ESTIMATION OF THE HYDROLOGICAL RESPONSE TO INVASIVE ALIEN PLANTS IN THE UPPER BLYDE RIVER CATCHMENT

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ABSTRACT

The change in total evaporation through alteration of vegetative cover is a major influence on catchment hydrology. The transformation of grassland and scrub habitats to commercial tree plantations, as well as the uncontrolled spread of invasive alien plants (IAPs) to ecologically sensitive systems, riparian zones in particular, are a threat to biodiversity and integrity of natural systems. Furthermore, critical low flow periods are of particular concern to water managers and local communities, as well as the associated impacts of potentially compromised water resources for rural livelihoods.

The Working for Water (WfW) programme was implemented in 1995 by the Department of Water Affairs and Forestry and its main goals are to remove IAPs in order to improve water supply while at the same time providing employment to marginalised communities.

In this study, the hydrological response to IAPs in the Upper Blyde River catchment is assessed. This is done by developing a classification structure for IAPs as a land use using detailed mapping available from WfW for use in a hydrological model, and then configuring and running the *ACRU* hydrological model for the Upper Blyde River catchment in Mpumalanga. In the classification, IAPs are represented as spatially explicit land use units in the *ACRU* model according to the type of habitat they invade, *viz.* riparian or non-riparian; as well as by type of plant, i.e. tree or shrub; and their area and density.

The results obtained from simulating catchment hydrological responses using the *ACRU* model indicate that riparian IAPs have a greater impact on streamflow than do landscape invasions alone, specifically during periods of low flow. An increase in streamflow after removing IAPs from riparian and non-riparian habitats is a consistent outcome at both sub-catchment and catchment scales. Using a spatially explicit method in order to model the hydrological response of different types of IAPs for different density classes in both riparian and non-riparian habitats is found to be a useful technique in determining the degree to which IAPs influence catchment streamflow.

Recommendations for future research include focussing hydrological assessments of IAPs on critical flow periods and their impacts on water quality; investigation into the water use

of invasive and indigenous vegetation for more accurate estimates from modelling exercises; and finally, applying the classification system for IAPs with other land use sensitive hydrological models for validation, and their wider application by incorporating methodologies into guidelines for use by WfW at national and provincial level.

DECLARATION

I wish to certify that this study represents original work by the author and have not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.

Signed: Hayes

Louise Hayes

Date: 2/12/03

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1. INTRODUCTION

A change in catchment land use is an inevitable consequence of development. In developing countries, large scale changes such as commercial afforestation and deforestation of natural resources are common-place, resulting in various degrees of impact on the natural environment. The introduction of exotic vegetation species to indigenous habitats has widespread implications for natural resources, including water. The impact of invasive alien plants (IAPs) in South Africa is one issue in particular that demands a great deal of attention. The transformation of grassland and scrub habitats to commercial tree plantations, as well as the uncontrolled spread of IAPs to ecologically sensitive riparian areas, and their potential impact on water resources are critical issues. In particular, IAPs have been highlighted as being a threat to the biodiversity and sustainability of natural ecosystems. Studies have revealed that as a rule, IAPs consume more water than the natural vegetation they replace and it has been estimated that they reduce mean annual runoff in South Africa by approximately 7% (Versfeld *et al.*, 1998; Calder and Dye, 2001).

According to the National Water Act (NWA) of 1998, streamflow reduction activities (SFRAs) are broadly defined as those land use practices that reduce the yield of water to downstream users. At present only commercial forestry is a declared SFRA. This poses an important and contentious question as to the status of IAPs, because they are neither classed nor controlled as a land use practice, yet they have been shown to consume substantially more water than the natural vegetation that they replace. Published estimates of water use by IAPs have, up until the present, been estimated by the use of hydrological models, based on estimates of biomass and estimates of the equivalent dense area these would cover in a catchment (Versfeld *et al.*, 1998; Chapman and Le Maitre, 2001). These hydrological models are used as tools in the decision support systems for water management in South Africa. Their strength lies in the ability to process a wealth of input information that is available from research and in climatic, topographic and geographic databases. The mapping techniques employed to estimate the extent of IAPs in South Africa allow very detailed information to be captured at national and provincial levels with the help of widespread expertise in the field.

Thus, key research questions are:

- How best to use the available high quality mapping of IAPs now available from Working for Water in hydrological assessments, and

- How, in such studies, to adequately consider the impacts of IAPs in the riparian zone.

The Blyde River catchment, located in the lower Olifants River basin provides a useful case study area in which to address these questions. The Olifants River has been identified as a benchmark basin in South Africa by the International Water Management Institute (IWMI). It consists of 145 DWAF Quaternary Catchments, including nine in the Blyde River catchment which makes an important contribution in terms of both water quantity and quality to the Olifants system. There is currently (2003) an initiative by the Department of Environmental Affairs and Tourism (DEAT) to expand the conservation areas in the Lowveld region over the next five years through an initiative known as the Kruger to Canyons Water and Nature Initiative (WANI). The Blyde River Canyon Nature Reserve and areas of commercially afforested land in key catchment areas of the Upper Blyde River are likely to be incorporated into a trans-frontier conservation area as part of a project to sustain biodiversity in the Kruger National Park.

The broad objective of the case study is to perform a hydrological assessment focussed on the potential impacts of commercial afforestation and IAPs in the riparian and non-riparian areas of the Upper Blyde River catchment, and to develop a methodology using information and data that is readily available that can be applied in other related studies. Within this broad objective, the specific aims of the study are:

- To develop a generic classification system based on information available from WfW mapping for the representation of IAPs as spatially explicit land use units for use with a hydrological model;
- To configure and test the *ACRU* Agrohydrological model (Schulze, 1995) in the catchment against available observed data; and
- To apply the model to determine the potential streamflow response to changes in land use in both riparian and non-riparian habitat as a result of IAPs.

In this dissertation, a review of literature on the principles and concepts of Integrated Water Resources Management (IWRM) is presented in order to ascertain its applicability and suitability to the assessment of water resources at a catchment level (Chapter 2). One of the strategies that is employed to aid the process of integration and understanding of catchment scale processes is strategic environmental assessment (SEA), focussing specifically on SFRAs and the impacts of land use, thereby providing a framework for management and planning options. In Chapter 3 the relationship between land and water resources is reviewed, focussing on the hydrological and environmental implications as a result of afforestation and IAPs in South African catchments. This review is followed by a brief overview of the use of hydrological models as a tool to assess the impacts of change in land use and introduces the *ACRU* model, which was used in this study (Chapter 4). A methodology for the classification of IAPs as a land use for hydrological modelling forms the core of Chapter 5. It focuses on the processes of invasion, examining the water use of invasive species and the density of their invasions, representing IAPs as spatially explicit land use units that can be used in land use sensitive hydrological models. Chapter 6 presents the Upper Blyde River catchment as a case study catchment in which to test the classification system for IAPs. Catchment characteristics and assessment of environmental resources and issues are described. The methodology, results and discussion of the application of the *ACRU* model for simulating catchment hydrological response to land use, and specifically the impacts of IAPs, follows in Chapters 7 and 8. Chapter 9 provides a discussion highlighting the significance of the findings and their context within the IWRM and SEA frameworks. Finally, the conclusions of the study, as well as recommendations for future research, are presented in Chapter 10.

2. INTEGRATED CATCHMENT MANAGEMENT: A REVIEW OF INTEGRATION APPROACHES

South Africa is a rapidly developing country whose growth and development goals are focussed on creating opportunities to improve the quality of life for the majority of the population (Muller, 2001). An inevitable consequence of social and economic development is an increase in demand for the country's water resources. South Africa's semi-arid climate and rainfall variability pose important challenges to water managers and the sustainable use of the increasingly limited water resources. There is ever increasing competition for natural resources between the rising population and increasing economic activity. The National Water Act, No. 36 of 1998 (NWA) aims to "...ensure that the nation's water resources are protected, used, developed, conserved, managed, and controlled in ways that take into consideration such factors as, *inter alia*, meeting the basic human needs of present and future generations, promoting equitable access to water, redressing past discrimination, facilitating social and economic development, and protecting aquatic and associated ecosystems" (Karodia and Weston, 2001: 13). The NWA provides a framework for the integrated management of water resources in South Africa through various water resource strategies at both national and catchment levels by way of a National Water Resource Strategy (NWRS) and a Catchment Management Strategy (CMS) respectively. The focus is on the protection and preservation of the river system as well as the resources the system provides to the people, i.e. goods and services. The framework for each Water Management Area (WMA) consists of an ecological component, a social and economic component and integrated management. This allows for the establishment of a variety of water management institutions at varying scales throughout South Africa and, in so doing, sets the stage for Integrated Water Resource Management (IWRM).

The table below summarises the framework strategies at both national and regional scale.

Table 2.1 Water resource strategies in terms of the National Water Act of 1998 (Adapted from Karodia and Weston, 2001)

	National Water Resource Strategy	**Catchment Management Strategy**
ECOLOGICAL	• Reserve – ecological sustainability • Water conservation and demand management principles • Water quality objectives	• Class of water resource, quality objectives and Reserve requirements • Consideration of geology, climate and vegetation
SOCIAL AND ECONOMIC	• Reserve - basic human needs • Determining international rights and obligations • Estimates of present and future water requirements • Stating WMA surpluses and deficits • Stating quantity of water available in each WMA • Inter-catchment transfers	• Meeting international obligations • Demography, land use and waterworks • Water allocation plans • Needs and expectations of existing and potential water users
INTEGRATED MANAGEMENT	• Objectives for establishment of institutions • Inter-relations between institutions in water resource management • Holistic and integrated catchment management	• Relevant national or regional plans prepared in terms of any other law • Public participation • Setting out institutions to be established

2.1 Integrated Water Resources Management (IWRM)

The current state of South African rivers and catchments is the result of accumulated disturbance over time and this disturbance has, consequently, caused a change in the hydrological system (Schulze, 2002). One can distinguish natural disturbances from anthropogenic disturbances. Natural disturbances are those events occurring in nature over time that, although they may disrupt the system, are required to maintain system diversity, for example, flow variability such as floods and droughts (Brown and King, 2002). Anthropogenic disturbances however, arise as a result of physical changes to features of the natural system for example, land use (afforestation, agriculture, urbanisation) and dam construction. Disturbances to natural ecosystems are primarily a result of increasing pressures on natural resources due to the increased demand by the population. In developing countries, increasing poverty further compounds the problem and this must be addressed. Therefore, the challenges facing IWRM in South Africa today in terms of awareness and understanding of the problems at hand, and cooperation between different sectors in society (Global Water Partnership, 2000) include securing water for people (supply and sanitation) as well as for food production (agriculture); job creation; protection of terrestrial and aquatic ecosystems; developing coping mechanisms for variability in water with regard to the effects of climate change; the management of disaster and risk, and education.

Among the many definitions of IWRM, two are included here. The Global Water Partnership (2000) defines IWRM as "...a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." DWAF and WRC (1998) define IWRM as "...simultaneously a philosophy, a process and an implementation strategy to achieve equitable access to and sustainable use of water resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits."

The framework for IWRM in South Africa is one that is administered by different hierarchical levels while at the same time finding application at the river basin scale. The concept of integration across different horizontal and vertical scales, as well as differing spatial and temporal scales needs to be recognised (Jewitt and Kotze, 2002). The IWRM process is made up of the National Water Resources Strategy (NWRS), a statutory framework for catchment management, and catchment management processes/strategies/plans in particular catchments (DWAF and WRC, 1998). In this way, the IWRM framework strives to integrate across differing scales relating to the management of water resources. However, the catchment scale is viewed as the most appropriate scale at which IWRM can be *applied* because it is the scale at which land use and water interactions are most evident and "controllable" (Schulze, 2002). In addition, the socio-economic implications of land and water use changes can be gauged and assessed for management purposes at this scale. The issues affecting catchment scale variables are detected much more easily on a smaller, manageable scale rather than trying to provide solutions at a broader scale where there are additional and more difficult issues to be dealt with.

IWRM aims at achieving equitable access to, and sustainable use of, water resources and at a broader scale, ICM recognises the links between different environmental systems, including land use and water resources, across the catchment (Pollard, 2001). Essentially, IWRM is a framework that is used to integrate and implement issues that concern the management of the biophysical, social and economic issues, and to provide a structure in which to apply them at the catchment scale. The river basin is the ideal unit for this approach and Schulze (2002) highlights six reasons for this:

- Both small and large-scale hydrological attributes are evident.
- Differences in hydrological responses between different regions can be identified.
- Anthropogenic impacts on the water resource have the greatest noticeable effect, notably through land use changes and water engineering systems.
- The river basin/catchment scale is "the scale of action and management" in terms of the NWA, No. 36 of 1998.
- It is the scale at which rehabilitation and restoration programmes are carried out.
- Hydrological models are used most effectively at this scale as tools for decision-making.

Practical applications of IWRM in South African catchments therefore need to consider the activities taking place therein specifically. The role of land use on water resources has been highlighted and the implications that simultaneous stresses may have on the aquatic ecosystem recognised. Falkenmark *et al.* (1999) distinguish between land use that is dependent on water and land use that impacts on water. Different strategies are employed to consider land and water use issues, but they are interlinked and interdependent and should therefore be planned together. Masundire and Mackay (2002) make general recommendations for the purpose of water resources management. These include the concept that water resources should be defined as including all components of the aquatic ecosystem, i.e. habitat, water, vegetation, biota and processes. These systems should be recognised as resource bases, and their biodiversity and ecological health should be made management priorities.

The following section provides a review of one of the strategies that is employed to help contribute to the process of integration and understanding of the processes taking place at the catchment scale, *viz.* strategic environmental assessment.

2.1.1 Strategic Environmental Assessment (SEA)

Strategic Environmental Assessment (SEA) is an integrated environmental management tool used for land use planning and environmental management in South Africa. It is part of the ongoing process of environmental assessment and management and can be used at different stages of planning. As an international system, SEA attempts to integrate environmental factors and goals for sustainability into development policies and, in so doing, it considers both environmental and socio-economic variables (DEAT, 2000).

The White Paper on Environmental Policy for South Africa (1998) refers to SEA as "a process to assess the environmental implications of a proposed strategic decision, policy, plan, programme, piece of legislation or major plan." A problem that has been identified with this definition is that it could imply that SEA is a separate process and not one that is used in conjunction with other planning. SEA aims to reinforce environmental issues in decision-making and to integrate biophysical, social and economic variables (DEAT, 2000). The CSIR (1997) provides definitions for plans and programmes which are contained in the Guideline Document for SEA in South Africa (2000):

Plan: "A purposeful, forward-looking strategy or design, often with coordinated priorities, options and measures that elaborate and implement policy"

Programme: "A coherent, organised agenda or schedule of commitments, proposal instruments and/or activities that elaborate and implement policy."

SEA guidelines are currently being used at planning and programme level, while separate methodologies are being put in place for application at policy level. The main objective of a SEA is to integrate environmental issues from an early stage in the planning process and the key principles are outlined as follows (DEAT, 2000):

- SEA is driven by the concept of sustainability.
- SEA identifies the opportunities and constraints which the environment places on the development of plans and programmes.
- SEA sets the criteria for levels of environmental quality or limits of acceptable change.

- SEA is a flexible process which is adaptable to the planning and sectoral development cycle.
- SEA is a strategic process, which begins with the conceptualisation of the plan or programme.
- SEA is part of a tiered approach to environmental assessment and management.
- The scope of a SEA is defined within the wider context of environmental processes.
- SEA is a participative process.
- SEA is set within the context of alternative scenarios.
- SEA includes the concepts of precaution and continuous improvement.

These principles are based on practical experience in South Africa (DWAF, 1999; Steyl, 1999) and allow for a flexible approach that can be applied at different spatial scales and across sectors. In other words, SEA can be defined by the specific requirements of its users. SEA should be used as a tool to complement existing procedures while addressing issues of resource use, efficiency and sustainability. The SEA process involves considerable data capture and information from different sources. In this way, participation across sectors is enhanced and different perspectives and requirements are represented. SEA is required to address different forms of land use and to consider whether that use is:

- Acceptable;
- The best way of using the resource; and
- Sustainable.

2.1.2 SEA for water use in catchments

SEA can be applied at all levels of policy, land use planning programmes and water resources management. In terms of the National Water Resource Strategy, SEA can most effectively be applied at the Quaternary Catchment level scale of catchment management for water resources, by linking biophysical processes and activities taking place therein (DWAF, 2001). "The SEA is designed to consider the nature of all water uses and related land uses within discrete catchments. Its primary functions are to ensure that:

- Complex hydrological data and models are simplified and interpreted in a form which is readily understood by ordinary people;

- Background information is gathered and interpreted through easily understood maps and plans;
- Opportunities and constraints in making better use of land and water are clearly defined;
- Public awareness of choices is increased, and local people are encouraged to take an interest in the possibilities for long term water use in their own area (i.e. catchment);
- The costs and benefits of taking particular courses of action are clearly articulated, and the information is presented using a simple negotiation and decision support framework;
- Decision-makers are presented with both the basic information, and the expression of public opinion on key issues before they take decisions affecting future water use;
- All decisions are transparent and the underlying reasons are published; and
- The effectiveness of decisions on water use can be monitored over time, and the corrective measures can be introduced where necessary to avoid social, economic or environmental damage" (DWAF, 2001).

The SEA process is structured in such a way that all the factors affecting water use can be included, for example hydrological issues, water demands, water availability, social and community interests, economic interests, biophysical impacts and development policies. It is an integrated task involving people with different skills and experience. The team follows a series of tasks beginning with a scoping study and progressing to stakeholder involvement and public participation. Decisions are made once key issues have been identified and analysed, following technical studies. The implementation of SEA recommendations is followed up in a monitoring and evaluation framework and all technical advisors are required to maintain an up-to-date database for informed decision-making (DWAF, 2001).

The Department of Water Affairs and Forestry carried out a SEA for water uses in order to provide a framework for decision-making (DWAF, 2001). The Mhlathuze catchment was chosen as the study catchment and the SEA was completed in September 2000 (DWAF, 2000). The outcome of the SEA component that considered forestry, highlighted an important point for streamflow reduction activities (SFRAs), *viz.* in order to comply with sustainable development objectives, the SFRA concept needed to be extended to other potential water uses (Steyl, 1999). Up until the time of writing (2003), afforestation is the only land use that has been declared a streamflow reduction activity, and this because of its impact on water resources.

2.1.3 Streamflow Reduction Activities

The working definition given by Steyl (1999; 7) to streamflow reduction activities (SFRA) for use in SEA, is as follows:
"An SFRA is any dryland land use practice, which reduces the yield of water (with reference to yield from natural veld in undisturbed conditions) from that land to downstream users. Such activities may be declared as SFRAs if found to be substantial". The National Water Act, No. 36 of 1998 allows that any activity that impacts substantially on streamflow be declared a streamflow reduction activity. At present, forestry is the only declared SFRA. Afforestation is viewed as a permanent land use change from the natural vegetation it replaces, for example veld or grassland, with relatively low water use, to a crop with higher water use. In addition, the forestry industry is located in areas that produce nearly 60% of South Africa's water resources.

The SFRA licensing system is an extension and revision of the Afforestation Permit System (APS), first instituted by the Forestry Chief Directorate in 1972 (Steyl, 1999). The APS lacked transparency in that there was no public accountability, no procedures for appeal by affected parties and no effective monitoring, control or audit of compliance with permit conditions or expiry of permits. There was also little control of illegal afforestation in certain catchments.

In 1994, the administration of permits was transferred to a new division in DWAF within the Water Affairs Branch, called Stream Flow Reduction Allocations. In conjunction with Regional Water Affairs Offices, this unit's goal is the protection of water resources that could potentially be affected by afforestation and other SFRAs. It was considered to be a conflict of interests for the Forestry Chief Directorate to continue in the role of administration, because the function of promotion is incompatible with that of self-regulation. There is more thorough consideration of the effect of afforestation on low flows (and possibly the drought cycle); greater consideration is now being given to environmental issues such as the effect of afforestation on rare or endangered flora and fauna, biodiversity, and the visual impact on the landscape. Where necessary, Environmental Impact Assessments (EIAs) are required of forestry developers. The economic viability of proposed forestry developments is now being evaluated in collaboration with provincial departments, and to compare its value with that from alternative uses of water; and, provision is now also being made for limited-term permits (DWAF, 2001). The declaration of any land use as a new SFRA will depend on various factors including the extent and duration of the reduction in streamflow as well as impacts on other water resources and water users (Steyl, 1999).

The adaptation of the SEA approach to planning, both water and non-water related, provides a tool in which social, economic and environmental concerns can be considered at spatial and temporal scales ranging from the Quaternary Catchment to the river basin. As such, SEA can be considered as a strategic approach that is used to help water managers and CMAs to make decisions about land and water uses in South African catchments. Streamflow reduction is a contentious issue and one that must be addressed within a solid framework, such as SEA, so that its impacts may be addressed locally and regionally. The SEA process, in turn, contributes to the process of integration and understanding of processes at the catchment scale which fulfils some of the objectives of IWRM.

In the chapters that follow, the hydrological issues surrounding change in land use and, specifically the impacts of invasive alien plants will be addressed.

