, all the ACRU ratios, except for the "pin" scenario, are less than one. Whereas, for the SHELL flow sequences, clearing afforestation from the current scenario is simulated to have a smaller impact on yield, proportionally, than clearing IAPs from the current scenario, the opposite is true for the ACRU flow sequences. Whereas, for the SHELL flow sequences, the proportional impact on yield of clearing afforestation from the current scenario is greater than that of clearing afforestation from the baseline scenario, the opposite is true for the ACRU flow sequences. Whereas, for the SHELL flow sequences, the proportional reduction in baseline MAR, caused by all the current day land uses, translates to a larger proportional reduction in reservoir firm yield, the opposite is true for the ACRU flow sequences. These differences between trends for the two models may be as a result of the gains in low flow (after clearing of afforestation or IAPs), which occur in the ACRU scenarios, but not in the SHELL scenarios. These gains in streamflow occur during the critical period of the yield analysis.

Table 6-3: Baseline Yield Estimates for the Upper Berg

Catchment	ACRU FLOW SEQUENCES		SHELL FLOW SEQUENCES	
	Baseline MAR Mm3/a	Baseline reservoir firm yield Mm^3/a	Baseline MAR Mm3/a	Baseline reservoir firm yield Mm^3/a
Berg	441	320	488	342

Table 6-4: Summary of Firm Yield Modelling Results for the Upper Berg

Scenario	ACRU FLOW SEQUENCES						SHELL FLOW SEQUENCES					
	% Reduction in				Ratio of % reduction		% Reduction in				Ratio of % reduction	
	Base-line MAR	Cur MAR	Base-line res yield	Cur res yield	Baseline res yield / baseline MAR	Cur res yield / cur MAR	Base-line MAR	Cur MAR	Base-line res yield	Cur res yield	Baseline res yield / baseline MAR	Cur res yield / cur MAR
current (cur)	15.20		2.68		0.18		14.57		21.46		1.47	
current with plantations cleared (cfo)		-0.95		-0.75		0.79		-4.29		-7.56		1.76
current with aliens cleared (cav)		-0.40		-0.25		0.63		-0.81		-2.03		2.51
afforested baseline (pin)	0.87		0.98		1.12		6.78		8.90		1.31	

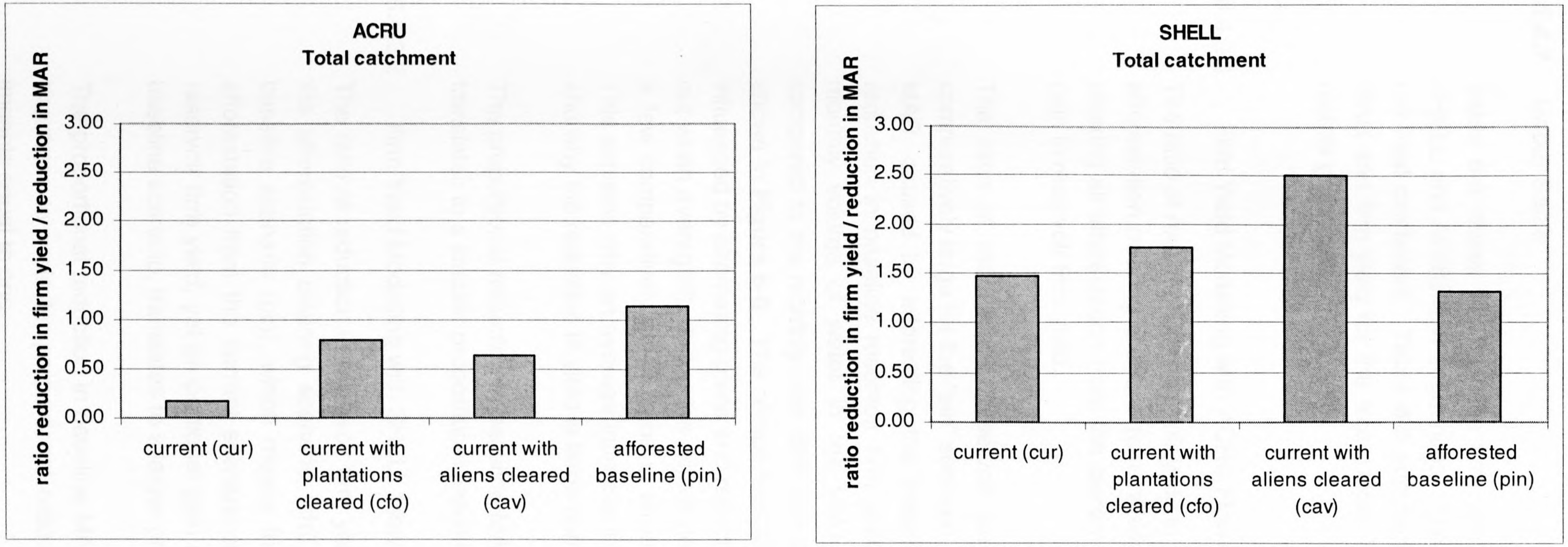


Figure 6-4: Summary of Yield Modelling Results for the Upper Berg

6.4.3 Upper Sabie

Table 6-5 shows the baseline firm yield estimates produced for the Upper Sabie SHELL and ACRU flow sequences. These are for a hypothetical dam at the end of the total catchment. **Table 6-6** summarises the comparison of impacts of SFR on MAR and firm yield for the total Upper Sabie catchment. **Figure 6-5** shows these results graphically.

6.4.3.1 Firm Yield Modelling with ACRU Flow Sequences

The ratio of reduction in reservoir yield to reduction in MAR is greater than one for the afforestation clearing scenario (cfo), which means that proportional gain in MAR from clearing all afforestation from the current scenario translates to a larger proportional gain in reservoir firm yield.

The ratio of reduction in reservoir yield to reduction in MAR is negative and comparatively large for the "pin" scenario. This means that the relatively small gain in MAR, caused by afforesting the baseline scenario, translates to a much larger reduction in baseline reservoir firm yield. To explain this apparent anomaly, the monthly volume of water in the yield reservoir for the baseline scenario was compared to the monthly total SFR due to the afforestation in the "pin" scenario, as shown in **Figure 6-6**. The comparison shows that, whereas the reduction in MAR is influenced by alternating gains and reductions in streamflow (which cancel each other out when averaged), during the critical period (1981 to 1985), mostly reductions, and a few comparatively small gains in streamflow, influence the yield of the reservoir. This explains why an average increase in MAR leads to a reduction in reservoir yield and why the reduction in yield is large compared to the increase in MAR.

The proportional reduction in baseline MAR, caused by all the current day land uses, translates to a smaller proportional reduction in reservoir firm yield.

6.4.3.2 Firm Yield Modelling with SHELL Flow Sequences

The ratio of reduction in reservoir firm yield to reduction in MAR is less than one for the afforestation clearing scenario (cfo), but greater than one for the afforested baseline scenario (pin), which means that proportional gain in MAR from clearing afforestation from the current scenario translates to a smaller proportional gain in reservoir firm yield, yet proportional gain in MAR from clearing afforestation from the baseline scenario, translates to a larger proportional gain in reservoir firm yield.

The proportional reduction in baseline MAR, caused by all the current day land uses, translates to a similar proportional reduction in reservoir firm yield, with a ratio of impacts equal to one.

6.4.3.3 Comparison of Impacts of Yield for ACRU and SHELL Flow Sequences.

The ratio of reduction in firm yield to reduction in MAR for SHELL flow sequences is smaller than that for ACRU flow sequences for the “cfo” scenario and larger for the current and “pin” scenarios. The anomalously large negative ratio, obtained for the ACRU “pin” scenario, does not occur with the SHELL “pin” scenario. Whereas, via SHELL, the gain in MAR from clearing afforestation from the current scenario, translates to a smaller impact on reservoir firm yield, via ACRU, the gain in MAR translates to a larger impact on reservoir firm yield. Whereas via SHELL, the decrease in baseline MAR, due to all the current day land uses, translates to a similar impact on reservoir firm yield, via ACRU, the decrease in baseline MAR translates to a smaller impact on reservoir firm yield

Table 6-5: Baseline Firm Yield Estimates for the Upper Sabie

Catchment	ACRU FLOW SEQUENCES		SHELL FLOW SEQUENCES	
	Baseline MAR Mm3/a	Baseline reservoir firm yield Mm³/a	Baseline MAR Mm3/a	Baseline reservoir firm yield Mm³/a
Sabie	364	259	512	406

Table 6-6: Summary of Firm Yield Modelling Results for the Upper Sabie

Scenario	ACRU FLOW SEQUENCES						SHELL FLOW SEQUENCES					
	% Reduction in				Ratio of % reduction		% Reduction in				Ratio of % reduction	
	Base-line MAR	Cur MAR	Base-line res Yield	Cur res Yield	Baseline res yield / baseline MAR	Current res yield / current MAR	Base-line MAR	Cur MAR	Base-line res Yield	Cur res Yield	Baseline res yield / baseline MAR	Current res yield / current MAR
current (cur)	39.8		27.1		0.7		49.5		51.9		1.0	
current with plantations cleared (cfo)		-2.2		-4.1		1.9		-69.0		-64.8		0.9
afforested baseline (pin)	-0.2		3.9		-18.8		36.9		41.3		1.1	