3. HYDROLOGICAL RESPONSES TO VEGETATIVE LAND USE CHANGE

A common thread to the preceding concepts and the frameworks within they are set, is that of integration and the inter-dependent relationships between associated factors and variables. The focus of this review is the relationship between land and water resources, specifically changes taking place in and around areas of commercial forestry and riparian zones, invasive alien plants (IAPs) and their associated impacts on the hydrology of South African catchments. In order to assess the impacts of changing land use in a given catchment, it is necessary to understand the physical processes taking place within that catchment. Table 3.1 provides a summary of the human disturbances on the aquatic ecosystem.

Table 3.1 A summary of environmental and economic impacts of human activities on aquatic ecosystems and water supply (After Turpie and van Zyl, 2002)

Human activity	Impact on aquatic ecosystems	Reduction in values/services
Afforestation, deforestation and poor land use in catchment areas	Alters runoff patterns, inhibits natural recharge; Erosion leads to silt deposition in aquatic ecosystems.	Decreased water quantity and quality for other users; Decreased economic life of water supply schemes; Reduced biodiversity and resource stocks.
Alien invasion of catchment areas	Alters runoff patterns, inhibits natural recharge; Change in water chemistry; Erosion leads to silt deposition in aquatic ecosystems.	Decreased water quantity and quality for other users; Decreased economic life of water supply schemes; Reduced biodiversity and resource stocks.
Agricultural and other land use within aquatic ecosystems	Loss of habitat; Release of inorganic and organic pollutants into aquatic systems.	Loss of infrastructure and arable land; Reduction in biodiversity and resource stocks; Decreased water quality for other users.
Alien invasion of aquatic ecosystems	Siltation of aquatic ecosystems; Change in water chemistry.	Reduced biodiversity and indigenous resource stocks; Decreased water quality for other users.

Different land uses affect hydrological responses of a catchment. Some of the hydrological processes that need to be considered are precipitation, evaporation, interception and soil water transpiration, infiltration and streamflow (Luce, 1995). Furthermore, streamflow reduction and total evaporation are dependent on age and biomass of vegetative growth, as well as the specific climatic and geographic conditions of the site. The change in biomass from low to high (grassland to trees) has consequences for interception and transpiration processes, which are highly influential in terms of water use. The biomass per unit area in a forested catchment is much greater than the equivalent area of grassland or cropland. The influence of an increased surface area for canopy interception and total evaporation, transpiration all year round from evergreen species, deeper root systems and a litter layer as well as any understorey vegetation can substantially modify the cycling of water through the system (Luce, 1995; Schulze *et al.*, 1995a). In order to be able to accurately predict streamflow, it is necessary to understand the relationships between the physical characteristics of a catchment and the flow characteristics of the stream.

The focus of much contemporary research is on the interaction between vegetation, soils, catchment topography and climate, and the associated hydrological response in each system. It is important to understand the influence of different vegetation types, and hence the different land uses, on the hydrology of the catchment. The focus of this review is on the hydrological and environmental impacts associated with commercial forestry plantations and invasive alien plants.

3.1 Commercial Forest Plantations in South Africa

Natural, indigenous forests are highly fragmented and today occupy only 0.2% of South Africa's land area (DWAF, 1998). These are a valuable resource in terms of their biodiversity and, as a result of their fragmented distribution they tend to support high levels of species diversity, sometimes rare or endangered. Indigenous forests also offer resources and contribute to the livelihoods of rural communities. The decline in the natural timber resources in the late 19th and early 20th centuries saw the introduction of fast growing timber trees to South Africa. Plantation forestry now covers 1.1% (1.5×10^6 ha) of the land area of South Africa (FSA, 2002). The species most commonly planted are *Pinus patula* and *Pinus radiata* (Pines), Australian *Eucalyptus grandis* (Gums) and *Acacia mearnsii* (Black Wattle), which are highly productive, but exotic trees. Thus, the benefits that plantation forestry has brought to the national and local economies through employment opportunities and GDP can be considered to be gained at the expense of natural environmental resources. The following sections discuss the impacts of the commercial forestry plantations on hydrology, soils and biodiversity.

3.1.1 Hydrological impacts

Even before the implementation of the National Water Act of 1998, afforestation was the only land use that was required to limit its impacts on water resources (Kruger *et al.*, 1995). Water use by forestry is defined in the National Water Act as being a streamflow reduction activity (SFRA) because plantations use more water than the natural land cover they replace. Because of high spatial and temporal variability of factors such as rainfall, temperature, atmospheric demand for water, soil properties, type and age of tree planted as well as different types of competing vegetation, it is very difficult to measure actual streamflow reduction (FSA, 2002). Current tools for the assessment of SFRAs calculate streamflow reductions on a Quaternary Catchment scale in South Africa, and 843 of the 1947 Quaternary Catchments may be suitable for forestry in that they receive, on average, more than 650mm rainfall per year (Gush *et al.*, 2001). There are, therefore, limited areas in South Africa that are climatically suitable for plantation forestry practices.

Forests use water in the processes of evaporation and transpiration. This includes the evaporation of rainfall that has been intercepted by the forest canopy, the water that is transpired from the plant's leaves and evaporative losses through the soil and litter layers. Total evaporation accounts for up to 80% of the forest hydrological cycle. It is therefore important to conduct studies on the original, i.e. baseline, vegetation to be able to understand the changes that take place when there is a change in the land use in a given area. According to the NWA, water use by commercial plantations is calculated as the difference between the streamflow from baseline vegetation and that of the plantation area. Water use impacts are felt at the catchment scale most often when there is less water available for downstream users. In particular, the most severe effects on aquatic ecosystems and run-of-river users are experienced during periods of low flow (Owen, 2000).

3.1.2 Soils and sedimentation

The management practices employed in plantations can have substantial impacts on soil structure and composition. Erosion and soil nutrient losses occur as a result of changing vegetation, especially for eucalyptus and pines (Carrere, 1997). The availability of nutrients in soils under forestation is influenced by long-term biological processes and inorganic equilibria. In natural forests, the long-term process of forest growth allows for the cycling of nutrients from the plant to the soil in the litter layer and root turnover. Nutrients are transferred from older tissues to actively growing tissues over time, therefore when harvested for timber, mature trees (older tissue) are removed from site and the tissue with high nutrient concentration is left on site as regrowth (Attiwill and Weston, 2001). However, plantation forestry usually involves moving species that are alien to the site where they are planted and, consequently, nutrient imbalances and deficiencies may result. Much work has been carried out with a focus on nutrient cycling in forest soils and specifically quantification of cycles and equilibria of inputs and outputs (Stone, 1979; Landsberg *et al.*, 1991).

Afforestation itself does not appear to increase erosion or sedimentation, and in some catchments afforestation may actually reduce erosion and improve water quality (Calder, 2000). However, forest management practices such as timber extraction, road location and maintenance can have adverse effects on sedimentation and the stability of hillslopes, thereby increasing erosion processes. Fire is an additional risk for potential erosion because of changes in the physical properties of the soils, resulting in soil water repellancy.

3.1.3 Biodiversity

In addition to direct impacts associated with the establishment of commercial plantations, environmental and hydrological impacts outside the commercial plantations themselves are of great concern for biodiversity of the natural ecosystem. Many plantation species have become major invaders to natural ecosystems adjacent to plantations and can have serious impacts on biodiversity. The most problematic are the *Acacia* and *Eucaplyptus* species respectively, which spread rapidly to riparian zones and non-afforested areas (Versfeld *et al.*, 1998). The invasion by alien species changes the habitat of an area, causing immigration of new species that favour alien trees, and a reduction in native species because of loss of habitat or competition with new species. The spread of alien vegetation can lead to fragmentation of the indigenous ecosystem. The uninvaded indigenous system would generally have a higher biodiversity than an afforested area (Kruger *et al.*, 1995; Richardson, 1998).

Noss (1990) presents a conceptual framework (Figure 3.1) which describes the interconnected structure and hierarchy inherent in natural ecosystems. The framework attempts to explain the complexity surrounding the definitions of biodiversity. Structure, composition and function can be described as the three primary attributes of ecosystems, and these make up biodiversity at all scales. This framework can be applied to the processes taking place at the catchment scale and can help to put into context the land use changes that are taking place and their possible implications for biodiversity.

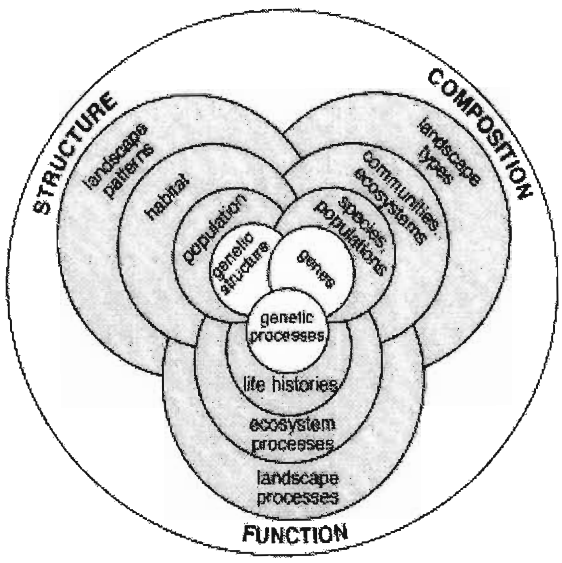


Figure 3.1 Conceptual framework of the interconnected nature of structural, compositional and functional biodiversity (Adapted from Noss, 1990)

3.2 Wetlands and Riparian Zones

"Wetland" is a generic term used for many different types of water bodies in different geographical locations. Common to all wetlands are three components: first, the presence of water either at the surface or within the root zone; second, differing soil conditions from adjacent uplands; and third, wetlands supporting vegetation that is adapted to wet conditions and that is flood tolerant. In South Africa, different systems of wetlands can be identified (Breen *et al.,* 1997):

- Marine systems – including estuaries;
- Lacustrine systems – including reservoirs and coastal lakes;
- Palustrine systems – including floodplains, pans and marshes.

The riparian zone is the area adjacent to a river or a water body, forming part of the river ecosystem and, therefore, the wetland system. Riparian ecosystems form a transition between terrestrial and aquatic ecosystems, performing important functions in both of these systems as well as being areas that support high biodiversity (Rogers, 1995). The riparian zone supports vegetation that is distinctive from that of surrounding areas as a result of regular inundation and flooding. It also serves several important functions in the river ecosystem in terms of flow regulation. For example, vegetation acts as a physical barrier as well as performing an absorptive function, thereby reducing flood impacts. Water quality is regulated by the filtering action of riparian vegetation to nutrients, sediments, bacteria and contaminants. It is an area of transition between terrestrial and aquatic ecosystems and is therefore an important habitat for both plants and animals (Naiman and Decamps, 1997). Under the NWA, wetlands have been identified as an integral part of the catchment system and they are recognised as playing an important role in storing water and managing water quality and quantity (Jewitt and Kotze, 2002).

3.3 Invasive Alien Plants (IAPs)

Globally, there is growing concern regarding the impacts of IAPs on biodiversity and natural systems. In South Africa alone, approximately 750 exotic tree and 8000 plant species have been introduced (Mondlane *et al.*, 2001). The dynamic processes involved in ecosystem functioning are closely interlinked, and any impacts thereon directly affect not only the organism, but also their interaction with the organisms around it. Ecosystems are inherently hierarchical and all components within this structure are interlinked (Figure 3.1). Some important points to consider when assessing the magnitude of the impact of invasive vegetation include determination of the degree to which invading species have altered the natural ecosystem, determination of potential impacts of invaders in the present ecosystem and development of strategies and appropriate management to restore an ecosystem to pre-invasion state (Walker and Smith, 1997).

It should be noted that IAPs includes forestry trees *viz. Pinus, Eucalyptus* and *Acacia* species, that are grown in commercial plantations in South Africa as well as other vegetation such as *Lantana* and *Chromolaena* that establishes itself in riparian zones and cleared areas of land. The spread of alien tree seedlings from commercial plantations to adjacent natural vegetation and riparian zones is one of the primary causes of the uncontrolled spread of IAPs. Le Maitre *et al.* (2000) define riparian invasions to be those that are confined to stream and river valleys, banks and beds, and wetland edges, while landscape invasions are those that occur in dryland areas. This distinction is made on the basis of the availability of water in the different areas, as well as affecting the type of invader likely to invade such habitats and, also, the amount of water that may be available for use.

Figure 3.2 shows a conceptual model that Higgins and Richardson (1996) use to provide a framework for the identification of the factors that influence the success of IAPs. The model includes a feedback that represents the influence of IAPs on the natural resource. The interaction between the plant and the environment has implications for hydrology and geomorphology of the ecosystem, in turn affecting the life cycle (demographic processes) of the vegetation. The successful replication of invasive individuals results in increased numbers (abundance), thereby altering the physical attributes of the habitat through disturbance and use of resources, as well as increased competition between indigenous and invasive species. This in turn feeds back to the plant-environment interaction and associated impacts on ecosystem geomorphology and hydrology in a continuous cycle that propagates IAPs. Furthermore, the conceptual model emphasises that knowledge of the attributes of the plant and the environment being invaded is required to be able to predict the spread of IAPs.

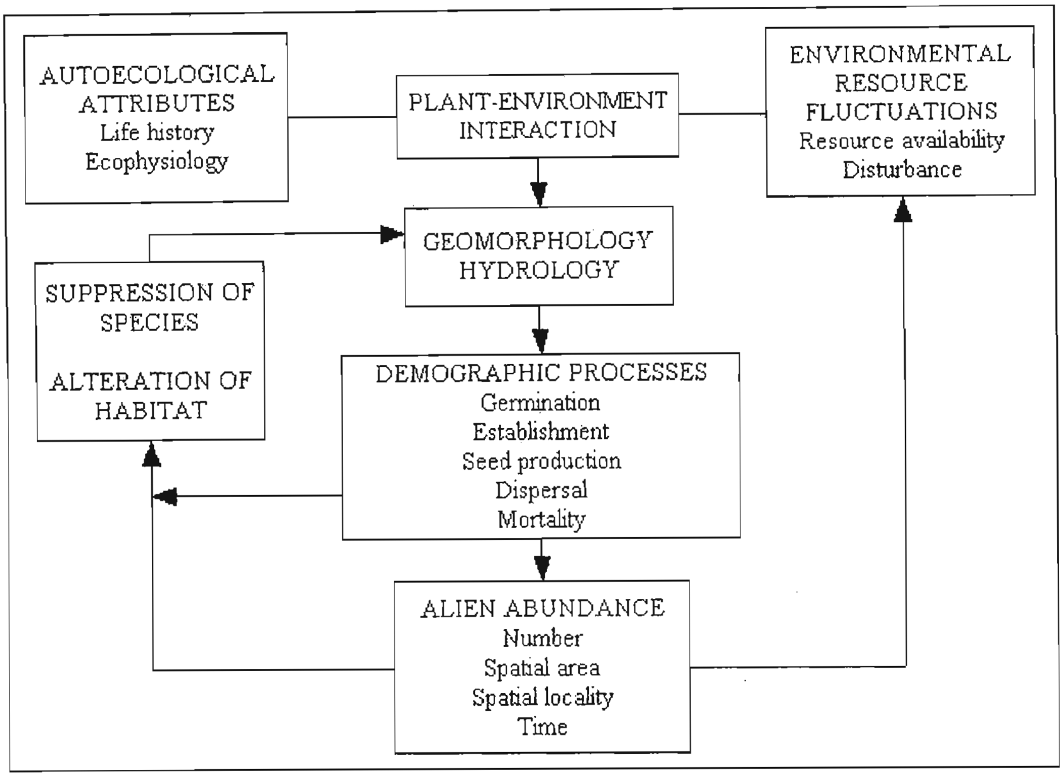


Figure 3.2 Model describing the interacting factors affecting the spread of invasive alien plants, and consequences of such spread (After Higgins and Richardson, 1996)

3.3.1 Water use by invasive alien plants

It has been well documented in the South African literature that exotic plantation forests consume more water than indigenous vegetation (Dye and Poulter, 1995; Kruger *et al.*, 1995; Dye, 1996; Le Maitre *et al.*, 2000). Estimations of water use by commercial plantations and IAPs reveal some convincing results. In a study which compared the estimated water use of commercial plantations and IAPs using a 100% equivalent condensed area method, Le Maitre *et al.* (1997) and Scott *et al.* (1998) found that IAPs used almost twice as much water per unit area as the commercial plantations, i.e. an area of 14 389 km^2 covered by commercial plantations used 1 399 million $m^3.yr^{-1}$ compared to an area of 17 364 km^2 covered by IAPs which used 3 303 million $m^3.yr^{-1}$. Typically, IAPs use substantially more water than the indigenous vegetation replaced, this resulting in approximately 7% reduction in mean annual runoff of South Africa (Versfeld *et al.*, 1998). It is also clear that the impact of IAPs is likely to increase in severity with increasing extent and density (Le Maitre *et al.*, 2000). In areas where low biomass indigenous vegetation has been replaced by tall alien trees, the impacts on the water resources include reductions in annual streamflow, mean annual low flows and alterations to the duration of flows above thresholds. Differences in total evaporation are also expected as a result of the differing biomass of different plant species. The invasion of alien trees in grasslands therefore threatens the ecosystem services and ongoing functioning of the ecosystem, as well as their hydrological functioning.

Calder and Dye (2001) present the "limits concept", i.e. knowledge of the limiting processes governing water use, to compare the water use of short crops versus that of trees. Under South African conditions, the primary limiting control on vegetative water use is identified as soil moisture. However, in riparian areas where there is frequently unlimited water, soil water limitations seldom occur. This limiting control applies to IAPs too, and in riparian areas Calder and Dye suggest that alien vegetation has a 1.13 times greater water use than indigenous vegetation it replaces. In dryland areas, the results showed that IAPs have access to greater soil water availability and that grasses use less water due to their being seasonally dormant.

3.3.2 Impacts of IAPs on wetlands and riparian zones

The riparian zone functions as a corridor, connecting habitats otherwise separated by changing land use, thereby facilitating the dispersion of plants and animals. As a result of the corridor functions that it provides, the riparian zone is also particularly vulnerable to invasion by alien vegetation. These invasions usually start in upper catchments and spread downstream (Le Maitre *et al.*, 2000). In addition, inappropriate land uses and disturbances compound the problem of invasions in riparian habitats.

The services that wetlands and riparian zones provide to the ecosystem as a whole are invaluable (Wissmar and Beschta, 1998). Wetlands are threatened by human activities, directly and indirectly, causing disturbance to the natural functioning and regime of the system. It is suggested that one of the main hydrological threats to riparian systems by IAPs is the amount of water that they use compared to the indigenous vegetation that they replace. Plants in the riparian zone have ready access to water and can use water at higher rates. Some of the most successful invasive species in riparian zones include *Acacia mearnsii* (Black Wattle), *A. dealbata, A. decurrens*, *Lantana*, *Solanum* (Bugweed) and Syringa in addition to the commercial forestry species, *Pinus* and *Eucalyptus* (Versfeld *et* *al.*, 1998). The proximity of forestry activities in particular is yet another potential disturbance to riparian habitats. It has been standard forestry practice to maintain a buffer around the riparian zone (Calder, 1999), thereby keeping the sensitive area clear of alien trees. The current methodology used to determine the outer edge of the riparian zone uses four specific indicators (Land Use and Wetland/Riparian Habitat Working Group, 2001):

- Terrain morphology identifies the riparian landscape as a unit;
- Vegetation indicators confirm vegetation associated with frequently saturated soils;
- Soil form identifies soils that are associated with wetness zones; and
- Soil wetness factor identifies morphological variables within the soil profile.

The lack of ground cover observed beneath invasive trees may result in unstable and easily erodible soils causing destabilisation of riverbanks. Furthermore, erosion and sedimentation caused by roads and plantations close to the riparian zone have substantial impacts on habitat health.

3.3.3 Effects of the removal of IAPs on environmental and hydrological resources

In catchment areas that have been invaded by alien vegetation, their eradication can often lead to substantial increases in water available for other uses and may offer an alternative to traditional engineering solutions of additions water provision, such as the construction of dams. Programmes to eradicate IAP species can have a number of benefits (Water Policy International, 2001), *viz.*:

- Increased water security with enhanced streamflow and improved water quality;
- More productive wetlands, estuaries and higher water tables;
- Rehabilitation of degraded land, with a strong emphasis on land care to secure the sustainable productivity of land;
- Conservation of biodiversity and catchment integrity;
- Reduction in the frequency and intensity of fires and floods;
- Development of secondary industries based on the cleared wood; and
- Empowerment and employment of people through the labour-intensive approach to the work, for example, the Working for Water programme.

After clearing stands of alien trees, there can be a lag time for streamflow recovery, which may be in the order of several years (Bruijnzeel, 2001). An important point to consider when removing plantations is the possibility of an initial reduction in streamflow as a result of regrowth of natural vegetation and, especially, the vulnerability of the site to rapid and uncontrolled alien vegetation re-invasions. Paired catchment experiments have nevertheless revealed that there is a general increase in water yield in the first year subsequent to clearfelling of a site which is approximately proportional to the percentage reduction in the area of the stand (Scott and Lesch, 1996; Bruijnzeel, 2001).

Studies that have been carried out to determine the effect of clearing IAPs from riparian zones include feasibility assessments incorporating mapping exercises, determination of water yield, hydrological modelling and costing analyses. Results have shown that the impact of land use in the riparian zone on the catchment water resource is relatively high and that the existence IAPs in the riparian zone has a negative impact on the water resource (Gillham and Haynes, 2001). Dye and Poulter (1995) measured the streamflow between two weirs on a stream in a forest plantation following the removal of *Pinus* and *Acacia* species from a riparian zone. The results showed that after these trees were cleared to a distance of 25 m from the stream, there was a 120% increase in streamflow over the study period of a month. A study by Jewitt *et al.* (2000) analysed different land use scenarios in the Pongola catchment using the *ACRU* agrohydrological modelling system. The focus was on the benefits of clearing IAPs from the riparian zone, with scenarios of cleared and uncleared riparian zones. The modelled results showed an overall increase in runoff after clearing, for low flows conditions and median annual streamflows.

3.4 Management Strategies

The National Forests Act (NFA), No. 84 of 1998 emphasises sustainable forest management for both plantation forests and indigenous forests and it highlights the links between community, conservation and commercial forestry. In light of the SFRA licensing and the international certification which most forests have attained, the forestry industry endeavours to keep all riparian areas clear of IAPs and to support environmental conservation programmes and alien plant control programmes such as the Working for Water (WfW) and Working for Wetlands programmes.

3.4.1 The Working for Water Programme (WfW)

The WfW Programme was started in 1995 with support from the Department of Water Affairs and Forestry (DWAF). It is currently the biggest conservation programme in Africa that actively addresses the issue of IAPs (DWAF, 2002). It has created employment and training opportunities for the poorest communities in South Africa through the removal of invasive alien plants. The objectives of the programme are specified as follows:

"Through the control of invading alien plants, we shall:

- Enhance water security;
- Restore the productive potential of the land;
- Improve the ecological integrity of natural systems;
- Develop economic benefits from wood, land, water and trained people; and
- Invest in the most marginalized sectors in South Africa and enhance their quality of life through job creation" (DWAF, 2002).

Through their objectives the WfW programme attempts to integrate social, environmental and economic needs. The social development of the programme has its own aims that enable it to pursue other research and biophysical goals. The first is poverty reduction by creating employment opportunities and income; the second by enhancement of skills and knowledge that ensures the ability of the worker to have long term, sustainable employment; the third, the improvement of health; and the fourth, fostering responsible citizenship (DWAF, 2002).

A range of methods exist that can be used for the effective clearing and control of IAPs and their integrated use will depend on the characteristics of the individual species as well as the nature of the invaded system. Any control programme must be followed up and maintained and the cleared area needs to be rehabilitated. The following three methods are used by the WfW programme in clearing IAPs:

- Mechanical control, i.e. by felling and removal of invading alien plants, often in conjunction with burning;
- Chemical control, i.e. by using environmentally safe herbicides and pesticides; and
- Biological control, i.e. by using species-specific insects and diseases from the alien plant.

3.4.2 Benefits of the WfW programme

Benefits of the WfW programme for water resources include enhanced long term water security, more optimal flows in rivers in dry seasons, more affordable and assured supply of water, reduced soil erosion, sedimentation and siltation of dams and reduced flooding of rivers (Calder, 1999). The effect that extensive, long term alien vegetation invasion would have on the ecology of natural systems includes the loss of indigenous plant and animal species, reduction in streamflow, and increased vulnerability of natural, and subsequently anthropogenic, systems to fire (Table 3.1). The environmental benefits, therefore, of the removal of the riparian IAPs would be reduced loss of plant and animal species, enhanced ecological functioning of water systems, and stability and diversity in ecological systems (Richardson, 1998). Some of the social benefits of the WfW programme include long-term employment (4000 jobs for 20 years), empowerment and community building, improved livelihoods, possible migration of people back to rural areas, possible increase in productivity of agricultural land and profitable harvesting of natural resources e.g. wild flowers, thatching grass and herbs.

3.4.3 Ecosystem rehabilitation and maintenance of clearing programmes

In order to find a solution to the persistent problem of IAPs, various control methods need to be integrated on an ongoing, long-term basis. Management options include manipulating disturbance regimes such as fire cycles and grazing (Richardson, 1998). The costs involved in the control of invasive species are offset by the indirect financial gains through improved water yield. In the commercial forestry industry, the most productive species are invasive if not controlled. Therefore stringent management practices and controls must be implemented and maintained to ensure the long-term sustainability of the industry. Partnerships between different sectors and industries that can contribute to the sustainability goals of rehabilitation programmes should be encouraged, such as those that have already been established through the WfW and the Working for Wetlands programmes in South Africa.

4. HYDROLOGICAL MODELLING AS A TOOL FOR ASSESSING THE IMPACTS OF CHANGE IN LAND USE

Hydrological models can be used as components of decision support systems to assess scenarios of change, to identify and solve problems and to analyse and present information for the management of water resources. As scenario tools, they are able to provide insight into potential problems, thereby assisting management decisions. Hydrological models can be applied at many different scales, spatially; from local (catchment) scale to global scale (Kite and Droogers, 2000) and temporally; from hourly to annual and longer term scales. The choice of spatial scale depends on the specific purposes of the modelling exercise. When considering a model for application to a particular problem, a number of factors need to be considered. These include the availability of data, complexity of the model, required output, accuracy, cost and the intended use of results (Singh, 1989).

Deterministic models describe the hydrological processes and relationships at various spatial and temporal scales linking rainfall to streamflow, i.e. they are physically based, requiring input of physical measurements (Schulze, 1998). These models are essential for simulating the impacts of land use change because they are able to mimic the behaviour of hydrological processes and system response under presumed conditions; they can be applied to ungauged catchments and can operate as continuous or event-based models. Their applications range from mimicking rainfall-runoff processes to flow forecasting, evaluation of land use practices, flood mitigation and drought management among others (Singh, 1989). Continuous simulation models attempt to simulate the hydrological cycle over a continuous time period whereas event-based models simulate a particular characteristic of the cycle e.g. the rainfall-runoff response for peak flow estimation (Singh, 1989). Land use sensitive models are continuous models that represent catchment processes by dividing the catchment into homogenous hydrological response units that contribute to the total catchment response i.e. they are distributed models (Schulze, 1998).

The following elements are required as a basis for simulation:

- Catchment representation – subdivision of a catchment into homogeneous subcatchments based on, *inter alia* rainfall, land use, soils and vegetation;
- Determination of effective rainfall;

- Calculation of runoff;
- Flow routing – routing from the upper reaches of the catchment to the outlet;
- Estimation of parameters – either physical measurements (assuming the model is physically based) or optimization of model parameters.

In addition, models need to calibrated and verified so that the output is as representative of catchment conditions as possible. When simulating streamflow from a catchment, additional information required for input to the model includes:

- Catchment characteristics e.g. subcatchment area, elevation, slope, length of the channel, information on land use, soils and vegetation;
- Rainfall characteristics for each subcatchment;
- Infiltration and other water "losses";
- Streamflow information.

Typically continuous models simulate two phases, namely the land and the channel. The important hydrological and terrestrial processes are represented in this type of model and they are suitable for impact studies of land use change. The *ACRU* agrohydrological simulation model has been used extensively in studies of the effects of land use on hydrological functioning (Schulze *et al.*, 1995a; Smithers and Schulze, 1995a). This model was selected for use in this study and will be presented in further detail in Section 4.2.

4.1 Modelling the Hydrological Impacts of Change in Land Use

As highlighted in Chapter 3, land use is one of the main factors that influence terrestrial hydrological processes. Therefore, in order to predict the impacts of change in land use or land cover on the hydrological cycle, appropriate modelling approaches are necessary. In such cases, modelling approaches need to simulate the hydrological cycle while describing natural variability and anthropogenic impacts at different scales. Land use activities and land use practices are always under the influence of humans and nature, and therefore changes will occur continually over time. Thus, impacts on the ecosystem are inevitable. It is, however, the scale of the impact that will determine its severity. Land use change in the catchment affects many elements of the hydrological cycle and these can be identified as point or non-point changes. The primary hydrological effects of change in land use are those on water yield, peak flows and low flows, surface water quality and groundwater quality and supply (Schulze, 1987). Changes in water yield, peak flows and runoff volume may have implications for flood frequency, sediment yield and water quality. Examples of land use parameters that affect the hydrological response of a catchment include:

- Vegetation cover – species or density;
- Change in total evaporation though vegetation and soil cover changes;
- Soil conditions – tillage, mulching;
- Land surface – contouring, terracing;
- Installation of subsurface drainage systems;
- Operation of irrigation systems; and
- Urbanisation.

The development of modelling scenarios requires a good understanding of physical processes and mechanisms in the environment, and it is also dependent on the output requirements of the modelling exercise, namely (Lahmer *et al.*, 1999):

- Aims of the study and associated restrictions;
- The type of model being used;
- Issues of scale, both temporal and spatial; and
- Characteristics and constraints of the study catchment.

The following sections provide a review of the application of modelling procedures to land use change, specifically to afforestation and invasive alien plants, as well as presenting the *ACRU* agrohydrological model as a tool for the purposes of this study.

4.1.1 Afforestation

In order to assess the impacts of afforestation on water resources, a model should be able to predict the hydrological response relative to previous and future land use on the same site, such as baseline conditions and previous land use practices (Schulze *et al.*, 2002). In addition, sensitivities to hydrological, vegetative and terrestrial parameters should be identified, as well as their response over time. In South Africa, afforestation is the only declared streamflow reduction activity (SFRA) and it is important to know how much water is being used by forestry species, and the extent to which different tree species use different amounts of water. Implications of management practices and location of afforestation within a catchment, as well as its extent, need to be determined and to this end, modelling can be a useful tool.

Specific functions relating to forest hydrological processes have been developed in models such as *ACRU* and in this case, these have been incorporated as a Forest Decision Support System (FDSS). The forest hydrological processes accounted for are changes in biomass, evaporation and transpiration, interception, infiltration, soil water redistribution and root characteristics. It also distinguishes between tree genera, i.e. pines, wattles and eucalypts, and age, as well as site preparation techniques (Schulze *et al.*, 1995d). Pines are considered to be more conservative water users, and eucalypts the most aggressive of exotic genera in terms of water use (Summerton, 1996).

4.1.2 Invasive alien plants

A change in catchment vegetative cover due to IAPs will share many characteristics of land use change described above. In addition, the likelihood of increased water use of IAPs relative to that of the vegetation that they replace has widespread implications for hydrology and biodiversity, as discussed in Chapter 3. In South Africa, models that have been developed to determine the streamflow reduction caused by IAPs are based primarily on biomass of the vegetation (Le Maitre *et al.*, 1996; Larsen *et al.*, 2001). Separate age-biomass models for each vegetation type, tall tree, medium tree and tall shrub, are used in conjunction with flow reduction models for low flows and annual flows as well as a distinction for riparian sites (Larsen *et al.*, 2001). It is anticipated that IAPs can be modelled more explicitly as a land use in the catchment using the *ACRU* agrohydrological model and their classification for use with the model is presented in Chapter 5.

4.2 Hydrological Simulation Models: The *ACRU* Agrohydrological Modelling System

The acronym *ACRU* is derived from the Agricultural Catchments Research Unit in the Department of Agricultural Engineering, now the School of Bioresources Engineering and Environmental Hydrology at the University of Natal, Pietermaritzburg. The *ACRU* agrohydrological model is a physical conceptual, multi-level, multi-purpose model that operates on a daily time step (Figure 4.1). It revolves around daily multi-layer soil water budgeting (Figure 4.2) which enables it to be hydrologically sensitive to climate and land use changes on soil water and runoff regimes, including impacts of irrigation practices, afforestation and riparian zone clearance (Schulze and Smithers, 1995a). *ACRU* can simulate streamflow, total evaporation, abstraction impacts and land management impacts on water resources.

The *ACRU* model requires input of relevant catchment information and can be operated in different modes dependent on input information and output requirements (Figure 4.1). Depending on specific user requirements, the model can be operated in distributed or lumped mode. In lumped mode, only point changes can be simulated, i.e. spatial variability of change is not accounted for across a catchment.

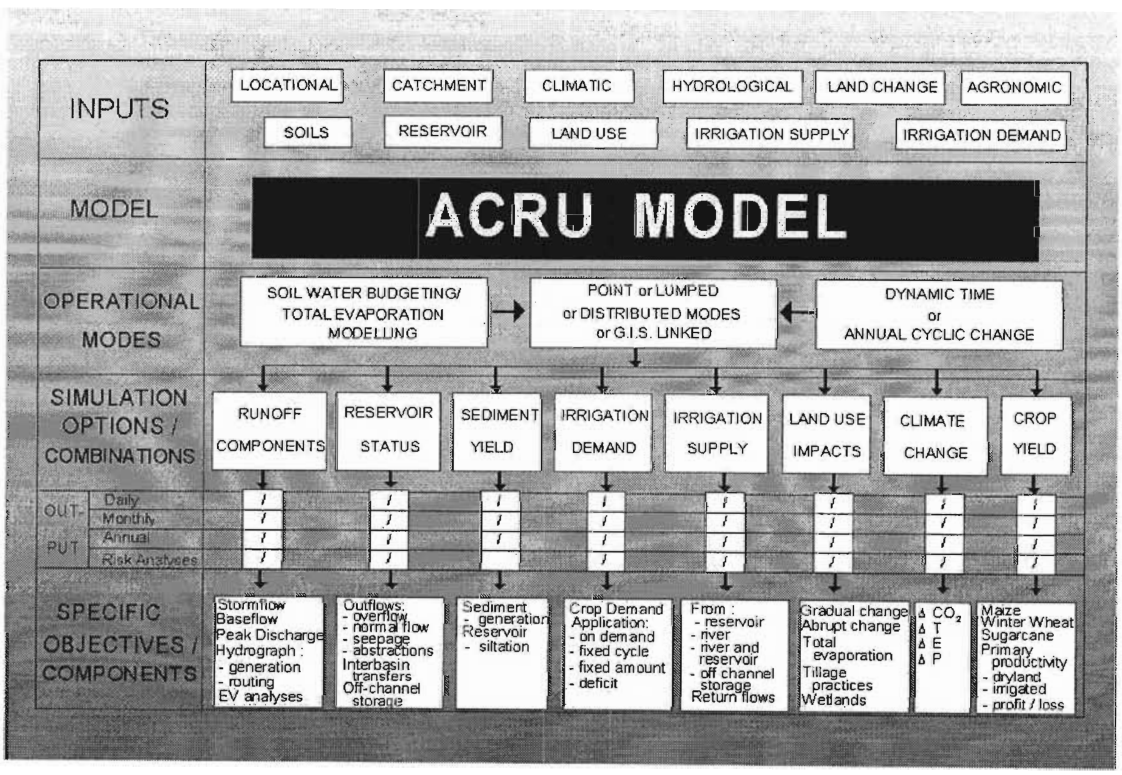


Figure 4.1 The *ACRU* agrohydrological modelling system: concepts (Schulze *et al.*, 1995b)

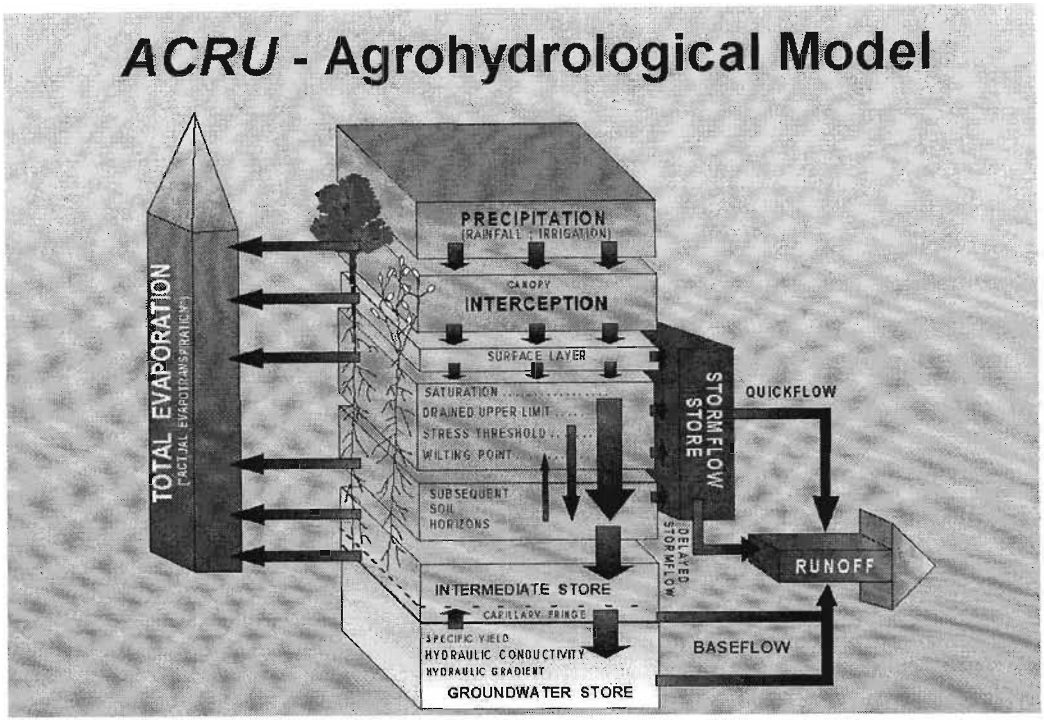


Figure 4.2 The *ACRU* agrohydrological modelling system: structure (Schulze *et al.*, 1995b)

Distributed mode allows for spatial variation of rainfall, soils and land cover. When *ACRU* is run in distributed mode, the catchment is sub-divided into relatively homogeneous subcatchments which are then further categorised into hydrological response units (HRUs). The latter are based on land use zones and facilitate the simulation of land use changes (Görgens, 2001). Each HRU is interconnected and is a lumped representation of that area. The layout of these units is represented in an inter-cell flow diagram depicting the major stream pattern of the catchment (Schulze *et al.*, 1995b). Each subcatchment requires individual input information, which can be time consuming and data intensive and, as a result, additional software known as *ACRU Utilities* are used to prepare input and output information for the *ACRU* modelling system.

4.2.1 Input requirements

Compulsory minimum input requirements for the *ACRU* model are listed below (Smithers and Schulze, 1995a):

- General catchment information - location, area, altitude, catchment configuration;
- Rainfall – daily (mm per day);

- Reference potential evaporation – at minimum mean monthly A-pan or monthly means of daily maximum and minimum temperature;
- Total evaporation – from soil surface (evaporation) and vegetated surface (transpiration);
- Land cover – up to 4 types of vegetation input i.e. crop coefficient (CAY), leaf area index (LAI), interception loss (mm per rain day) (VEGINT) and fraction of root mass distribution in topsoil horizon (ROOT A);
- Soils information (horizon depths; soil water retention at critical soil water contents; drainage characteristics);and
- Streamflow – daily (mm/day).

Additional catchment information of measured or known factors can be input to the model for specific studies including (Smithers and Schulze, 1995a; Horan *et al.*, 2000):

- Commercially planted tree species (species distributions; levels of site preparation; above and below-ground vegetation characteristics at average plantation ages);
- Other dryland land uses (crops types; management level; areas; above- and below-ground vegetation characteristics);
- The aereal extent, location and species of alien invasives both riparian and non-riparian;
- Dams (full supply capacities; surface areas; environmental releases; abstractions);
- Irrigation practices (crop type/seasonality; mode of scheduling; areas; source of water; application efficiencies) and
- Other abstractions (e.g. domestic or livestock; amounts; sources of water; seasonality).

Climatic and hydrological information, catchment information and output variables need to be formatted into *ACRU* format using *ACRU Input Utilities* to create the input information file, or MENU. Depending on the user requirements and information available for input, any one of the following utility programmes listed in Table 4.1 can be used to format files for input to *ACRU.*

Table 4.1 Summary of the *ACRU Input Utilities* software

ACRU INPUT UTILITIES	**Function**
ACRU Menubuilder	Controls input to the menu
ACRU Outputbuilder	Output variables simulated by model required for analysis after the simulation.
CreatemenufromGIS	Generates expanded menu using land use areas in each subcatchment (Hydrological Response Units).
Autosoils	Converts soils land type information from ISCW to soils input information.
Grid Extractor	Extracts gridded images of mean monthly A-pan and monthly means of maximum and minimum temperatures
Reformatting daily rainfall data (Programme = Weirfor)	Converts from DWAF format to *ACRU* single or composite
CalcPPTCor	Selects rainfall driver stations and their corresponding correction factors for each subcatchment.

Catchment input information is transformed in the model in the daily multi-layer soil water budget by considering the components of the hydrological cycle that affect the soil water budget. These components are canopy interception, rainfall to the ground surface, infiltration into the soil, total evaporation from the various soil horizons, effects of the litter layer, redistribution of soil water and percolation of soil water to the groundwater zone (Smithers and Schulze, 1995a).

4.2.2 Model output

The *ACRU* model's simulation output is controlled by the *ACRU Outputbuilder* which generates values for a list of variables (chosen by the modeller) that are simulated by the model. These values can be used in statistical analysis, shown graphically or used in risk analyses (Smithers and Schulze, 1995a). The results of simulation may include any of the soil water budget components, as well as elements of simulated streamflow responses that can be chosen by the user, at a daily, weekly, monthly or annual time step, for example:

- Streamflow, stormflow and baseflow (on a daily basis from different parts of the catchment, including those generated separately for the riparian zone) and low flows which can be accumulated and

- Risk analysis (month-by-month and annual statistical analysis, including flows under median conditions and for the driest flow in, say, 5 or 10 years; flow variability; low flow analyses).