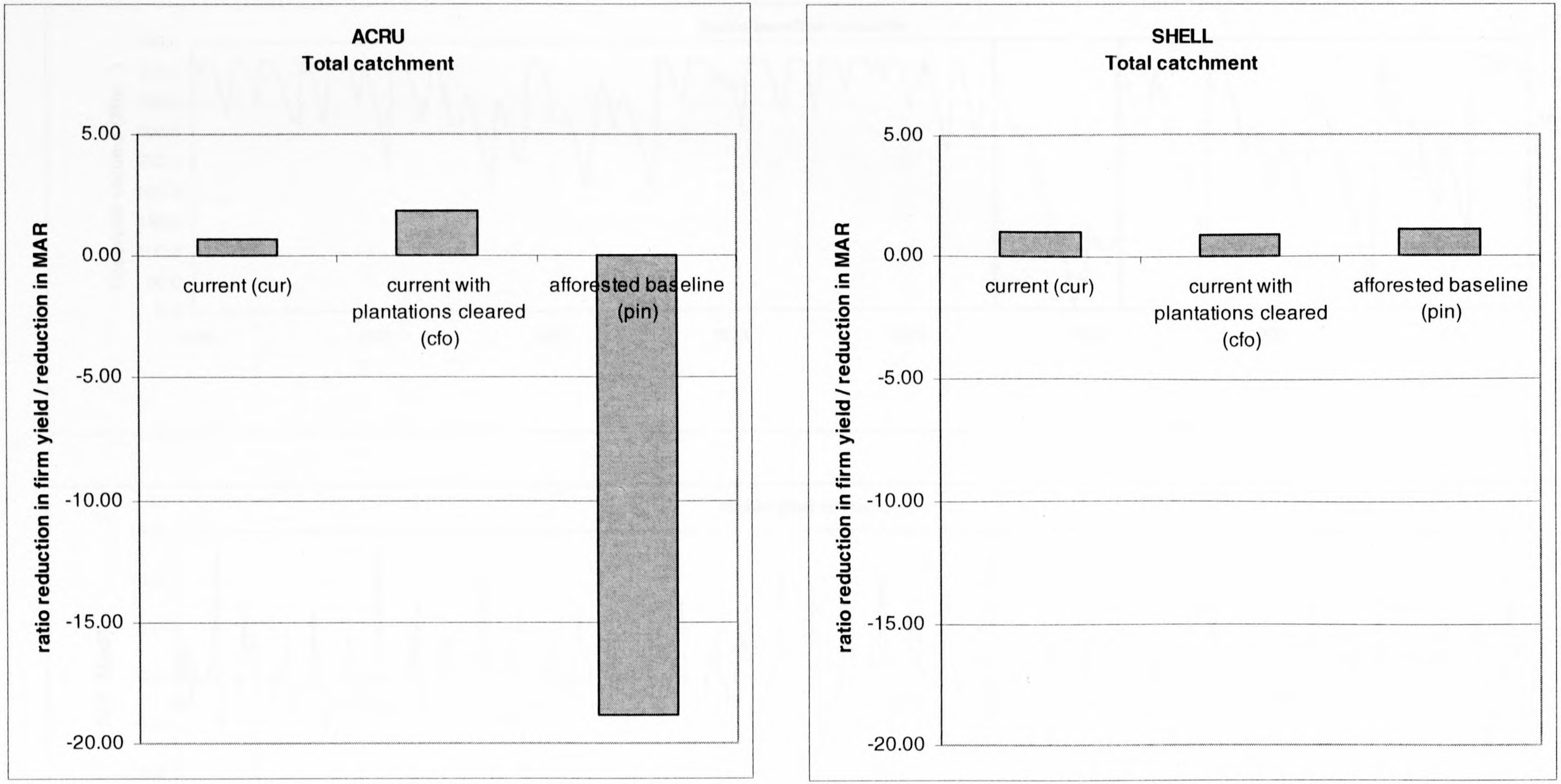


Figure 6-5: **Summary of Yield Modelling Results for the Upper Sabie**

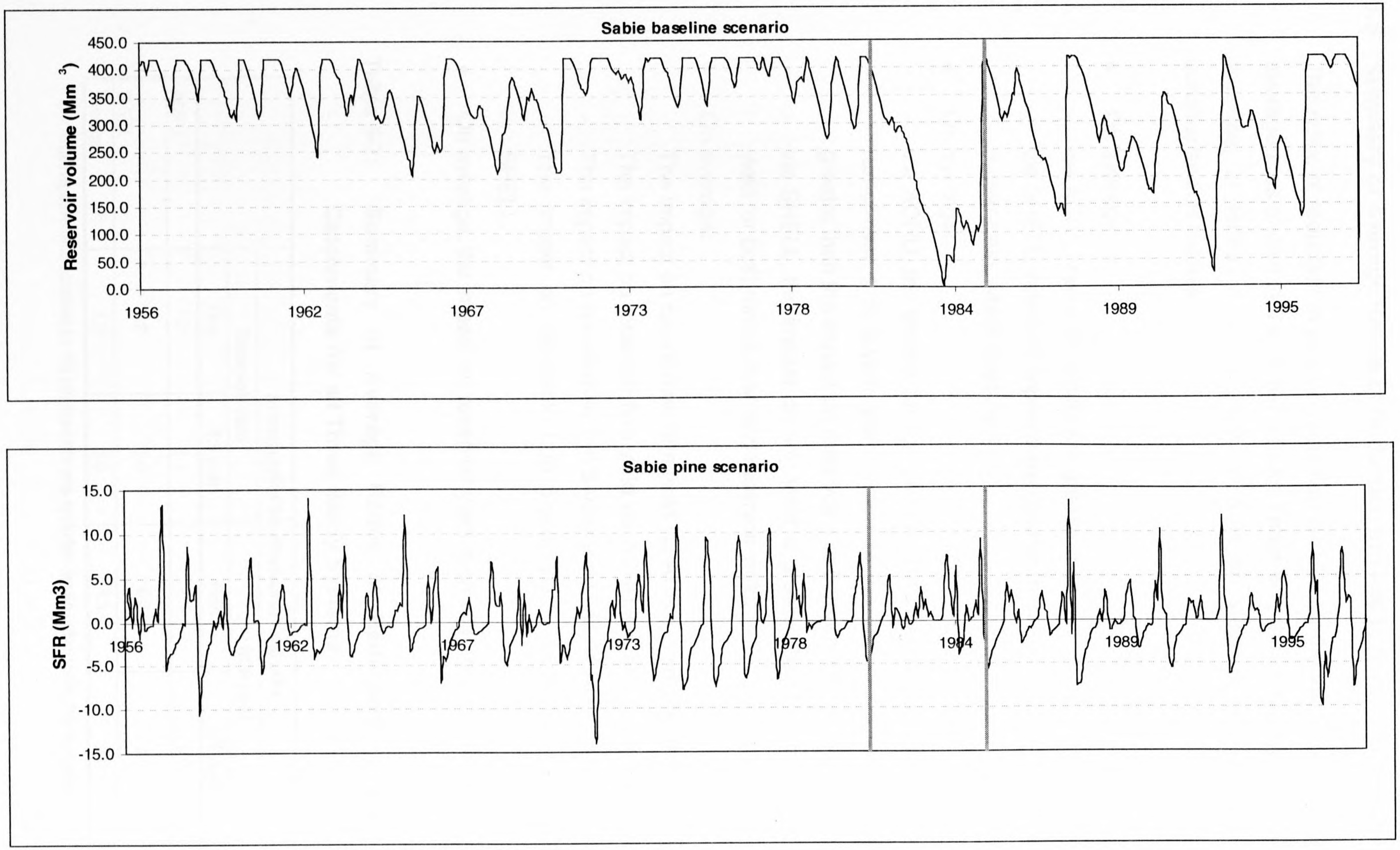


Figure 6-6: Comparison of Yield Reservoir Volume for the ACRU Baseline Scenario and SFR for the ACRU Pine Scenario for the Total Sabie Catchment

6.5 Summary of Average Ratios of Reduction in Yield to Reduction in MAR

The ratios of reduction in yield to reduction in MAR for the three total catchments were averaged, as shown in **Table 6-7**. From **Table 6-7,** the results of the yield modelling exercise, in terms of the impacts of SFR on yield at a given assurance, are summarised as follows:

- On average:
  - via ACRU, ratios of impact are greater than one.
  - via SHELL, ratios of impacts are greater than one, except for the reservoir 1 in 5-year ratio, which is equal to one.
- On average:
  - via ACRU, the impact on run-of-river firm yield is smaller than the impact on run-of-river 1 in 5-year yield, whereas the impact on reservoir firm yield is greater than the impact on reservoir 1 in 5-year yield.
  - via SHELL, the impact on firm yield is greater than the impact on 1 in 5-year yield for both run-of-river and reservoir yield.
- On average:
  - The impact on run-of-river firm yield via ACRU is smaller than via SHELL.
  - The impact on reservoir firm yield via ACRU is greater than via SHELL.
  - The impact on run-of-river 1 in 5-year yield, via ACRU, is similar to via SHELL.
  - The impact on reservoir 1 in 5-year yield, via ACRU, is greater than via SHELL.
- On average, the impact on reservoir yield is smaller than on run-of-river yield

Table 6-7: Summary of Average Ratios of Reduction in Yield for Total Catchments for all Three Study Systems

	Average ratios for afforestation and IAPs			
	Reservoir yield		**ROR yield**	
	Firm	**1:5 year**	**Firm**	**1:5 year**
ACRU	1.3*	1.1	2.5	5.0
SHELL	1.2	1.0	6.2	5.0
Average	1.2	1.0	4.3	5.0

*The large negative ratio obtained for the pin scenario was excluded (as an outlier) from this average

7 GUIDELINES FOR THE TREATMENT OF STREAMFLOW REDUCTION IMPACTS DUE TO AFFORESTATION AND INVASIVE ALIEN VEGETATION AT NATIONAL AND CATCHMENT LEVELS IN WATER RESOURCE ANALYSIS

7.1 Orientation