4.2.3 Decision support systems and simulation options: *ACRU* modules

The decision support system concept is one that is used to provide assistance in selecting input information to distributed hydrological models because of the large amounts of data that they require, especially when land cover and soils information for large catchment areas are considered. Sub-models or modules are also available for specific research on land cover, wetlands and afforestation, i.e. decision support systems exist for land use and land cover, wetland hydrological modelling and forestry respectively. The decision support system for land use and land cover includes an information database for South Africa that contains relevant monthly variables for more than 160 land uses. This information file is accessed by the *ACRU Menubuilder* when a particular land use is selected and the relevant vegetation input information is extracted (Schulze *et al.*, 1995a). The wetland hydrological modelling sub-model (Smithers and Schulze, 1995b) is conceptualised as a water budget and includes features such as inflow hydrograph attenuation, evaporation from open surfaces, transpiration from riparian vegetation, rainfall onto the wetland area, losses to or gains from underlying aquifers and outflows from these features. The morphology of the wetlands and associated affects of increases in ponded surface areas are also accounted for. The forestry decision support system that is used in the *ACRU* modelling system accounts for the effects of site preparation which impacts soil drainage characteristics, and tree species and age impacts on land cover characteristics. These options are all available in the *ACRU Menubuilder*.

In addition to the output from the water budget described above, the *ACRU* modelling system has various options and utilities that can be applied to a range of different problems faced in the field of water resources management. These options (Figure 4.1), which are enabled by the *Menubuilder*, include: sediment yield analysis, shallow groundwater modelling, irrigation demand and supply, reservoir yield analysis, hydrograph routing and crop yield estimation.

4.2.4 Verification of model output

The general aims of a verification study are to ensure that variables output by the model simulate observed values as closely as possible. A graphical illustration provides the best means of initial verification of simulated results against observed values. Thereafter, statistical analyses are conducted in order to test the viability of simulated versus observed values, including testing of conservation of means and deviations and testing the goodness of fit 1:1 relationship (Smithers and Schulze, 1995a). In such an exercise, it is necessary to ensure that all input values for a catchment are of good quality and sufficiently detailed so that false conclusions cannot be drawn.

4.2.5 Applications of the *ACRU* agrohydrological model

The *ACRU* model has been used extensively in the following water resources assessments since the 1980s and updates and refinements to the model are ongoing (Smithers and Schulze, 1995a):

- Water resources assessments;
- Design hydrology;
- Irrigation water demand and supply;
- Crop yield and primary production modelling;
- Assessments of impacts of land use changes on water resources;
- Assessments of hydrological impacts of wetlands;
- Groundwater modelling; and
- Assessments of potential impacts of global climate change on crop production and hydrological responses.

In this project, the *ACRU* model will be used to estimate the hydrological response to IAPs in riparian and non-riparian habitats of the Upper Blyde River catchment. Chapter 5 will present a classification for IAPs as a land use and a methodology for input of spatially explicit land use units to the *ACRU* model.

5. CLASSIFICATION OF INVASIVE ALIEN PLANTS AS A LAND USE FOR HYDROLOGICAL MODELLING

The change in total evaporation (interception and transpiration) as a result of altered vegetation cover is one of the primary influences on catchment hydrology. In an already water scarce country this is an important issue and is one that should be addressed as part of a national water management strategy. Estimates of the impact of invading alien plants (IAPs) on catchment water resources can be performed with land use sensitive hydrological models that are able to account for the type, density and extent of invasion in a catchment. However, information available from accepted mapping techniques for catchments affected by IAPs is not explicitly classified for use in such hydrological models, and should be addressed.

IAPs are mapped by Working for Water (WfW) according to *inter alia,* area, density, age, genus, species and methods used for eradication. These variables are used as input to a hydrological model, which requires some background information regarding water use (e.g. interception, rooting and evaporation parameters). A critical question is therefore, how information contained in alien vegetation coverages obtained from WfW mapping is best classified for use in a hydrological model.

The successful invasion of an area by an alien plant can be attributed in varying degrees to the abovementioned variables, so it remains to select the most appropriate variables for the modelling procedure. The consideration of the current area occupied by invading plant species, as well as the potential area that they may occupy, can be related to density, but also requires an understanding of the rate of spread of the invading species, which, for most species, is currently estimated at 5% per year (Le Maitre *et al.*, 1998). Typically, it is assumed that areas of high density plants will have a greater impact on the water resource than areas where the plants are more widespread and isolated. Owing to different processes and species dominating in landscape compared to riparian invasions, the impact on the water resource varies. In addition, the plant species is important in terms of its water use. Streamflow reductions resulting from stands of trees such as pines, Wattle and eucalypts have been studied, whereas the water use of short, shrub-like and grass invaders has been less studied and is largely unknown.

In this chapter, a method of classifying IAPs for use in a hydrological model is presented (Figure 5.1). It is suggested that the type of habitat invaded should be the primary basis for classification, i.e. riparian or landscape invasion; second, a classification for the type of plant in each habitat, i.e. tree or shrub/grass; and third, density, i.e. sparse (<25% canopy coverage), medium (25-75% canopy coverage) and dense (>75% canopy coverage). Species information is not included in the hierarchical structure presented in the following pages, but may be added at a later stage as a fourth level classification for more in depth studies where specific impacts by key species is required. These classification units can then be as input land use units to the *ACRU* hydrological modelling system, which was described in Chapter 4.

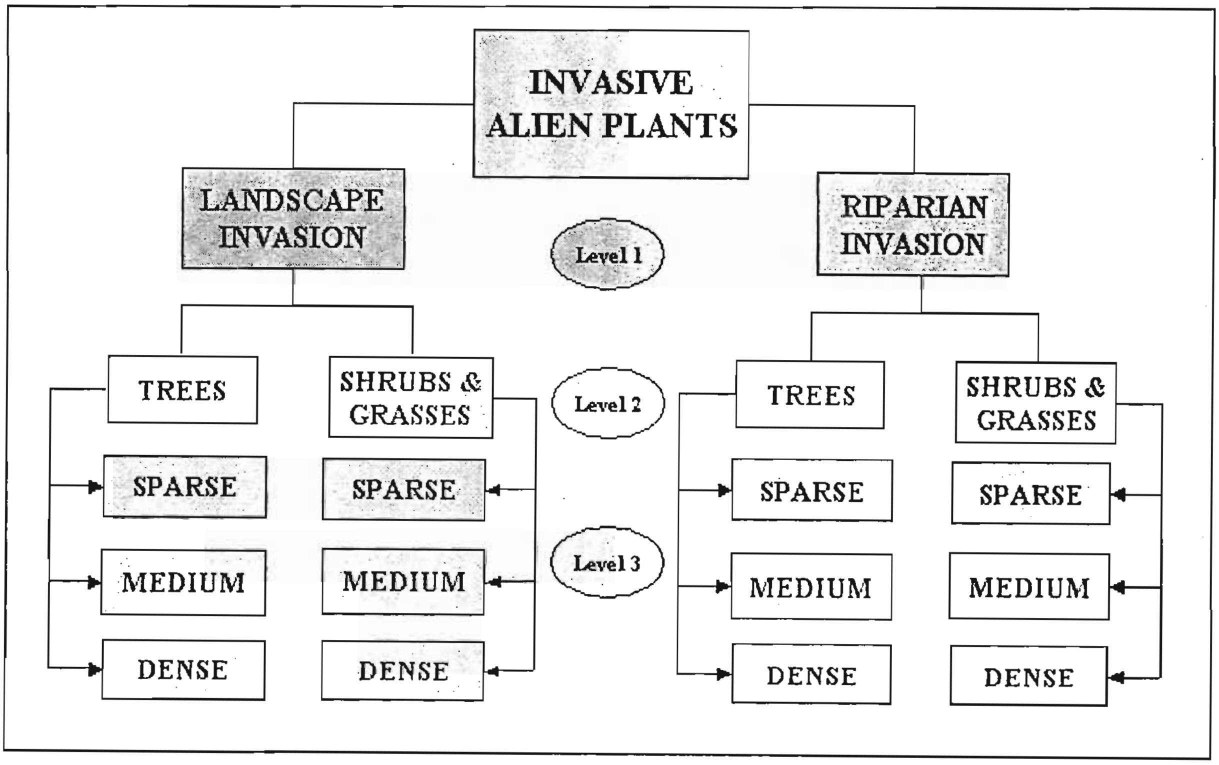


Figure 5.1 Schematic classification of IAPs for use in a hydrological model

5.1 Working for Water Mapping

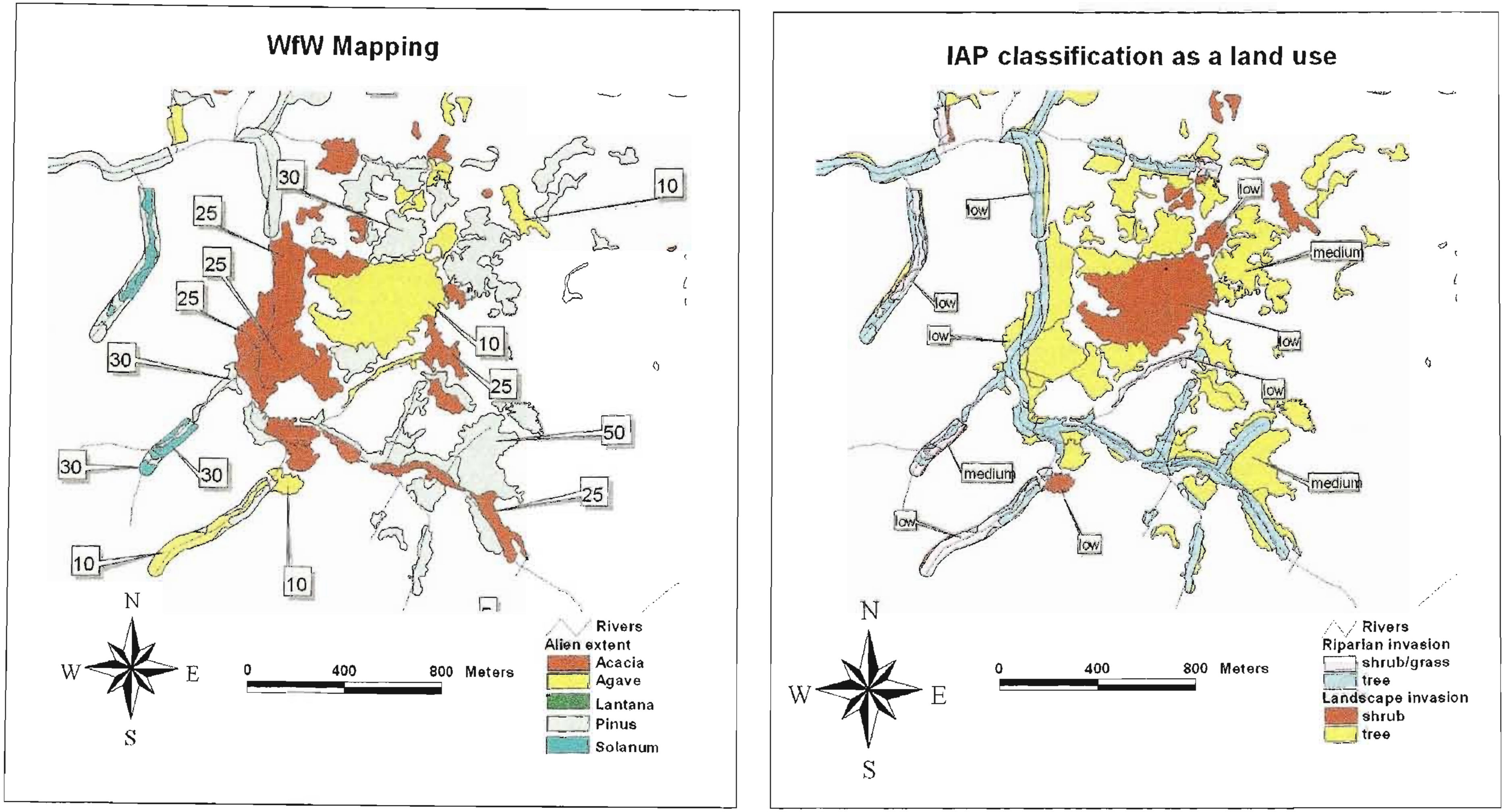
The maps obtained from WfW were digitised from 1:10 000 orthorectified aerial photographs, flown over the Blyde River catchment in February 2002. The basic map coverage provides the area of coded polygons (IAPs) and detailed information on the specific characteristics of the invaded area accompanied the mapped coverage (Table 5.1) as a series of reference tables that define polygon codes for species identification according to genus and species, size or age of the plant (SIZE CODE), treatment stages 1-31 (representing amongst others: initial treatments, number of follow-ups, maintenance and rehabilitation stages), control methods applied (METHOD) and density of invasion (DENS CODE), which is mapped according to seven categories, *viz.*:

- Closed (>75% cover);
- Dense (50.1-75% cover);
- Medium (25.1-50% cover);
- Scattered (5.1-25% cover);
- Very scattered (1.1-5% cover);
- Occasional (0.02-1% cover); and
- Rare (<0.02% cover).

This very detailed information is invaluable and provides important information that can be widely used for different studies on IAPs. A graphical comparison (Figure 5.2) shows the difference between the information mapped by WfW and that mapped using the three level classification structure.

Table 5.1: Example of detailed information contained in mapped coverages of IAPs

AREA_HA	SP_CODE	SIZE CODE	STAGE	METHOD	DENS CODE	GENUS	SPECIES	ENG_NAME
0.45	148	a	1	6	10	Rubus	spp	Brambles spp
0.45	158	a	1	9	10	Solanum	mauritianum	Bugweed
0.46	126	a	1	6	90	Pinus	spp	Pines
0.47	126	a	1	6	30	Pinus	spp	Pines
0.50	7	a	1	6	25	Acacia	mearnsii	Black Wattle
0.53	7	a	1	6	25	Acacia	mearnsii	Black Wattle
0.57	158	a	1	9	30	Solanum	mauritianum	Bugweed
0.58	7	a	1	6	25	Acacia	mearnsii	Black Wattle
0.59	7	a	1	6	25	Acacia	mearnsii	Black Wattle
0.63	126	a	1	6	100	Pinus	spp	Pines
0.71	148	a	1	6	10	Rubus	spp	Brambles spp
0.73	148	a	1	6	10	Rubus	spp	Brambles spp
0.75	126	a	1	6	90	Pinus	spp	Pines
0.76	7	a	1	6	45	Acacia	mearnsii	Black Wattle
0.79	126	a	1	6	90	Pinus	spp	Pines



(a) WfW mapping technique showing species and density

(b) Classification of IAP to habitat, plant type and density

Figure 5.2 Graphical representation of detailed WfW mapping to classify IAPs as a land use for use in a hydrological model

5.2 Invasion Processes

The vulnerability of a particular habitat to invasion by an alien plant can be attributed to several factors, in particular, environmental disturbance, absence of natural predators and absence of competitive species (Ashton and Mitchell, 1989).The distribution of IAPs can be associated with both anthropogenic and natural disturbances, for example, change in land use, flooding and fire regimes. Therefore, the success of an IAP, be it in an aquatic or terrestrial environment, can be attributed to its ability to not only survive and reproduce, but also to dispersing its seeds, establishing itself and adapting to a new environment, and colonising new habitats (Figure 5.3; Ashton and Mitchell, 1989). This is a sequential process that comprises several discrete steps. A successful invasion process can be divided into three main stages: 1) arrival/introduction of the individual, 2) establishment of a population through reproduction, and 3) dispersal to a new location (Ashton and Mitchell, 1989). The invasion process is also limited to the availability of resources and in particular, constrained by the area of land available for invasion (Chapman and Le Maitre, 2001).

In a South African study by Wells *et al.* (1986, cited in Henderson and Wells, 1986), the greatest concentration of IAP species (82%) were found in the subtropical regions of the savanna biome, and wetland areas (including riparian zones, swamps and marshes) were recorded to have been invaded by 51% of IAP species. In their study, alien species were classified according to their habitat moisture regime:

- Terrestrial dry habitats (594 species);
- Streambanks (261 species);
- Terrestrial moist (swamps and vleis) (211 species); and
- Aquatic (21 species).

The primary classification for the purposes of hydrological modelling is made according to the type of habitat that is invaded, namely riparian and landscape (or terrestrial) invasions. This distinction is made primarily on the ecosystem properties of each habitat based on the availability of water to the plant. It is assumed that the invasion processes, and the type of invasive plant that is likely to establish in each system, will be significantly different in these two landscape types.

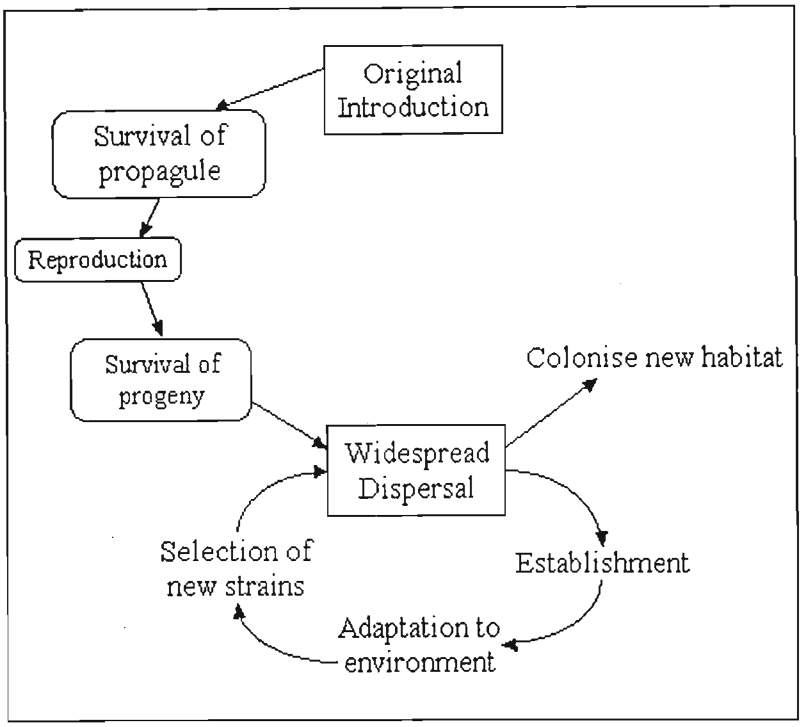


Figure 5.3 Stages in the invasion and establishment of IAPs (Ashton and Mitchell, 1989)

5.2.1 Riparian invasions

The riparian zone is an important feature in the landscape and performs many important functions, including acting as a chemical filter, reducing the impacts of floods and supporting high levels of biodiversity. It is an ecotone that forms the interface between aquatic and terrestrial ecosystems (Malanson, 1993). These ecotones act as buffers to the impacts of land use activities on rivers and wetlands (Buttle, 2002). Although buffer zones are easily distinguishable from the surrounding landscape they are, however, difficult to delineate as a result of differences in vertical and lateral extents. In South Africa, in the absence of a detailed soil survey, an area of 30 m on either side of a watercourse is assumed to be the riparian zone (Meier, 1997). Ideally, delineation should be based on terrain morphology, vegetation indicators, soil form and soil wetness (Land Use and Wetland/Riparian Habitat Working Group, 2001).

The riparian zone is particularly vulnerable to invasion by alien plants because it is frequently disturbed by floods, thereby making it more conducive to establishment of new species because there is ready access to water and seeds are easily dispersed downstream (Malanson, 1993; Le Maitre, 1998). Invasion is further facilitated by the natural and anthropogenic disturbance regimes that are important for riparian system functioning and biodiversity (Tabacchi *et al.*, 1998). Once invasive species have established themselves, they compete with indigenous species for resources. Perennial rivers appear to be the most densely and extensively invaded by landscape invader species (as opposed to aquatic weed species) including *Acacia* spp., *Lantana*, *Melia*, *Caesalpinia*, *Salix*, *Populus*, *Sesbania*, *Jacaranda* and *Rubus*. It is hypothesised that riparian invasions tend to occur more rapidly than those in the open landscape (Le Maitre, 1998).

5.2.2 Landscape Invasions

South African native vegetation can be distinguished into several biomes, each of which have their own unique characteristics and regional preferences, and hence are susceptible to invasion by different alien plant species, depending on their individual physiological requirements (Richardson *et al.*, 1997). These terrestrial biomes are: fynbos, grassland, forest, savanna, karoo and desert. The most studied of these is the fynbos biome which has been heavily invaded by tree and shrub species. Grassland and savanna biomes have been less studied, but research has shown that some invasive species invade these biomes exclusively, for example, *Pyracantha angustifolia*. Henderson and Wells (1986) identified the greatest concentration of alien species in the savanna and grassland biomes of the summer rainfall regions of South Africa.

Landscape invasions are usually related to land use practices and the rate of invasion can be related to the degree of degradation of the natural vegetation (Le Maitre, 1998). Disturbance of the landscape, as in the riparian zone, plays an important role when the establishment of IAPs is considered. Fires, agricultural practices and other land uses may also limit or exert an element of control over the invading species, undermining its invasive success. In addition to these factors, rainfall is a key constraint in the arid and semi-arid regions of South Africa. Le Maitre (1998) indicates that landscape invasions appear to be restricted to areas where there is at least 500-600 mm rainfall per year, with exceptions in the southern Cape coastal regions and the Zululand Coastal Plain where there is a reliable and easily accessible groundwater store. The most successful, large scale landscape invaders are *Pinus*, *Hakea* and *Acacia* species.

5.3 Invading Species and their Water Use

Successful IAPs adapt well and spread prolifically, and usually have no natural predators in their new environment (Tickner *et al.*, 2001). The successful replication of IAPs can however, not only be attributed to their physiology, but also to other factors which include habitat availability, climate, soil type, competition, hydrology and geomorphology of the site itself. To date, calculations of water use have largely been based on experiments in commercial plantations of alien species such as pines, eucalypts and Wattle (Versfeld *et al.,* 1998), but a body of research on the water use of IAPs is emerging (Dye and Poulter, 1995; Scott and Lesch, 1996; Dye *et al.*, 2001). Streamflow reduction is dependent on age and biomass of the vegetation and also on the geo-climatic site conditions (WfW, 2003). A study by Sala *et al.* (1996) on the water use of the woody shrub, *Tamarix*, in the riparian zone, found that stand density and leaf area index (LAI) were important variables affecting stand water use. Their results showed that transpiration rates of the invader *Tamarix* were no higher than those of native vegetation when there was enough water available. In addition, their results indicated that on the basis of LAI, the maximum water use of individuals in dense thickets of *Tamarix* might be lower than that of individuals in thickets of lower LAI. This has important implications for management because it implies that sparse thickets of woody riparian shrubs with low LAI can be maintained with low impact on water resources; an aspect that requires further investigation with other species.

To date, much of the research on water use calculations using hydrological models has been based on the aforementioned catchment experiments in and around commercial forest plantations and, therefore, predominantly provides information on the water use of invasive alien trees (Dye and Poulter, 1995; Scott and Lesch, 1996; Dye *et al.*, 2001). In South Africa, 63% of IAPs are trees and shrubs, and 79% of these are perennials (Richardson *et al.*, 1997). Certainly some of this can be attributed to the introduction of woody species as timber resources. Current estimates of water use by Le Maitre *et al.* (2002) are derived from regression equations that estimate vegetative biomass from age and flow reductions from biomass with 95% confidence limits. The mean predicted flow reductions for a KwaZulu-Natal catchment study were 1 900 $m^3.ha^{-1}.year^{-1}$ using the biomass model which converted to a total of 11-19 million $m^3.year^{-1}$ using the *ACRU* model (Le Maitre *et al.*, 2002). The values are summarised by species and province by Versfeld *et al.* (1998) who show that out of the major invading species in South Africa, 15 of 34 species are trees and that these account for approximately 82% of the total water use. Nineteen of the 34 major invading species are shrubs and grasses, accounting for approximately 17% of total water use (Table 5.2).

Invasive alien tree species (*Pinus*, *Eucalyptus* and *Acacia*) that establish themselves in the riparian zones adjacent to commercial forestry activities have, arguably, the highest impact on streamflow (Dye *et al.*, 2001). Many of the invasive shrub species are botanically also classified as small trees, or woody shrubs, that form dense thickets. Some of those plants classified as grasses, are large reeds which also form dense woody thickets. Therefore, the water use of these plants may be equivalent to medium or low density trees.

Research on the water use estimates as well as expert knowledge in the field (Calder, 1999) suggests that trees are likely to be more voracious water users than shrubs and grasses, hence this is used as the basis for distinguishing these two types of IAPs for classification in the hydrological model.

5.4 Density of Invasion

The density and the area that an IAP occupies are important factors related to its water use. It also gives an indication of the distribution of a particular plant species in the landscape. The criteria for mapping of IAPs should be consistent and the methodological approach is outlined in Versfeld *et al.* (1998). The density classes as mapped by WfW are captured as a percentage invaded area which are then allocated density categories as described in Section 5.1 (Versfeld *et al.,* 1998).

Table 5.2 Total water use by invading alien plants in South Africa (Adapted from Versfeld *et al.*, 1998, Appendix 6)

Plant type	**Species**	**Common name**	**Water use (million m^3 per year)**
Tree	*Cupressus glabra*	Cypress	0.003
Shrub/tree	*Cestrum laevigatum*	Inkberry	0.013
Tree	*Gleditsia triacanthos*	Honey locust	0.092
Shrub (small tree)	*Myoporum serratum*	Manatoka	0.252
Shrub (small tree)	*Nicotiana glauca*	Wild tobacco	0.287
Shrub/tree	*Phytolacca octandra*	Forest inkberry	0.541
Shrub	*Paraserianthes lophantha*	Stinkbean	0.586
Shrub (small tree)	*Tamarix* spp	Tamarisk	0.800
Shrub	*Verbena bonriensis*	Wild verbena	0.848
Tree	*Morus alba*	Mulberry	1.086
Tree	*Leptospermum laevigateum*	Australian myrtle	3.654
Grass	*Arundo donax*	Giant reed	4.348
Tree	*Quercus* spp	Oak	4.883
Shrub	*Ricinus communis*	Castor oil plant	6.726
Shrub	*Nerium oleander*	Oleander	6.754
Tree	*Jacaranda mimosifolia*	Jacaranda	11.331
Aquatic plant	*Pistia stratiotes*	Water Lettuce	12.692
Shrub (small tree)	*Sesbania punicea*	Red sesbania	18.325
Shrub (small tree)	*Ligustrum lucidum*	Chinese wax-leaved privet	27.074
Tree	*Salix* spp	Willow	32.200
Tree	*Psidium guajava*	Guava	33.345
Shrub	*Caesalpinia decapetala*	Mauritius thorn	33.820
Shrub	*Rubus* spp	Bramble	40.127
Tree	*Hakea* spp	Hakea	66.302
Shrub	*Chromalena odorata*	Triffid weed	68.250
Tree	*Melia azedarach*	Persian lilac	79.458
Shrub (small tree)	*Mimosa pigra*	Giant sensitive plant	85.198
Tree	*Populus* spp	Poplar	89.262
Shrub	*Lantana camara*	Lantana	107.133
Shrub	*Solanum mauritianum*	Bugweed	154.062
Tree	*Pinus* spp	Pines	180.677
Tree	*Prosopsis* spp	Mesquite	194.022
Tree	*Eucalyptus* species	Gums	213.981
Tree	*Acacia* spp	Wattle	1807.939

In previous modelling studies of water use estimates of IAPs (Dye and Poulter, 1995; Meier et al., 1997; Versfeld *et al.*, 1998; Chapman and Le Maitre, 2001; Le Maitre et al., 2002), the extent and density of the IAP in the landscape is simplified to an area equivalent to 100% (dense) infestation. However, as discussed in Section 5.3 and illustrated in Figure 5.4, equating sparse infestation to a 100% equivalent may not be hydrologically valid because of the differences in water use of sparse and dense vegetation (Sala *et al.*, 1996). While this method is useful in determining large scale streamflow reductions by different species, it does not adequately represent the impacts of lower density stands that may be more extensive and, therefore, have wider implications for spread and further densification in the future. In the methodology presented here, IAPs are classified as a unique land use unit that can be input into a hydrological modelling system. Streamflow estimates are obtained using inputs of vegetative water use parameters, soil characteristics as well as specifying how much of the landscape is occupied by a particular land use. Therefore, using a methodology that retains density classes, allows for the creation of land use scenarios which will be more useful and representative of the impacts of change in land use.

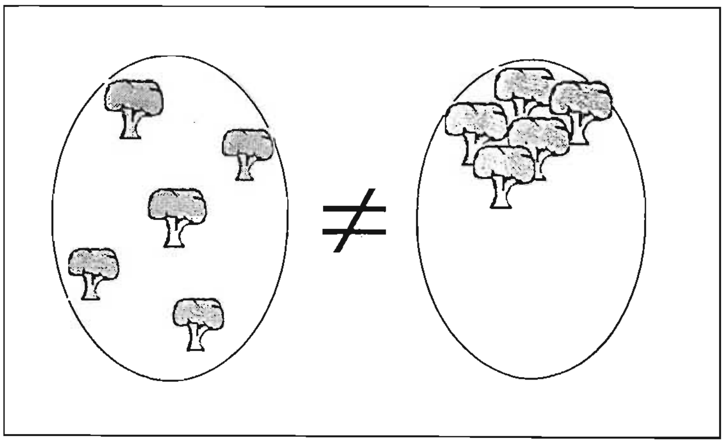


Figure 5.4 Diagrammatic representation of stand density equivalence

In this study the existing density classification used by WfW for mapping IAPs is reclassified into three categories, according to rules and assumptions detailed in Table 5.3. For each density class, the vegetation is assumed to be comprised of a percentage invasive plant and percentage natural vegetation to which appropriate vegetative water use parameters are applied (Section 7.2.4).

Table 5.3 Assumptions for the density classification of IAPs for hydrological modelling.

Category with % infestation	TREES	SHRUBS
DENSE >75% **(closed canopy/thicket)**	90% invasive species 10% natural vegetation	90% invasive species 10% natural vegetation
MEDIUM 25-75% **(intermediate cover)**	50% invasive species 50% natural vegetation	50% invasive species 50% natural vegetation
SPARSE <25% **(open scrub/thicket)**	20% invasive species 80% natural vegetation	20% invasive species 80% natural vegetation

5.4.1 Rate of spread

The spread of IAPs in the riparian zone in semi-arid areas is driven by disturbance through flooding, increased water availability and proximity of humans (Mackenzie *et al.*, 1999; Chapman and Le Maitre, 2001). Spread rates are influenced by environmental conditions such as the level of disturbance, fragmentation, nutrient fluxes and vectors available for propagation. They are, however, difficult to estimate owing to the complex mechanisms and interdependent relationships at work. The rate of spread of IAPs is believed to be highest in the riparian zone as a result of frequent disturbance regimes (Chapman and Le Maitre, 2001). The invasion process can be divided into two phases: expansion and densification (Versfeld *et al.*, 1998). Expansions are invasions propagated by dispersal of IAPs from their original location, while densification is the increase in density of existing plants. It is assumed that increases in density are exponential. In reality, large areas tend to become invaded at a slower rate than smaller areas for the following reasons: landscape areas have more varied habitats and ecosystems, which are not equally suitable for invasion; and landscape areas are usually fragmented by different land uses creating a mosaic of non-invadable land units (Dyer, 1995).

In the early stages of invasion, the expansion rates can be expected to be low, whereas the expansion of already established stands of IAPs can be expected to spread at a rate of ~5% per year (Le Maitre *et al.*, 1998), as well as to increase in density if they are not cleared. Therefore, the classification of IAPs into three density classes can potentially be a useful method of monitoring their rate of spread in different landscapes as well as providing a baseline for the impacts of water use in different density classes. This information will be important for managers implementing control activities and also in identifying those stands and types of plants that have the most impact on the water resource. Thus, priority for clearing in cases where manpower and financial constraints are limiting factors for controlling IAPs may be identified.

5.5 Modelling the Hydrological Impacts of IAPs

In this study, the IAP classification system is used to provide input to the *ACRU* hydrological model in order to determine the impact of existing IAPs on streamflow in the Upper Blyde River catchment (Chapter 6). The classification system is intended to provide information for the parameters which provide input for the model to assess the impacts that the current land use, including IAPs, has on streamflows in the catchment. Based on the discussions alone, six unique land use classification units can be identified (Figure 5.1):

- Dense invasive trees;
- Medium invasive trees;
- Sparse invasive trees;
- Dense invasive shrubs and grasses;
- Medium invasive shrubs and grasses; and
- Sparse invasive shrubs and grasses.

These land use classifications can then be used to identify hydrological response units in a catchment and their areas calculated with a GIS. Furthermore, the type of vegetation the IAP replaces can be determined. Each hydrological response unit has unique hydrological attributes that are based on vegetative interception, biomass, infiltrability and root distribution derived from known parameters and following the assumptions presented in Table 5.3. This methodology will be explained more fully in Chapter 7.

6. THE UPPER BLYDE RIVER CATCHMENT: A CASE STUDY

In order to test the classification system presented in Chapter 5, the Upper Blyde River catchment was selected as a case study area. The catchment is very important in terms its hydrological contribution to the over-exploited and degraded Olifants River. The Working for Water and Working for Wetlands programmes are active in the catchment and detailed mapping coverages were made available for the purposes of assessing the impacts of IAPs on catchment streamflow.

6.1 Catchment Description

The Blyde catchment is situated in the lower Olifants River basin, west of the Kruger National Park, straddling the Mpumalanga and Limpopo provinces of South Africa. It lies between 1 500 and 2 400 m above sea level on the Drakensberg escarpment, with the Mount Anderson mountains the most dominant at 2 000 m above sea level, rising between the sources of the Ohrigstad and Blyde rivers in the west and east respectively (Theron *et al.*, 1991; Figures 6.1 and 6.2). The Blyde catchment drains an area of 2 842 km^2 and it makes an important contribution to the Olifants River in terms of both water quality and quantity.

Figure 6.1 The Blyde River catchment at the Blyderivierspoort Dam

For the purposes of this study, however, the focus is on the Upper Blyde River catchment to the east of the Mount Anderson divide above the Blyderivierspoort Dam, which has a catchment area of 838 km^2. The area is an important water catchment and supports high levels of biodiversity. The area under commercial forestry land falls in the Upper Blyde River Catchment area comprises 241 km^2. In an initiative by the Department of Environmental Affairs and Tourism (DEAT) to expand the conservation areas in this region over the next five years, it is intended that this afforested land be deforested and incorporated into the Kruger to Canyons conservation area. The impacts of afforestation have widespread implications for environmental resources, as do their removal and the rehabilitation plans and practices associated with them. The focus of this research therefore, is on the likely impacts of change in land use caused by IAPs with regards to water yield and the associated environmental and hydrological impacts to sensitive riparian areas in the Upper Blyde River Catchment.

6.2 Hydrology

The Blyde and Treur Rivers and their tributaries are the main rivers draining the Upper catchment. The Blyde River has its source in the north-eastern Drakensberg Mountains near the town of Sabie in Mpumalanga Province, south of Pilgrim's Rest along the eastern escarpment (Figure 6.2). It flows northwards through the Blyde River Canyon Nature Reserve (BRCNR) where the Treur River joins at Bourke's Luck, continuing to the Blyderivierspoort Dam. Downstream of the Blyderivierspoort Dam, the Blyde River flows across the Lowveld to its confluence with the Olifants River north of the town of Hoedspruit. The Blyderivierspoort Dam is located at 24° 32'15"S and 30° 47'45"E and forms a divide between the upper and lower catchments. Its total catchment area is approximately 2 165 km^2 (1 315.5 km^2 on the Ohrigstad River and 838.4 km^2 on the Blyde River). The dam has a surface area of 263.1 ha and capacity of 54.110×10^6 m^3. It supplies water to the Lower Blyde River Irrigation District as well as to the Phalaborwa Water Board downstream for domestic and mining use. The town of Hoedspruit and the associated Air Force Base also receive their primary water supply from the dam (Ravenhill, 2002, personal communication). Abstractions from the Blyderivierspoort Dam are dependent on prevailing flow conditions in the Blyde River on the assumption that normal flow occurs four out of every ten years. The average allocated rate is 9 900 $m^3.ha^{-1}.year^{-1}$ with a maximum weekly abstraction rate of 400 $m^3.ha^{-1}$ (Swart *et al.*, 1997).

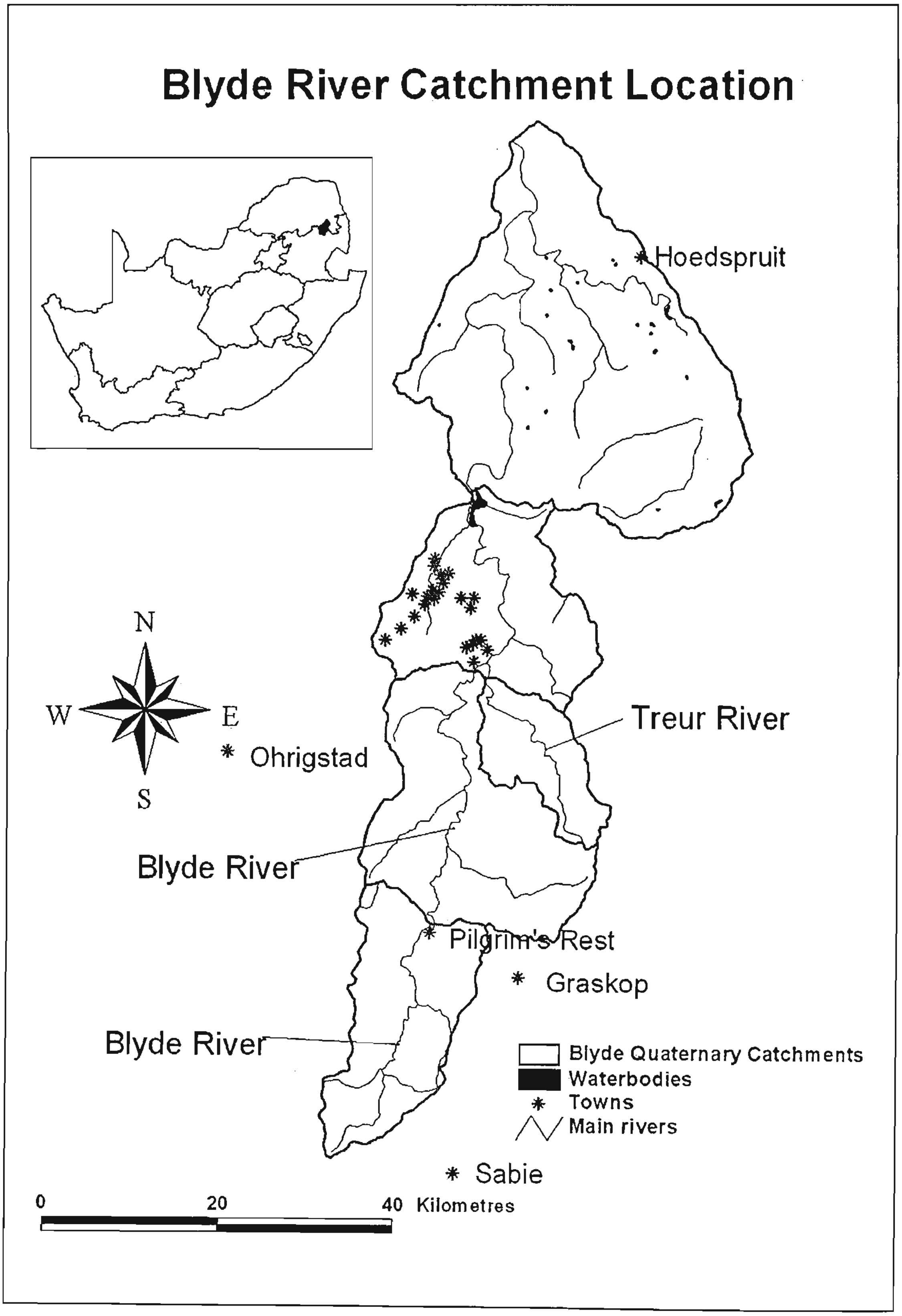


Figure 6.2 Location of the Blyde River Catchment, Mpumalanga, South Africa

6.3 Climate

The catchment of the dam receives some of the highest rainfall in South Africa. In the mountainous areas near the town of Graskop, a mean annual rainfall (MAR) of 2 000 mm occurs (Geldenhuys *et al.*, 1997). The Blyde catchment MAP varies from 430 to 1 500 mm across the catchment (Dent *et al.*, 1989). It is located in the summer rainfall area of South Africa, with the heaviest rainfall occurring in January when thunderstorms are common. The Upper Blyde valley, east of Mount Anderson, experiences more temperate summers with severe frost in winter. The Lower Blyde region has a typical very hot summers and warm winters. The catchment region has a mean annual temperature of 17-20°C with mean maximum summer temperatures ranging between 26-30°C and mean minimum winter (July) temperatures ranging between 3-5°C (Schulze, 1997).

6.4 Geology and Soils

The main geological formation in the catchment area is the Transvaal Sequence which consists of dolomite, chert, shale and sandstone (Figure 6.3). The Chuniespoort Formation in the eastern portion of the upper Blyde catchment features deep layered dolomites that are interspersed with layers of shale and quartzite from the Transvaal Sequence. These rocks are hard and resistant to erosion, forming steep cliffs in the Drakensberg Mountains on the Mpumalanga Lowveld and the Chuniespoort dolomites in the south-east provide an important source of groundwater to the Blyde River (Ashton *et al.*, 2001). The rocks of the Transvaal Sequence are prone to erosion and sediment accumulation which, coupled with the naturally steep slopes, results in high runoff potential (DWAF, 1991). The lower catchment, downstream of the Blyderivierspoort Dam, is characterised by the erosion-resistant Basement Complex which is made up of crystalline gneissic and granitic rocks. A number of intrusions are evident in this complex, namely syenite formations and dolerite dykes. The dykes are more easily erodible and tend to form troughs that act as watercourses and favourable sites for groundwater abstraction (Ashton *et al.*, 2001).

An important feature in the Blyde catchment are the Tufa deposits. These unique features are formed when water that has been saturated with calcium carbonate in the deep layers of the Chuniespoort dolomites, appears above ground level. The waterfalls in the area have characteristic, growing tufa deposits which are dynamic features forming an important part of the landscape in terms of biodiversity, as well as tourism potential.