The material presented in the preceding chapters of this document illustrates and engages many of the uncertainties in SFR quantification that confront water resource managers and analysts in South Africa. A range of research initiatives are currently underway in recognition of these uncertainties (Görgens, 2003), but given their complexity, considerable "calendar time" needs to elapse before the uncertainties can be expected to become diminished by maturing research. In the interim, water resource management activities, such as licensing and other water use authorisation, water use allocation scheduling, bulk and strategic water supply planning, water resource augmentation design and water resource operations, all continue to require some form of SFR quantification. It follows, therefore, that some form of "systematic guidance" for the appropriate inclusion of SFR quantifications in water resource management activities may be a useful addition to the collection of "tools" that are currently being used in this domain. Based on the generic lessons learnt in the research reported above, the following section proposes a set of provisional guidelines relevant to the analysis component of the water resource management process. (Additional guidelines may be needed for other components of water resource management.)

7.2 Guidelines

This section endeavours to provide some guidance for SFR modelling, using the ACRU and SHELL modelling packages. Primarily, it focuses on a number of important considerations, related to SFR modelling, drawn from the findings of this research (including information gleaned from the literature review), which should be taken into consideration when conducting an SFR modelling exercise during a water availability assessment or other water resource analyses. The guideline for each consideration describes how the ACRU and SHELL modelling packages perform around the consideration, pointing out any strengths and weaknesses of each modelling package, thereby allowing the user of the guidelines to make an informed decision on which modelling package is most suitable for a particular analysis. The minimum data requirements of each model are included in the guidelines to alert the user to situations where the data availability for the analysis does not match the model input requirements.