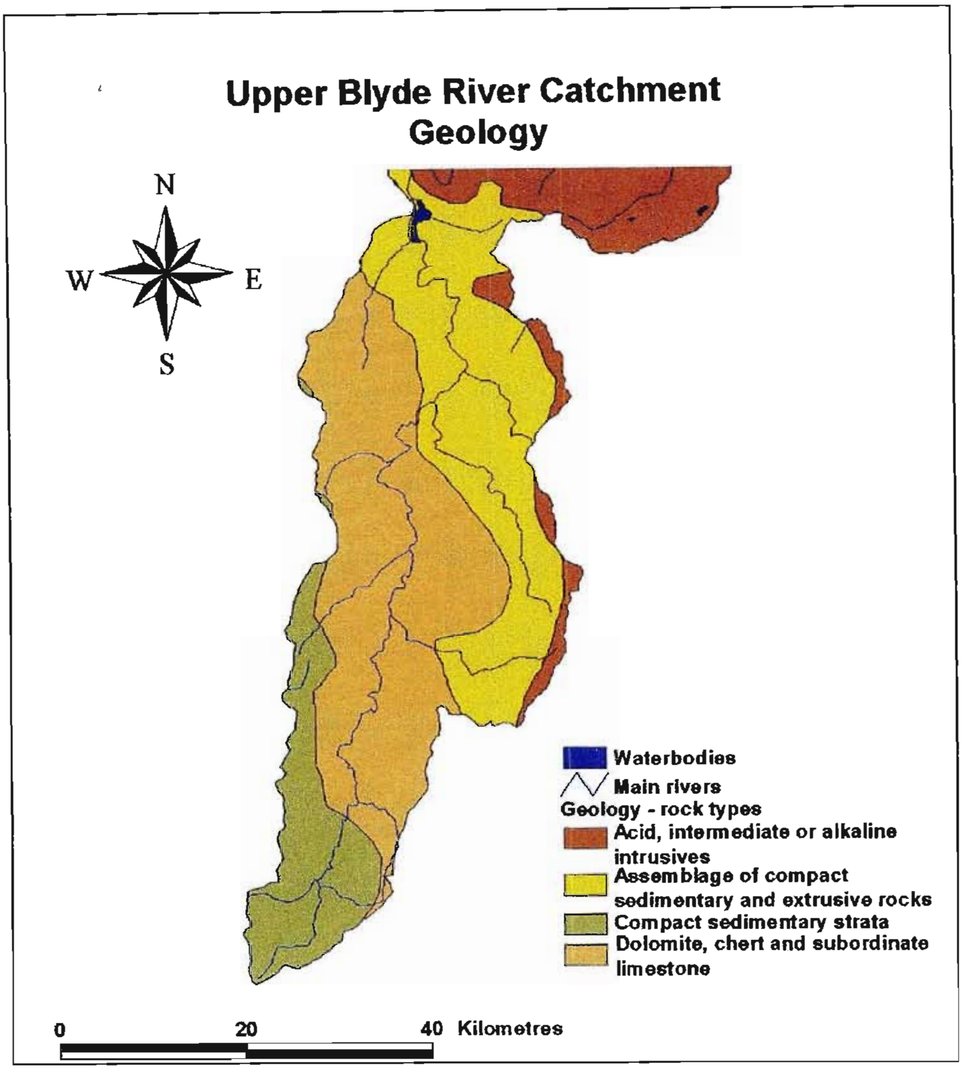


Figure 6.3 The Upper Blyde River catchment geology

The most widespread soil group in the Blyde catchment are those of the Hutton form. These are well-drained, red, apedal soils (DWAF, 1991). In the upper catchment, there are moderate to deep sandy and clay-loam soils, overlying dolomite, limestone and sandstones. Stretches of the Blyde River valley have moderate to deep sandy to clay loam soils; the middle portions of the catchment have moderate to deep clay loam soils overlying porous, unconsolidated sedimentary material; and the lower catchment, dominated by granites and gneisses, has moderately shallow to moderately deep, coarse grained sandy loam to clay rich, fine grained soils (Ashton *et al.*, 2001). The soils map for the Upper Blyde River catchment is derived from the ISCW soils database classified into 84 broad soil zones (Figure 6.4).

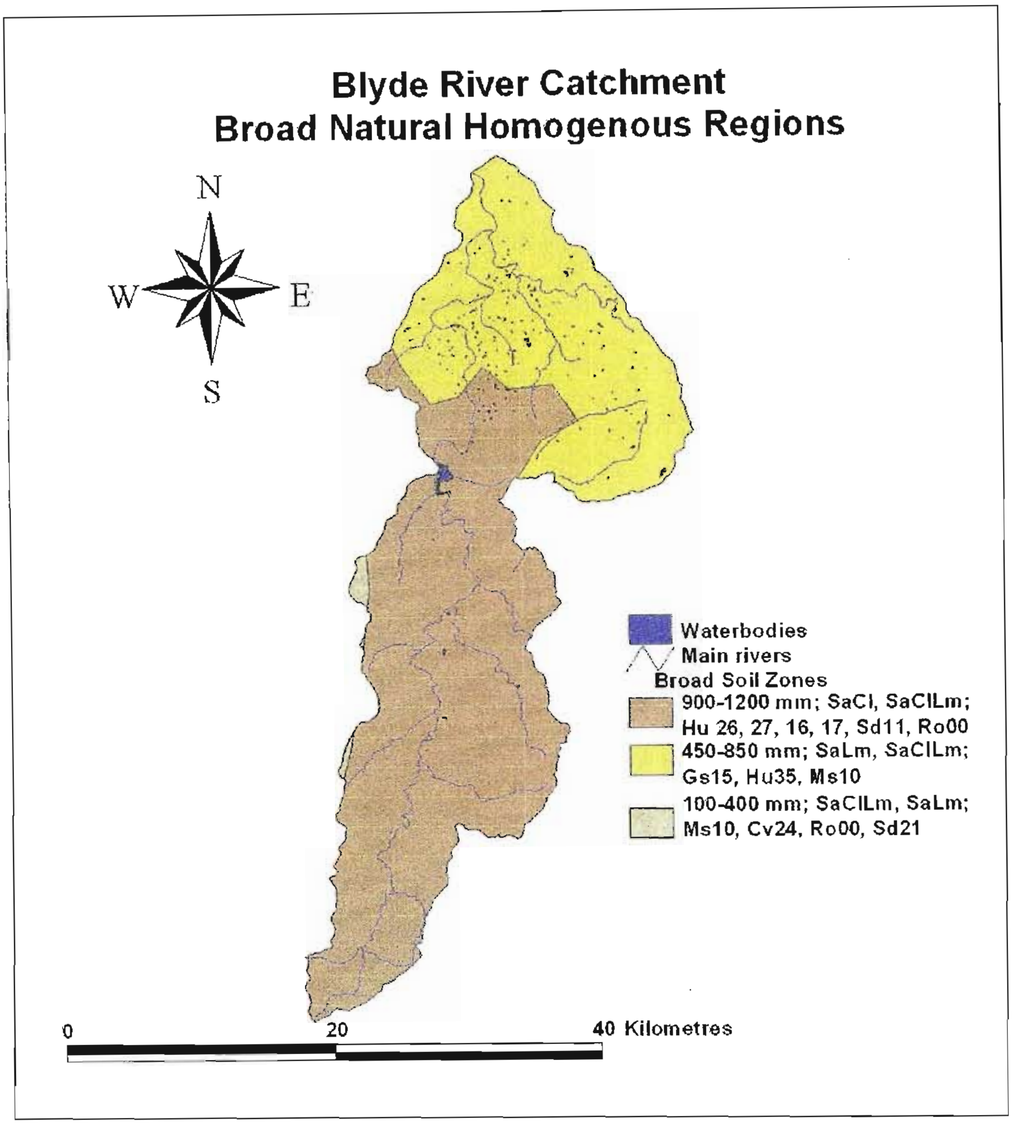


Figure 6.4 ISCW 84 Soil Zones based on Broad Natural Homogenous Regions, as used by Schulze (1997)

6.5 Natural Vegetation and Biodiversity

There are three South African terrestrial biomes represented in the Upper Blyde catchment, these being grassland, forest and savanna. The vegetation is predominantly grassland, but still contains has many savanna and forest species. Grassland and forest patches can also be found in the Lowveld region and on the montane escarpment. The baseline vegetation represented by Acocks' Veld Types (1988; Figure 6.5) shows the most dominant veld type to be North-Eastern Mountain Sourveld, followed by Sourish Mixed Bushveld and Arid Lowveld types.

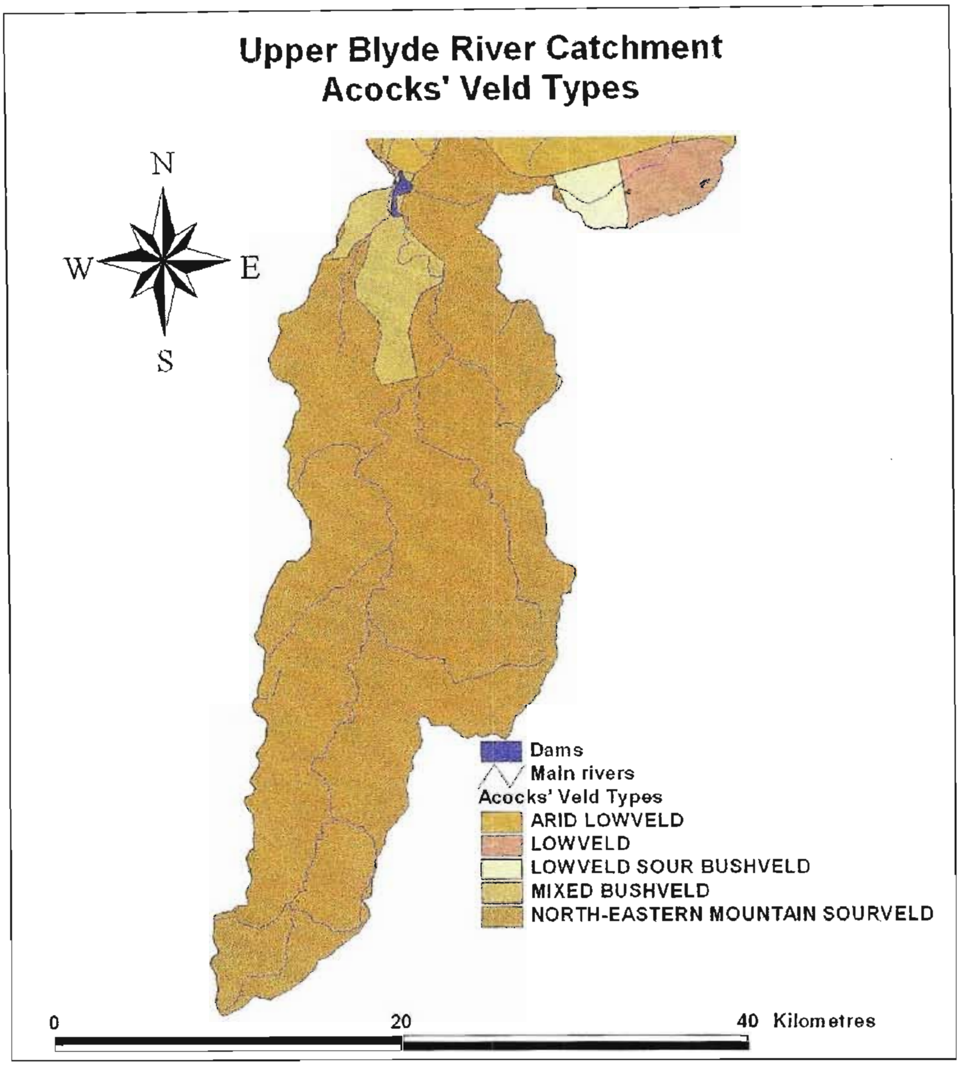


Figure 6.5 Acocks' Veld Types (1988) in the Upper Blyde River Catchment

The area features a high rate of endemism, i.e. species that are unique to the area, which can be attributed to the geological and climatic isolation along the Mpumalanga escarpment with quartzite and dolomite the principal geology types (Mpumalanga Parks Board, 2001). The Wolkberg centre of endemism consists of two sub-units, namely the Serala sub-centre north of Olifants River and Blyde sub-centre in the south (Sekhukhuneland Centre). The Blyde sub-centre has an estimated plant diversity of around 1 800 species, with an estimated 5% rate of endemism. The Blyde River Canyon Nature Reserve is situated on the Mpumalanga Drakensberg Escarpment, featuring the third largest canyon in the world and spanning an area of approximately 30 000 ha. The reserve serves as an important catchment area for downstream users in the Lowveld, Hoedspruit, and in the lower Olifants River supplying the town of Phalaborwa and the Kruger National Park. It has been earmarked for consolidation, together with key catchments in the Central Lowveld region, in a project that aims to sustain one of South Africa's biodiversity "hotspots", *viz.* the Kruger National Park and surrounding nature reserves. Together these will form part of a trans-frontier conservation area known as the Great Limpopo Transfrontier Park (Figure 6.6; Clarke, 2001).

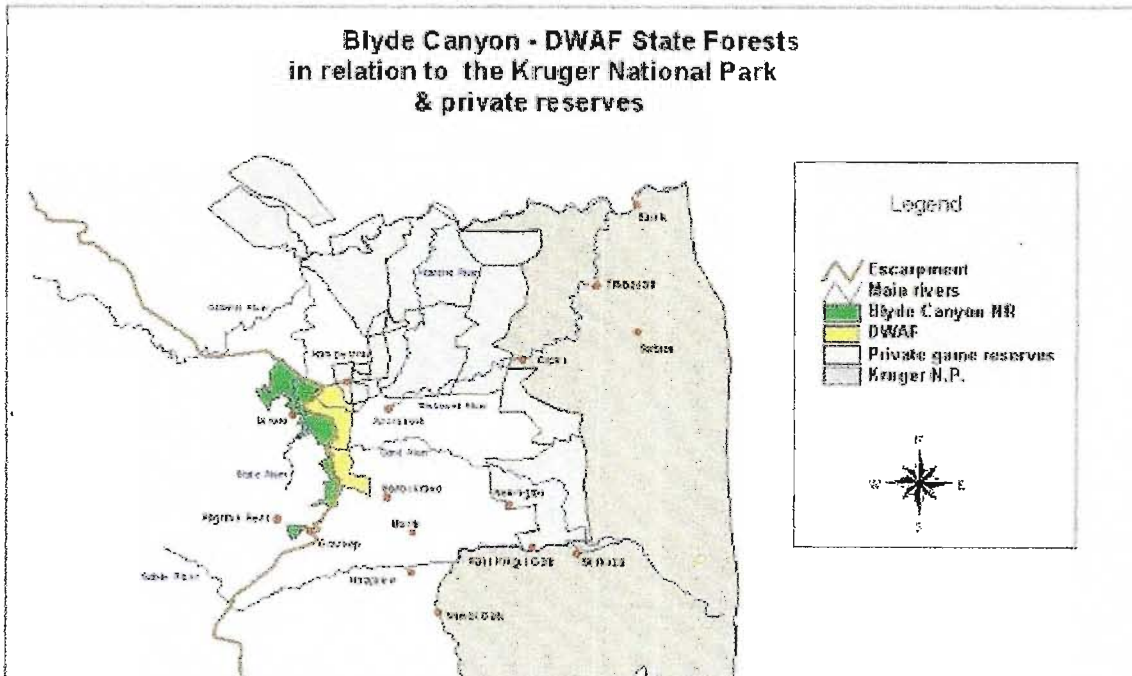


Figure 6.6 Location of the Blyde River Canyon Nature Reserve in relation to the Kruger National Park and private reserves (Clarke, 2001)

A section of the Upper Blyde River was declared a National Heritage Site in 1985 because of the rediscovery of Treur River Barb (*Barbus treurensis*) that disappeared in the 1960s. The Natal Mountain Catfish (*Amphilius natalensis*), also found in this section of the Blyde

River, is one of the only isolated populations in the Limpopo system. The Treur River is also home to the rare Dobson Fly (RHP, 2001).

One of the major threats to biodiversity is land use change such as transformation of grasslands to afforestation. This results in habitat fragmentation, altered grazing patterns and altered burning regimes (CSIR, 2002). The afforested areas in the Blyde region tend to be situated in the high rainfall, mist-belt grasslands that have high biodiversity and provide habitat to endemic and threatened species.

6.6 Present Land and Water Use

The Blyde River catchment is characterised by afforestation, agriculture and conservation activity. Broad land use categories for the upper catchment are derived from the LANDSAT TM (CSIR, 1996) satellite images (Figure 6.7):

- Approximately 67% of the upper catchment is covered by natural vegetation which includes thicket and bushland (168.24 km^2), grassland (358.54 km^2) and forest and woodland (35.55 km^2);
- Commercial forest plantations cover approximately 241.34 km^2;
- Invasive alien plants cover approximately 46.00 km^2 in the upper catchment;
- Agriculture covers approximately 34.74 km^2 comprising 9.49 km^2 irrigated, 10.88 km^2 dryland and 14.36 km^2 subsistence farming;
- The total urban area in the Upper Blyde River catchment is relatively small, constituting only 7.42 km^2 of the total catchment area.

6.6.1 Commercial forest plantations and their secondary industries

Commercial forest plantations (Figure 6.8) cover an area of 241.34 km^2, and are located in the upper catchment of the Blyde River. These plantations were previously owned by the Department of Water Affairs and Forestry (DWAF), but have now been transferred to private companies, four of which operate in the Blyde region, namely Komatiland Forests, Global Forest Products, Mondi and Northern Timbers. Some commercial forestry areas in the Upper Blyde catchment have been earmarked by the DWAF for incorporation into the Kruger National Park and, including adjacent indigenous forests, will be transferred to the

Kruger National Park and, including adjacent indigenous forests, will be transferred to the South African National Parks (SAN Parks) over the next five years (WildNet Africa, 2002). This transition forms part of an integrated conservation plan for the area as a whole, recognising the region as an important catchment area that has high biodiversity.

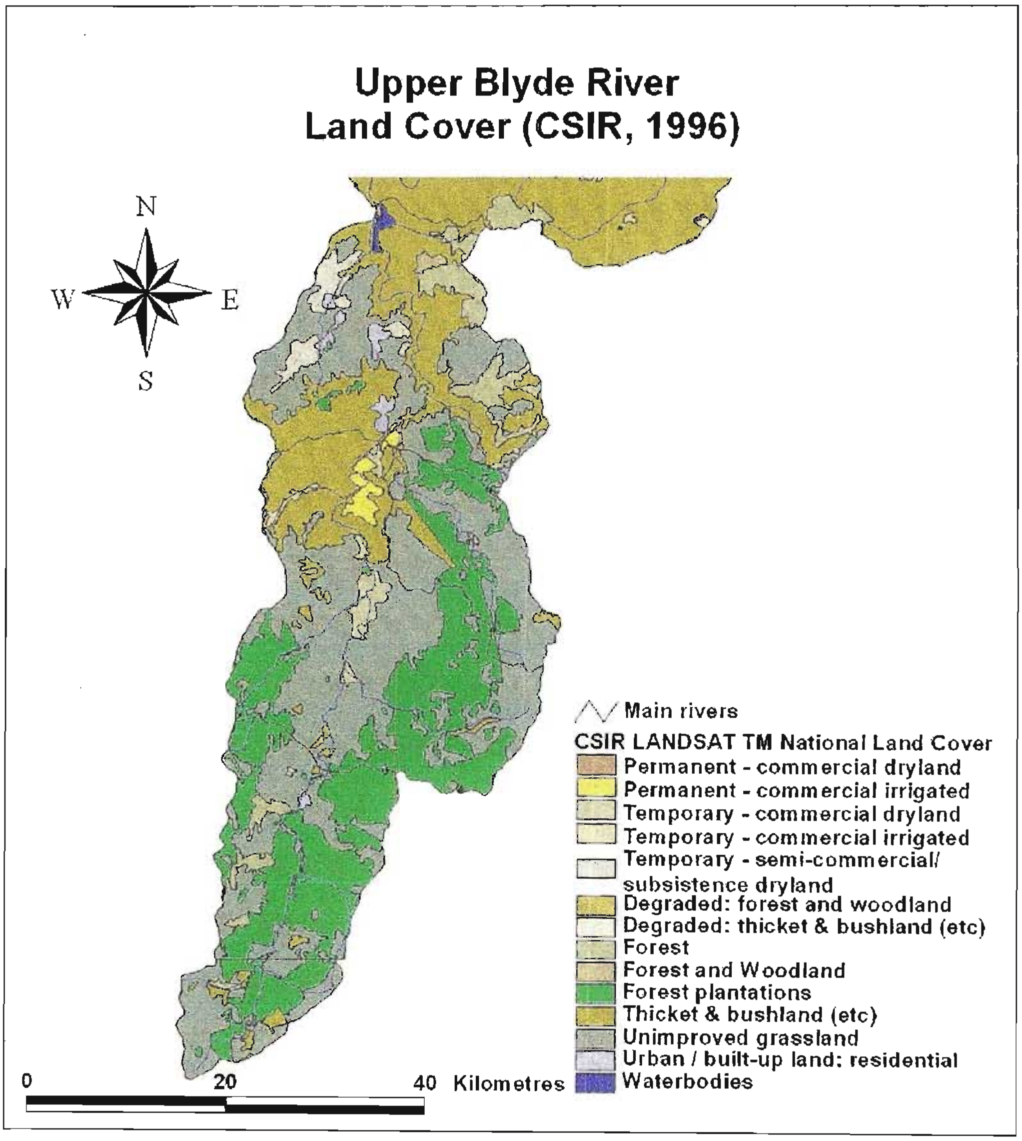


Figure 6.7 Broad land cover categories for the Upper Blyde River catchment (CSIR, 1996)

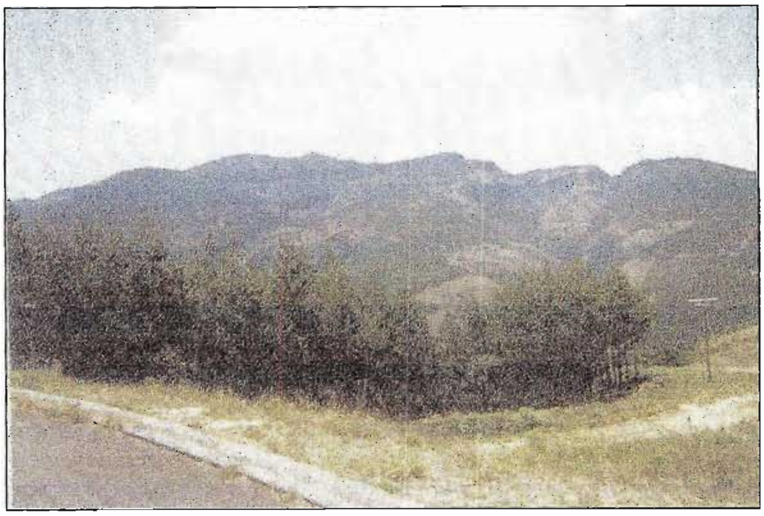


Figure 6.8 Commercial pine forestry above Pilgrim's Rest

In a study carried out in the Blyde catchment area by Ballot and Ashton (1997), the reduction in mean annual runoff (MAR) and mean annual low flow (MALF) for areas under afforestation (*Pinus* and *Eucalyptus* species) was estimated in areas suitable for afforestation versus areas with sub-optimal conditions for afforestation. The results obtained are summarised in Table 6.1. *Pinus* species deemed most suitable to the area were estimated to have a greater impact in the catchment during periods of low flow as compared to *Eucalyptus* species. *Eucalyptus* species had a greater impact during low flow periods in areas with sub-optimal suitability to afforestation. It should be noted however, that large areas of sub-optimally suitable land is planted to Eucalypt species (nearly twice the area of Pine species planted to sub-optimally suitable land) and that nearly 10 times the land is expected to be available for pines as for eucalypts. It is clear that the impacts on streamflow are most severe during periods of low flow and in areas that are sub-optimally suited to afforestation.