It should be noted that the points included in this chapter are only guidelines and exceptions to what has been noted here are possible

Table 7-1: Minimum Input Data Requirements for ACRU and SHELL

Modelling package	Input data requirements	
ACRU (Smithers and Schulze, 1995)	Catcment	Location, area, altitude, catchment configuration
	Rainfall	Daily rainfall
	Reference evaporation	Mean monthly A-pan or Mean monthly maximum and minimum temperature
	Total evaporation	Fraction of plant available water when total evaporation < maximum evaporation, root depth
	Land cover	Types of land cover (land cover parameters of crop coefficient, interception loss, rooting depth, etc)
	land use, water use	irrigation, reservoirs, abstractions, imports, etc.
	Soils	Depth, texture class
	Streamflow	Response factors for stormflow, baseflow, catchment
SHELL (Berg et al, 1991) (Pitman and Kakebeeke, 1993)	Catchment	Area, catchment configuration
	Rainfall	Monthly rainfall, MAP
	Reference evaporation	Mean monthly A-pan
	Land cover, land use, water use	IAPs, commercial afforestation, irrigation, reservoirs, abstractions, imports
	Observed Streamflow	Monthly observed streamflow

Table 7-2: Guidelines for the Treatment of SFR Impacts due to Afforestation and Invasive Alien Vegetation in Water Resource Analysis

No.	Consideration	Guideline
i	**Focus on characteristics of the total flow regime that are relevant to the specific water resource analysis**	The proportional impact of SFR on dry season low flows is more severe than on total MAR. This trait is prevalent in both ACRU and SHELL SFR estimation. Application of the 2004 default values in the ACRU Menubuilder may lead to apparent gains in simulated streamflow rather than streamflow reductions during dry season low flows. This phenomenon is modelled by ACRU and by the PET riparian model used in conjunction with SHELL, and is highly dependent on the land use parameters used for the tree species and the natural vegetation replaced. The SHELL routines for upland IAPs and commercial afforestation do not produce this apparent anomaly.

<table>
<tr><th>No.</th><th>Consideration</th><th>Guideline</th></tr>
<tr><td></td><td></td><td>
<p>The impact of SFR on yield at a given assurance is generally greater than the impact of SFR on MAR. This is apparent in yield impacts determined via both ACRU and SHELL It is therefore important to also model the impact of SFR on yield at a given assurance if this is the character of the flow regime relevant to the analysis. The impact of SFR on yield at a given assurance determined via ACRU may be different from that determined via SHELL. The following average ratios of impact on yield to impact on MAR were produced in the yield analysis which contributed to the formulation of this guideline:</p>
<table>
<tr><th></th><th colspan="4">Average ratios of impact on yield to impact on MAR due to SFR after afforestation, or invasion by IAPs</th></tr>
<tr><th></th><th colspan="2">Reservoir yield</th><th colspan="2">ROR yield</th></tr>
<tr><th></th><th>Firm</th><th>1:5 year</th><th>Firm</th><th>1:5 year</th></tr>
<tr><td>ACRU</td><td>1.3</td><td>1.1</td><td>2.5</td><td>5.0</td></tr>
<tr><td>SHELL</td><td>1.2</td><td>1.0</td><td>6.2</td><td>5.0</td></tr>
<tr><td>Average</td><td>1.2</td><td>1.0</td><td>4.3</td><td>5.0</td></tr>
</table>
<p>A simulated reduction in MAR can result in a simulated increase in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow gains; likewise, a simulated increase in MAR can result in a simulated reduction in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow reductions.</p>
</td></tr>
<tr><td>ii</td><td>Distinguish between riparian and upland origins of the SFR impacts</td><td>
<p>SFR by riparian IAPs, in unit terms (mm per unit area invaded), is generally greater than by upland IAPs of the same species. The SFR modelling exercise, which contributed to the formulation of this guideline, produced ratios of unit riparian SFR to unit upland SFR ranging from 3 to 10 for ACRU and from 3 to 6 for SHELL</p>
<p>In volumetric terms, reduction in MAR by upland plants may be more severe if the upland area invaded is much larger than the riparian area invaded, however, even in cases where the invaded upland area is much larger than the invaded riparian area, the mean annual reduction in dry season low flows by riparian IAPs tends to be greater than by upland IAPs. It is therefore of particular importance to differentiate between upland and riparian origins of SFR impacts when the analysis is concerned with the impacts on dry season low flows.</p>
<p>These distinctions in SFR impacts are prevalent in both ACRU- and SHELL-modelled SFR.</p>
</td></tr>
</table>

No.	Consideration	Guideline
iii	**Define a "baseline" or "reference" land-cover scenario against which the SFR-impacted streamflows are to be juxtaposed**	Streamflow losses over time (after clearing of trees) occur if the "baseline" vegetation growing in place of cleared trees uses more water than the trees. This is very sensitive to the selection of baseline vegetation types. In ACRU, selection of the "baseline" land cover is flexible in that the user has the option of selecting what specific land and water uses make up the baseline. In SHELL, the "baseline" land cover consists of all land and water uses which can not be defined independently in the catchment configuration and are therefore implicit in the catchment calibration parameters. Definition of a "baseline" land cover in SHELL is therefore less flexible than in ACRU.
iv	**Recognise different categories of SFR-causing vegetation**	The category of SFR-causing vegetation influences the magnitude of the SFR caused. In general tall trees cause more SFR than medium trees and tall shrubs. In ACRU modelling, this is highly dependent on the land use parameters used for the vegetation categories and may not always be the case, while in SHELL modelling this is fixed by the CSIR curves used for upland SFR estimation and dependent on the crop coefficients used with the PET method for riparian SFR estimation. ACRU is therefore more flexible than SHELL in terms of modelling different varieties of SFR-causing vegetation, particularly in the upland case.
v	**Define the age and species mosaic of SFR-causing vegetation**	Mature and slow growing vegetation is likely to use less water than young and fast-growing vegetation and reversals in streamflow gains after clearing of trees can occur when the trees being cleared are mature and replaced by young plants. This phenomenon can be modelled in ACRU through the land cover parameters allocated to the different vegetation types, but the SHELL routine for upland IAPs and commercial afforestation does not have the capability of modelling this, since it is based on fixed proportional reduction curves. The curves can estimate SFR for three tree classes of user-defined age. The riparian routine used with SHELL (PET method) may be able model this phenomenon through the crop coefficients allocated to the different vegetation types.
vi	**Define the age and species mosaic of the baseline / natural vegetation**	Mature and slow growing vegetation is likely to use less water than young and fast-growing vegetation and reversals in streamflow gains after clearing of trees can occur when the trees being cleared are mature and replaced by young natural vegetation. Different ages and species of natural vegetation can be modelled in ACRU through the land cover parameters allocated to the different vegetation types, but the SHELL routine for upland IAPs and commercial afforestation does not have this flexibility, since it is based on fixed proportional reduction curves. The riparian routine used with SHELL (PET method) may be able to model different ages and species of natural vegetation through the crop coefficients allocated to the different vegetation types

No.	Consideration	Guideline
vii	**Determine if the analysis should be for an SFR-causing vegetation scenario that is static, or dynamic, in terms of vegetation type mix, age and location**	SFR caused by woody plants, such as pines and eucalypts, tends to decrease as they mature. It is possible for SFR-causing vegetation to spread through a catchment if clearing operations are not carried out, therefore the simulation may need to be dynamic in terms of area covered. Cycles of burning in a catchment can affect the spread of vegetation and the pattern of SFR over time. In ACRU, changes in vegetation over time can be modelled by allowing the input land cover parameters of the vegetation to change over time, however there is no facility to change the catchment area covered by the vegetation over time. In SHELL, changes in vegetation over time can only be modelled by changing the catchment area covered by the vegetation over time.
viii	**Consider coarser spatial scales for bulk water resource augmentation planning, but finer scales for water allocations under compulsory licensing as well as for site-specific investigations to support conflict resolution**	ACRU operates at finer spatial scales, while SHELL operates at coarser spatial scales. It may therefore be more practical to use ACRU for analyses concerning SFR impacts at smaller spatial scales and SHELL for analyses where SFR impacts at larger spatial scales are of interest. Impact of SFR on yield of a given assurance is generally higher for smaller individual upstream catchments than for larger (sub)catchments with more attenuating water resource development influences.
ix	**Determine the required temporal scale of the analysis**	Input data, computer resources and time requirements for daily ACRU modelling are more rigorous than for monthly SHELL modelling. If the analysis requires daily flow sequences, such as interrogating the SFR-caused change in flow duration curves for reserve operationalisation, then ACRU is the appropriate model to use. If, however, output is required at a coarser time scale, say, to assess SFR impacts on firm yield, then, use of SHELL should be considered.
x	**Recognise ambient rainfall or natural land-cover gradients in discretisation of modelling units for SFR impact modelling**	In areas of steep MAP gradients, rainfall may be underestimated if subcatchments are not delineated along MAP boundaries, as averaging of MAP may occur in subcatchments which span high and low MAP zones. In ACRU modelling, land cover gradients may not be critical in subcatchment delineation as subcatchments can be further divided into different land cover units.

No.	Consideration	Guideline
		In SHELL modelling the natural land cover included in a subcatchment can influence the calibration of the Pitman model for the subcatchment (however, subcatchment delineation is often heavily dependent on the position of streamflow gauging stations).
xi	**Take cognisance of inherent longitudinal differences between aggregated main-stem SFR impacts and impacts in individual tributary subcatchments**	Impacts that are significant in small upstream catchments are usually attenuated down the main-stem system. If impacts in upstream catchments are of interest, finer subcatchment discretisation should be considered to isolate areas of higher impact. If impacts at the flow exit point of the catchment are of interest, coarser subcatchment discretisation should be considered. The fineness or coarseness of subcatchment discretisation required may influence the choice of ACRU or SHELL as the SFR-estimation method.
xii	**Take cognisance of differences in outcome via different models**	ACRU SFR produced by ACRU tends to be less than that produced by SHELL, all other inputs being effectively identical. ACRU modelling may produce gains in streamflow due to afforestation or IAPs during dry season low flows.
		SHELL SFR produced by SHELL tends to be greater than that produced by ACRU, all other inputs being effectively identical. Streamflow gains due to afforestation or IAPs may occur only from the riparian SFR estimation technique (PET method) used with the monthly modelling
		System Yield Modelling The catchment model used to produce the flow sequences being fed into the system model, will have an impact on the simulated system yields / assurances.
xiii	**Take cognisance of differences in requirements via different models**	ACRU Data input requirements tend to be more rigorous and daily modelling may be only worth while if the necessary input data of reasonable quality is available. The user must have confidence in the input data available, especially soils, land cover, land use and plant species information.