In addition to streamflow reduction, afforestation practices may produce sediment from erosion which causes siltation of watercourses resulting in reduced water quality. Secondary afforestation industries such as sawmilling can have additional negative impacts on the surrounding ecosystems, specifically riparian zones, when sawdust is washed into the river during rain events. Sawdust has an acidifying effect on the soils and water, as well as smothering vegetation and in-stream habitats, decreasing habitat health and diversity (Ballot and Ashton, 1997).

Table 6.1 Reduction in MAR and MALF by afforesting suitable and sub-optimal land areas (Adapted from Ballot and Ashton, 1997)

Blyde Catchment (B60)	MAR (mm)	MALF (mm)	Pines (ha) Suitable	Eucalypts (ha) Suitable	Pines (ha) Sub-optimal area	Eucalypts (ha) Sub-optimal area
	2163.1	151.79	54259	4584	42800	79224
Reduction in MAR			573.26	20.73	121.61	340.64
Reduction in low flow			62.581	2.115	18.15	67.40
% reduction of MAR			26.50%	0.958%	5.62%	15.75%
% reduction of low flow			41.23%	1.39%	12.00%	44.40%

6.6.2 Invasive alien plants

Estimates of the extent of IAPs are approximately 46 km^2 and 94 km^2 in the upper catchment and lower catchment respectively (Figure 6.9). In the upper catchment this equates to approximately 5% infestation of the total area at varying density. Based on techniques described in Section 5.1.1, the riparian zone is estimated to cover nearly 10% of the catchment area, 17% of which is infested to varying degrees of density. The most predominant invasive species in terms of their extent are *Pinus, Lantana, Rubus,* and *Acacia.* Plants from these species are considered a threat to the natural systems and biodiversity in the area, especially in wetlands and riparian zones. The Working for Wetlands project has launched a rehabilitation programme that, in addition to removing IAPs, aim to restore wetlands by putting structures in place that help stop erosion and trap sediment. Current WfW projects in the Blyde River catchment aim to clear all IAPs from the top of the catchment to the bottom (Ross, 2003, personal communication). The Blyde River gorge has been cleared of wattles and pines, reportedly having a positive impact on streamflow and water quality for downstream users (RHP, 2001). Table 6.2 shows the extent and density of tree and shrub invasions in the Upper Blyde River catchment according to the classification procedure described in Chapter 5.

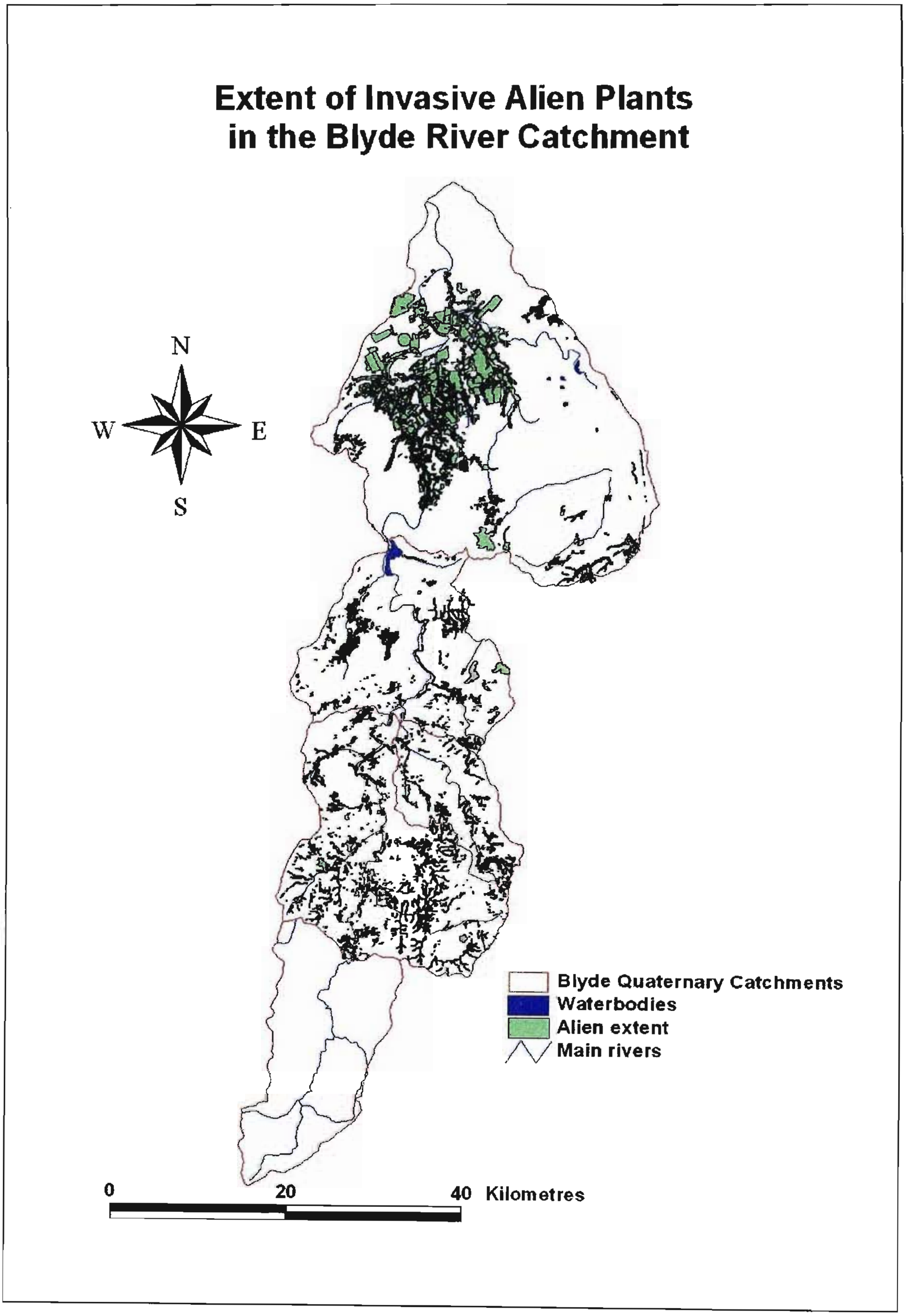


Figure 6.9 Extent of IAPs in the Blyde River Catchment (WfW, 2002)

Table 6.2 Extent and density of invasive trees and shrubs (non-woody plants) in the Upper Blyde River catchment (WfW, 2002)

Genus	Common name	Total area (km^2)	Density		
	TREES		**Sparse**	**Medium**	**Dense**
Acacia spp	Wattle	5.192	4.191	0.989	0.012
Eucalyptus	Gum	2.957	0.936	1.108	0.913
Jacaranda	Jacaranda	0.006		0.005	0.001
Pinus	Pine	18.087	9.188	4.495	4.404
Populus	Poplar	0.198	0.153	0.04	0.005
Psidium	Guava	0.042	0.042		
Quercus	Oak	0.006		0.006	
Salix	Willow	0.061	0.033	0.025	0.003
	TOTAL TREES	**26.549**	**14.543**	**6.668**	**5.338**
	SHRUBS		**Sparse**	**Medium**	**Dense**
Agave	Sisal	0.002	0.002		
Arundo	Giant reed	0.233	0.215	0.014	0.004
Cirsium	Thistle	0.064	0.064		
Lantana	Lantana	0.361	0.359		0.002
	Residential Mix	6.211	6.066	0.13	0.015
Ricinus	Castor-oil plant	0.035	0.035		
Rubus	Bramble	10.77	10.649	0.109	0.012
Solanum	Bugweed	1.722	1.638	0.083	0.001
	TOTAL SHRUBS	**19.398**	**19.028**	**0.336**	**0.034**

6.6.3 Agriculture and irrigation

Semi-commercial subsistence agriculture (14.36 km^2), dryland agriculture (10.88 km^2) and commercial irrigated agriculture (9.49 km^2) make up the agricultural sector (34.74 km^2) in the Upper Blyde River catchment. The main agricultural crops are mangoes (55%) and citrus (35%). The remaining 10% of cultivated land made up mainly of cash crops (Swart *et al.*, 1997). The Blyde River Irrigation District (BRID; Figure 6.10) in the Lower Blyde River catchment extends over an area of 424 km^2 (42 366 ha) of which 81.53 km^2 (8 153 ha) have water rights from the Blyde River (Swart *et al.*, 1997). The area is served by a newly constructed pipeline that has replaced a canal system that supplied water from the dam for irrigation purposes. The Blyderivierspoort Dam supplies irrigation for 83.76 km^2 (8 376 ha) of cultivated land at an allocation of 9 980 $m^3.ha^{-1}.yr^{-1}$ (Ravenhill, 2003, personal communication). Downstream water users include agricultural land under irrigation, the Phalaborwa Water Board for the town and mining, as well as primary supply to the town of Hoedspruit and its surroundings, and finally to the Blyde River. Pollution agrochemicals is a potential problem as well as increased erosion and sedimentation after clearing land of fruit trees (RHP, 2001).

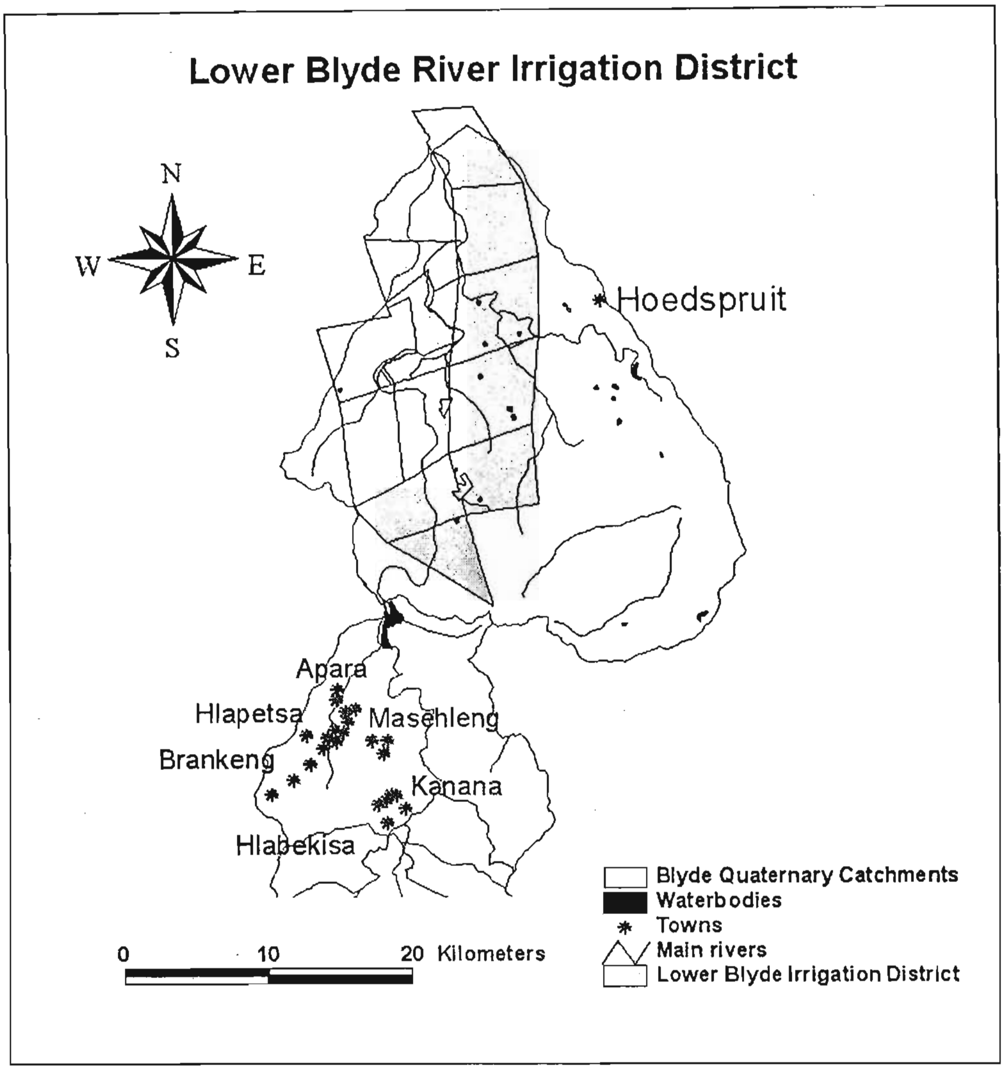


Figure 6.10 The Lower Blyde River Irrigation District

6.6.4 Wetlands and Riparian Zones

Wetlands and riparian zones are vulnerable yet important ecosystem components and are under threat due to agricultural pollution (fertilizers and pesticides), afforestation (sedimentation), mining activities (toxicity and contamination by chemical pollutants) and invading alien plants. Small-scale gold and sand mining operations have damaged more that 60 ha of wetland area in the Blyde catchment. Forestry, agriculture and urban development activities have also contributed to impacted wetlands by 43% (CSIR, 2002).

species have a high impact on the wetland water storage function as well as reducing the overall habitat value of the wetland.

6.6.5 Domestic, urban and mining

Large areas of the Blyde catchment used to be part of the former homeland of Lebowa and, as a result, have large rural populations. Several informal settlements with subsistence farming and low service levels exist and as a consequence of limited access to tap water and sanitation services, rural communities make use of rivers and streams for their basic water supply. This results in increased surface pollution and a high risk for water-borne diseases. The main towns in the region are Hoedspruit, Pilgrim's Rest, Ohrigstad, Sabie and Graskop. There is a large rural community in the region just above the Blyderivierspoort Dam (Figure 6.2) on the Kadisi River. There are five municipal areas in the catchment, the largest being Thaba Chweu, then Drakensberg, Bushbuckridge, MPDAMP32 and Greater Tubatse. The Phalaborwa Water Board is entitled to $50x10^6$ m^3 per annum for water supply to the township and mines at Phalaborwa. There are few operational mines left in the Blyde catchment, therefore their impact may only be localised. The Transvaal Gold Mining Enterprises (TGME) mine in Pilgrim's Rest abstracts water directly from the Upper Blyde River (Figure 6.11) for its operations at an average rate of 193 m^3 per day on a monthly basis, i.e. 5 790 m^3 per month, and does not release any wastewater back to the river (Baskis, 2003, personal communication).

Figure 6.11 Abstraction of water from the Blyde River for the TGME mine at Pilgrim's Rest

6.7 Water Resource Issues in the Catchment

The Blyde River catchment land use and hydrology is governed largely by its topography. Large areas of the catchment are undeveloped and unsuitable for land use practices such as afforestation, agriculture or urban development. The catchment has high rainfall and runoff which makes a substantial contribution to the Olifants River downstream. Current water users in the Blyde catchment include commercial forest plantations; domestic, industrial and mining use; irrigation abstractions; stock watering and the environmental reserve (Theron *et al.*, 1991). The upper catchment (above the Blyderivierspoort Dam) currently supports commercial afforestation extending from Pilgrim's Rest to Graskop on the eastern side. Much of the area is mountainous and not suitable for development. The Blyderivierspoort Dam is located in the Blyderivierspoort Nature Reserve, characterised by mountainous terrain and indigenous vegetation. It falls under the jurisdiction of the Mpumalanga Parks Board. The dam supplies irrigation for 8 376 ha of cultivated land downstream. The lower catchment (area below the Blyderivierspoort dam) is governed by the Lower Blyde Water Users Association and serves the Blyde River Irrigation District (BRID). The water distribution network was recently upgraded from a canal system to a pipe network that makes a much more efficient delivery of water to the farmers in the irrigation district. The Phalaborwa Water Board is also entitled to water from the dam for supply to the township and mines. In a move to implement economic development programmes, the Limpopo Province has implemented a spatial development initiative (SDI) which has approved the establishment of the Blyde River Sugar Project that will incorporate production and refining facilities. "This project will empower more than 50 small-scale producers and create in excess of 5 000 employment opportunities in the primary sector and a further 250 at the envisaged sugar mill. According to projections, this development can generate annual export earnings in excess of 30 million US dollars" (Ramatlhodi, 2002).

The main concern, therefore, is the sustainable and integrated management of hydrological and environmental resources in the upper catchment, so that the activities in the lower catchment can be maintained and development needs met. The distribution of water from the Blyde River extends downstream of the Blyderivierspoort Dam to the BRID and

Hoedspruit town, to the mining and industrial complex at Phalaborwa and then into the Kruger National Park and finally into Mozambique. The BRID has highly developed infrastructure, farming enterprises and associated business activities, and the crops grown in the region have an average annual value of approximately R 50 000 000 (Ballot and Ashton, 1997). The Blyde River has become a critical resource due to the over-exploitation of the Olifants River. The socio-economic activity in the Lower Blyde and Olifants River region is directly dependent on the Blyde River water resources, yet people who live in the area have little or no influence on development or activities taking place in the catchment. The catchment straddles the Mpumalanga and Limpopo Provinces. This means that economic activity in the lower catchment being controlled by Limpopo Province, and the basic resources on which development is dependent are controlled by Mpumalanga. Potential threats to the upper catchment include the impacts of informal settlements, uncontrolled development, tourist activity, inappropriate farming methods and uncontrolled land use change resulting in erosion and environmental degradation, in addition to the spread of IAPs.

The aforementioned activities require monitoring and control in order to ensure that sustainable development projects are viable downstream of the dam because the socio-economic activity in the area has widespread influence and consequently, any change in the upper catchment areas, be it political, social or natural, has an effect on the river flow and thus the sustainable supply of water to the BRID.

Therefore, in the consideration of competing demands on water resources in the Upper Blyde River catchment, such as those highlighted above, IAPs may exacerbate an already stressed system, and the role of tools such as SEA (Section 2.1.1) will be particularly useful in the decision making process. This issue is discussed in more detail in Chapter 9.

7. METHODOLOGY

This chapter presents the application of the *ACRU* model in the Upper Blyde River catchment, providing relevant information required as input for simulation of streamflows. This study used *ACRU* Version 3.31. The model was operated in distributed mode, generating output for different land uses in the catchment with varying levels of information. According to this approach, a catchment is subdivided into sub-catchments and land use based response units. Sub-catchments are subdivided according to *inter alia*, land use or vegetation type, soils and hydrological information using topographical maps as a basis to define the sub-catchment boundary (Schulze *et al.*, 1995b). As a further subdivision, a sub-sub-catchment or hydrological response unit (HRU) can be used to define a homogenous unit representing unique land use or vegetation cover in a sub-catchment. This methodology can be used to assess the impacts of change in land use at the catchment scale and is described further in Section 7.2.4.