No.	Consideration	Guideline
		Detailed catchment configurations may take an unacceptably long time to set up Simulation of detailed catchment configurations take time and are computer-resource-intensive. ACRU model applications do not rely heavily on the availability of observed streamflow data; rather the representativeness of the model configuration in terms of the catchment being studied depends on the availability of required input data describing the physical processes in the catchment. Observed streamflow data is used to verify that the model configuration is indeed representative of the catchment being studied.
		SHELL The Pitman model calibration process suffers from a degree of subjectivity, which is less of a problem in ACRU applications. Data input requirements are less rigorous than for daily modelling. It is not necessary to have detailed information on catchment soils and land cover; generalised information is usually adequate. Catchment model configuration may be relatively quick Simulations are very quick. In the absence of reliable observed streamflow data, it is difficult to gauge the representativeness of the monthly model configuration in terms of the catchment being studied.

8 CONCLUSIONS

The following conclusions were drawn from the results of the study.

1. In calibration of SHELL configurations and verification of ACRU configurations, both models are capable of achieving a reasonable average seasonal correspondence of high and low flows with the observed averages, though the actual averages produced by the two models can differ substantially.

2. MAR simulated by the models has a strong influence on SFR simulated by the models. Comparison of proportional reductions simulated by the models with that from the experimental catchments showed that if the MAR for the models were similar to that for the experimental catchments, the models would produce reductions of the same order of magnitude as the experimental catchments.

3. ACRU simulation produces much less SFR than SHELL simulation.

4. ACRU simulation of the Upper Sabie catchment produces much less SFR than expected, based on comparisons of ACRU-simulated SFR for Sabie with ACRU-simulated SFR for the Berg and Mhlatuze, from this study and from the "Gush" Tables (Gush *et al*, 2002).

5. Gains in SFR after afforestation or invasion by IAPs may occur during dry periods. The simulation of this (in ACRU, or in the SHELL riparian SFR method) depends greatly on the selection of crop factors for the baseline vegetation.

6. Comparative SFR between different tree classes may vary depending on season and catchment conditions; for example, tall shrubs may use more water than medium trees or tall trees. This is also very dependent on crop factors chosen for the different tree species (in ACRU, or in the SHELL riparian SFR method).

7. The output produced by SHELL is predictable in that the modeller knows what to expect, based on the values of the input variables used. Empirical methodology used means that the output produced by ACRU, on the other hand, is less predictable, as it is based on the representation of a number of different physical processes.

8. In the assessment of impacts on yield, on average, impacts on yield by SFR due to IAPS and afforestation is greater than the impact on MAR. This indicates that the assessment of impact on yield is important in SFR analysis.

9. The impacts on yield at upstream subcatchments in a catchment can be very different from the impact at the end of the whole catchment. The impact tends to be larger at upstream subcatchments.

10. Assessment of run-of-river yields in smaller upstream catchments is not a useful exercise as these subcatchments tend to dry up in the critical periods.

11. A simulated reduction in MAR can result in a simulated increase in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow gains; likewise, a simulated increase in MAR can result in a simulated reduction in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow reductions.

9 RESEARCH RECOMMENDATIONS

In this section, research recommendations stemming from this study are presented.

1. If calibration-based models, like Pitman, are to be used extensively in water resources analysis, the availability of reliable observed streamflow data must be improved.

2. More field measurements of processes, which impact SFR, are required to gauge the performance of physical models (like ACRU) in simulating these processes. An example of this is the direct measurement of evapotranspiration by trees.

3. Improved (finer scale) mapping of vegetation types within catchments is required to capitalise more on models (like ACRU), which run at small spatial scales. This should also include the distinction between vegetation in riparian and upland areas of catchments, particularly vegetation for inclusion in model configuration baseline scenarios.

4. More rainfall gauging is necessary in high altitude catchments, to capture the correct rainfall patterns in catchments with steep MAP gradients, like the Upper Berg and Upper Sabie. Alternatively, relationships that translate rainfall information for the low altitude catchments to information for the high altitude catchments need to be developed. The use of radar rainfall mapping to improve aerial rainfall estimates of high-lying ground should be investigated.

5. The anomalies observed in the seasonality of the published A-pan data for the Upper Berg, described in **Section 3.2.1** of this report need to be investigated.

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APPENDIX A: LAND COVER INPUT PARAMETERS USED IN THE ACRU CONFIGURATIONS

Table A- 1 Land Cover Input Parameters Used in the ACRU Configuration of the Upper Berg

Land cover in the Upper Berg catchment	Land cover parameter	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pine	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.90											
Eucalyptus	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.10											
Medium tree (wattle)	CAY	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	VEGINT	1.70	1.70	1.70	1.70	1.60	1.55	1.55	1.55	1.60	1.65	1.70	1.70
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	CONST	0.50											
Tall shrub (hakea)	CAY	0.64	0.58	0.58	0.58	0.58	0.52	0.47	0.58	0.70	0.76	0.82	0.76
	VEGINT	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	ROOTA	0.70	0.65	0.70	0.75	0.80	0.80	0.80	0.85	0.95	0.95	0.90	0.80
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	CONST	0.40											
Macchia (fynbos)	CAY	0.55	0.50	0.50	0.50	0.50	0.45	0.40	0.50	0.60	0.65	0.70	0.65
	VEGINT	1.00	1.00	1.10	1.20	1.20	1.20	1.20	1.20	1.10	1.10	1.00	1.00
	ROOTA	0.70	0.65	0.70	0.75	0.80	0.80	0.80	0.85	0.95	0.95	0.90	0.80
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	CONST	0.40											
Coastal rhenosterbosveld	CAY	0.40	0.30	0.40	0.45	0.40	0.40	0.40	0.45	0.55	0.60	0.60	0.50
	VEGINT	0.80	0.80	0.80	1.00	1.20	1.20	1.20	1.20	1.00	0.80	0.80	0.80
	ROOTA	0.85	0.80	0.85	0.90	0.90	0.95	0.95	0.98	0.98	0.98	0.98	0.95
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	CONST	0.40											

Table A- 2 Land Cover Input Parameters Used in the ACRU Configuration of the Upper Sabie

Land cover in the Upper Sabie catchment	Land cover parameter	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pine	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.90											
Degraded: forest and woodland	CAY	0.65	0.65	0.65	0.50	0.50	0.35	0.35	0.40	0.55	0.65	0.65	0.65
	VEGINT	1.75	1.75	1.75	1.60	1.50	1.50	1.50	1.50	1.50	1.60	1.70	1.75
	ROOTA	0.85	0.85	0.85	0.90	0.95	0.95	0.95	0.95	0.95	0.90	0.85	0.85
	COIAM	0.25	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25
	CONST	0.40											
Degraded: thicket & bushland (etc)	CAY	0.70	0.70	0.70	0.65	0.55	0.45	0.30	0.30	0.50	0.55	0.70	0.70
	VEGINT	1.75	1.75	1.75	1.55	1.40	1.15	1.15	1.15	0.80	1.30	1.50	1.75
	ROOTA	0.85	0.85	0.85	0.95	0.95	0.95	0.95	0.95	0.95	0.85	0.85	0.85
	COIAM	0.25	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25
	CONST	0.40											
North-eastern mountain sourveld	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75
	VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80
	COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	CONST	0.40											
Forest and Woodland	CAY	0.75	0.75	0.75	0.65	0.55	0.40	0.40	0.50	0.65	0.75	0.75	0.75
	VEGINT	2.00	2.00	2.00	1.80	1.60	1.60	1.60	1.60	1.60	1.80	1.90	2.00
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.90	0.85	0.80	0.80
	COIAM	0.25	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25
	CONST	0.40											
Lowveld	CAY	0.80	0.80	0.80	0.65	0.55	0.40	0.40	0.40	0.60	0.75	0.75	0.80
	VEGINT	2.50	2.50	2.50	2.10	1.90	1.90	1.90	1.90	2.10	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	CONST	0.40											
Lowveld sour bushveld	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75
	VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	CONST	0.40											
Thicket & bushland (etc)	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.35	0.35	0.55	0.65	0.80	0.80
	VEGINT	2.00	2.00	2.00	1.70	1.50	1.30	1.30	1.30	1.00	1.60	1.80	2.00
	ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80
	COIAM	0.25	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25
	CONST	0.40											
Forest	CAY	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.80	0.85	0.90	0.90	0.90
	VEGINT	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	COIAM	0.25	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25
	CONST	0.40											

Table A- 3 Land Cover Input Parameters Used in the ACRU Configuration of the Mhlatuze

Land cover in the Mhlatuze catchment	**Land cover parameter**	**jan**	**feb**	**mar**	**apr**	**may**	**jun**	**jul**	**aug**	**sep**	**oct**	**nov**	**dec**
Pine	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.90											
Eucalyptus	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.10											
Medium tree (wattle)	CAY	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	VEGINT	1.70	1.70	1.70	1.70	1.60	1.55	1.55	1.55	1.60	1.65	1.70	1.70
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	CONST	0.50											
Tall shrub (combination of lantana, solanum,psidium)	CAY	0.81	0.75	0.61	0.50	0.50	0.45	0.45	0.45	0.46	0.50	0.76	0.81
	VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10
	ROOTA	0.81	0.81	0.81	0.80	0.80	0.80	0.80	0.80	0.80	0.81	0.81	0.81
	COIAM	0.30	0.30	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.31	0.30
	CONST	0.40											
Bushveld	CAY	0.75	0.75	0.75	0.65	0.55	0.40	0.40	0.50	0.65	0.75	0.75	0.75
	VEGINT	2.50	2.50	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80
	COIAM	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	CONST	0.40											
Grassveld	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	VEGINT	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
	COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	CONST	0.40											
Indigenous Forest	CAY	0.85	0.85	0.85	0.85	0.70	0.70	0.70	0.70	0.70	0.80	0.80	0.85
	VEGINT	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
	ROOTA	0.85	0.85	0.85	0.85	0.70	0.70	0.70	0.70	0.70	0.80	0.80	0.85
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CONST	0.40											