7.1 Delimitation and Hydrological Configuration of the Upper Blyde River Catchment

The Blyde River catchment (B60) has been subdivided into nine Quaternary Catchments (QCs) by DWAF. Five of these cover the eastern portion of the catchment on the Blyde River above the Blyderivierspoort Dam. The identification and further subdivision of these five QCs was the first step in configuring the *ACRU* modelling system. The 1:50 000 topographical mapsheets provided by the Chief Directorate of Surveys and Mapping were used as a basis for delimitation, using natural watersheds and topography as sub-catchment boundaries. Additional criteria for delimitation of sub-catchments in the Blyde River catchment included:

- Weirs and gauging stations (at the outlet of a sub-catchment);
- Impoundments (at the outlet of a sub-catchment);
- Land cover;
- Coverages of invasive alien plants (IAPs).

The upper catchment was delineated into 17 sub-catchments (Figure 7.1) with areas ranging from 4.60 km^2 to 86.08 km^2. The area of each sub-catchment was calculated in a

GIS and was numbered in sequential order from the source to the mouth for the purposes of representing the flow routing pattern of the catchment (Figure 7.2). The *ACRU* model was configured for the Upper Blyde River catchment to simulate streamflows for a 40 year period from 1960-2000 for which rainfall data are available. Simulated results were compared to observed data where possible in order to verify the simulation results.

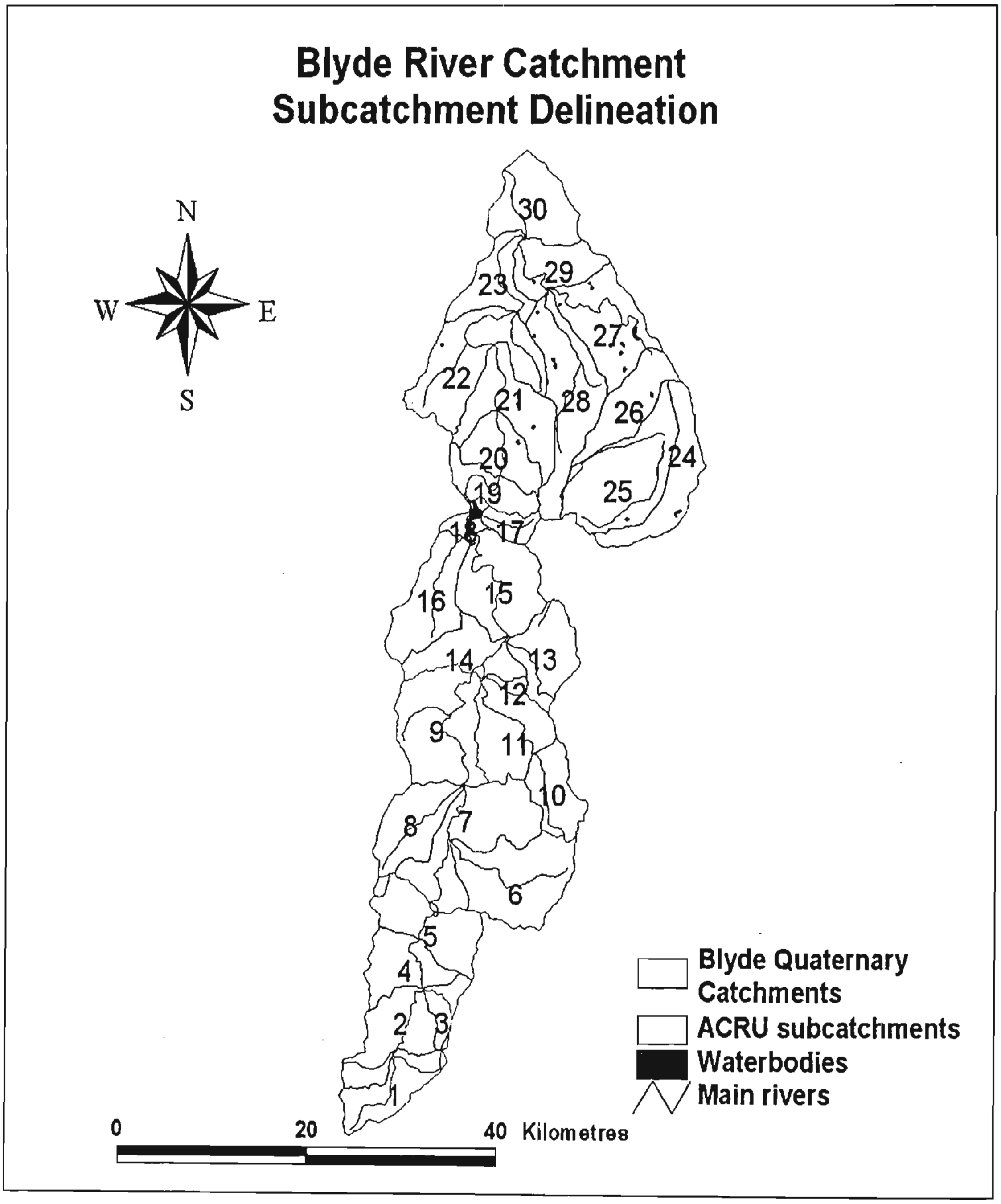


Figure 7.1 Blyde River catchment sub-catchment delineation

7. 2 Model Input

Model inputs and data requirements, as well as a summary of the *ACRU* model, were presented in Chapter 4 (Figure 4.1). Data for the Blyde River catchment were obtained from different sources and was compiled and converted into appropriate formats of hydrological variables for the *ACRU* model as described in the following sections. Input to the model is facilitated with the use of a set of utilities designed for the purpose of converting data and information into hydrological variables for the *ACRU* model. Apart from input time series of rainfall and streamflow, all other parameters are stored within an input file known as the "menu". The user typically interacts with the menu through a *Menubuilder.*

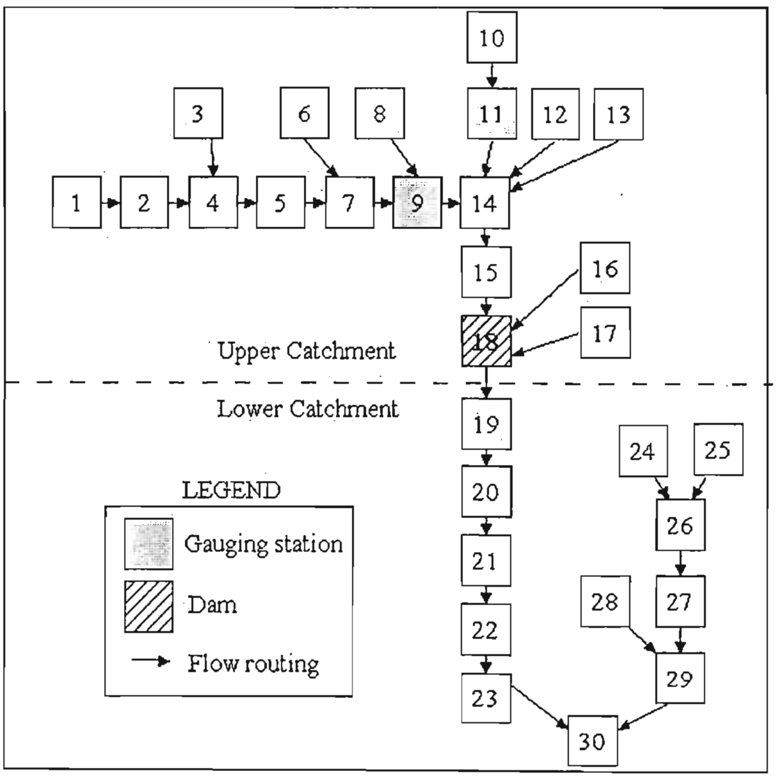


Figure 7.2 Sub-catchment configuration and flow routing

7.2.1 Rainfall

Hydrological processes are driven by rainfall. Streamflow response is highly sensitive to rainfall input and when modelling this response, one has to consider several influential factors including rainfall variability, rainfall estimation, spatial and temporal distribution and missing records (Schulze *et al.*, 1995c). It is therefore important to select appropriate rainfall "driver" stations for a study catchment so that they represent both the spatial and temporal distribution of catchment rainfall as realistically as possible. A rainfall driver station is a rainfall station that is selected to be the most representative of rainfall in a catchment or sub-catchment, therefore "driving" its hydrological response. Catchment and rainfall station altitude and MAP must be comparable, and the driver station is therefore selected on the basis of its location, altitude and length of record. A utility used in the *ACRU* modelling system known as *CalcPPTCor* helps the user in the process of selecting the most representative rainfall driver stations for the catchment in question. This procedure requires input information of:

- Altitude, MAP and median monthly rainfall for each rainfall station in the region,
- Average altitude, MAP and median monthly rainfall surface for each sub-catchment using the *ACRU* Grid Extractor (Lynch, 2001).

The *CalcPPTCor* utility selects the most appropriate rainfall stations based on input specifications of minimum length of record and distance of rainfall station from the centroid of the sub-catchment. A monthly precipitation adjustment factor (CORPPT) is calculated for each sub-catchment, i.e. the ratio between estimated catchment median monthly rainfall and station median monthly rainfall. This adjustment is applied to each recorded rainfall value (either daily or monthly variation for daily data) from the driver station to ensure that topographical and/or climatological influences which may be operative in the catchment are minimised so that the resulting data are a fair representation of the rainfall received by the catchment as a whole (Pike, 2001). Catchment median monthly rainfall is estimated from a one by one minute of a degree grid of median monthly precipitation (Schulze, 1997) available in the School of BEEH. In addition to these correction factors, *CalcPPTCor* also includes the following output:

- Length of record;
- Average MAP (station and catchment);
- Average altitude (station and catchment);
- Distance of each station from the centroid of the catchment;
- A score of representivity for each station (rank 1 being the most representative according to the input criteria).

Rainfall information was obtained from the rainfall database at the School of BEEH at the University of Natal. Sixty rainfall stations were identified in and around the Blyde catchment area, from which a driver station for each sub-catchment was selected on the basis of:

- Threshold distance of 10 km from the centre of the sub-catchment (centroid) to limit rainfall stations in output;
- The DRY season extends from May to September (during this season the rainfall station is not penalised for correction factors which are outside of the range of 0.80 - 1.20);
- Rainfall stations with more than 1 month with CORPPT values out of the range of 0.80 - 1.20 during the WET SEASON have not been included;
- Central meridian of 31 degrees used in distance calculations;
- All stations in this output have a record length of 10 years or more;
- All stations have an end year of 1993 or more recent.

Verification of the driver stations selected by *CalcPPTCor* was made by checking those stations ranked first against coverage of rainfall stations, the sub-catchment boundaries and contours. Some of the stations ranked as representative by the programme were not considered suitable when checked against a map and a more suitable station was selected. The location of the driver stations in each sub-catchment are shown in Figure 7.3 and listed in Table 7.1.

7.2.2 Potential evaporation and temperature

Mean monthly A-pan and monthly means of daily temperature data are used to derive reference potential evaporation and thus drive the model's evaporative processes. Gridded images at a resolution of one by one minute of a degree latitude/longitude of mean monthly A-pan data, median monthly maximum and minimum temperatures, and daily maximum and minimum temperature data have been developed by the School of BEEH at the University of Natal (Schulze, 1997). Catchment values for these parameters are extracted using the *ACRU* Grid Extractor tool (Lynch, 2001), an extension which is loaded in ArcView (ESRI, 1998). The relevant catchment information is clipped from a grid and the summary statistics for each parameter for each sub-catchment are output. This file is then converted to a format that can be used as input to the *ACRU* Menubuilder.

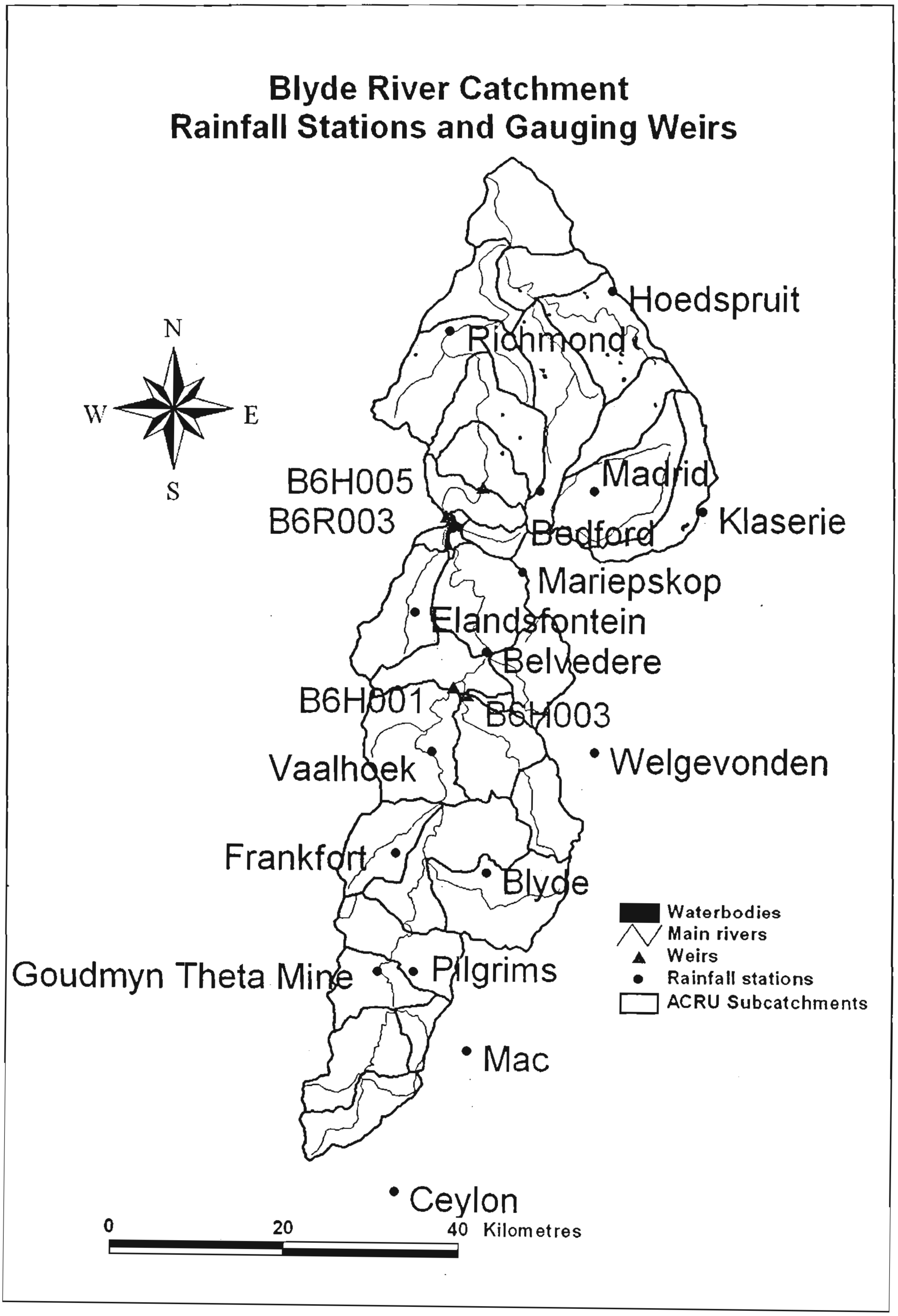


Figure 7.3 Rainfall and streamflow gauging stations in the Blyde River Catchment

Table7.1 Rainfall drivers for the 30 sub-catchments of the Blyde River Catchment.

Sub-catchment	Altitude (m)	MAP (mm)	SAWB Station No.	Station Name	Lat (°,')	Long (°,')
1	1757.3	1349.5	0555455 W	CEYLON	25.06	30.45
2	1690.8	1225.8	0594415 W	GOUDMYN THETA MINE	24.55	30.44
3	1533.8	1414.2	0594539 W	MAC	24.59	30.49
4	1602.7	1117.2	0594415 W	GOUDMYN THETA MINE	24.55	30.44
5	1532.9	1125.8	0594444 W	PILGRIMS	24.55	30.46
6	1484.5	1359.0	0594590 W	BLYDE	24.50	30.50
7	1391.8	1035.4	0594590 W	BLYDE	24.50	30.50
8	1542.1	967.2	0594379 W	FRANKFORT	24.49	30.45
9	1326.8	778.7	0594494 W	VAALHOEK	24.44	30.47
10	1587.8	1487.8	0594764 W	WELGEVONDEN	24.44	30.56
11	1386.0	1077.9	0594590 W	BLYDE	24.50	30.50
12	1349.4	1057.0	0594590 W	BLYDE	24.50	30.50
13	1500.7	1418.3	0594635 W	MARIEPSKOP	24.35	30.52
14	1329.9	892.3	0594609 W	BELVEDERE	24.39	30.50
15	1219.5	936.5	0594609 W	BELVEDERE	24.39	30.50
16	1319.9	805.1	0594457 W	ELANDSFONTEIN	24.37	30.46
17	1249.1	1114.6	0594635 W	MARIEPSKOP	24.35	30.52
18	923.4	847.0	0637720 W	BEDFORD	24.31	30.53
19	957.4	1084.1	0637720 W	BEDFORD	24.31	30.53
20	753.7	770.3	0637720 W	BEDFORD	24.31	30.53
21	648.0	666.8	0594781 W	MADRID	24.31	30.56
22	668.0	668.4	0637720 W	BEDFORD	24.31	30.53
23	500.0	452.3	0637503 W	RICHMOND	24.23	30.48
24	607.5	602.5	0595032 W	KLASERIE	24.32	31.02
25	694.7	708.5	0594781 W	MADRID	24.31	30.56
26	591.3	550.6	0637801 W	HOEDSPRUIT	24.21	30.57
27	535.2	483.4	0637801 W	HOEDSPRUIT	24.21	30.57
28	662.3	597.4	0594781 W	MADRID	24.31	30.56
29	514.5	456.2	0637801 W	HOEDSPRUIT	24.21	30.57
30	487.6	430.2	0637609 W	INYOKO	24.08	30.52

7.2.3 Soils information

Soils form the interface for many catchment hydrological processes, controlling infiltration of precipitation, storage of water for plant use and redistribution of water by evaporation, transpiration and drainage processes through the soil profile. *ACRU* operates with a surface layer and two soil horizons through which the above-mentioned hydrological processes are simulated (Schulze *et al.*, 1995d). The source for soils information in this study is the Institute of Soil, Climate and Water's (ISCW) 84 Broad Natural Homogenous Soil Zones, which have been deemed suitable for hydrological comparative studies at the regional level

(Schulze, 1997). Soils information for the Blyde River Catchment was "clipped" from the ISCW database for the *ACRU* sub-catchments GIS coverage (Figure 6.3) and the *ACRU* variables for each sub-catchment were calculated. The following soils information are utilised in the *ACRU* model (Smithers and Schulze, 1995a):

- Thickness of topsoil of soil profile (m) (DEPAHO);
- Thickness of subsoil of soil profile (m) (DEPBHO);
- Soil water content at permanent wilting point for topsoil ($m.m^{-1}$)(WP1);
- Soil water content at permanent wilting point for subsoil ($m.m^{-1}$) (WP2);
- Soil water content at drained upper limit for topsoil ($m.m^{-1}$) (FC1);
- Soil water content at drained upper limit for subsoil ($m.m^{-1}$)(FC2);
- Soil water content at saturation for topsoil ($m.m^{-1}$) (PO1);
- Soil water content at saturation for subsoil ($m.m^{-1}$) (PO2);
- Fraction of "saturated' soil water to be redistributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit (ABRESP);
- Fraction of "saturated' soil water to be redistributed daily from the subsoil into the intermediate/groundwater store when the subsoil is above its drained upper limit (BFRESP).

These variables are used in the *ACRU* soil water budgeting routine which operates with a surface layer and two soil horizons in which rooting development, evaporation and transpiration, soil water uptake and drainage occur (Schulze *et al.*, 1995a). These are important variables in terms of modelling catchment hydrological response specifically with regard to streamflow generation *viz.*, stormflow and baseflow.

7.2.4 Land cover information

Land cover influences interception and infiltration, as well as evaporation, and transpiration rates of soil water from the soil (Chapter 3). Therefore inputs to *ACRU* account for these components of the hydrological cycle by including:

- An interception loss value (VEGINT) that accounts for the estimated interception of rainfall by the plant canopy on a given day;

- A monthly water use coefficient ("crop" coefficient; CAY) representing the ratio between vegetative water use and evaporation relative to a reference potential evaporation;
- A fraction of plant roots that are actively extracting soil moisture from the topsoil horizon in a given month (ROOTA);
- A coefficient of initial abstraction (COIAM) that provides for the influence of vegetation, soil surface and climate on stormflow generation. This variable may change on a monthly/seasonal basis.

Land use under present conditions is represented by the national LANDSAT TM coverage for South Africa (CSIR, 1996) and the coverages of IAPs (WfW, 2002), which were used to determine land cover for each sub-catchment in the study area. The coverage of IAPs (WfW, 2002) for the catchment was used to obtain the extent of IAPs in the Upper Blyde River catchment and the classification system explained in Chapter 5 was applied. The digital boundaries of the 30 sub-catchments was overlaid onto the 1996 LANDSAT TM land cover coverage (CSIR, 1996) to obtain the area of each land use in each sub-catchment. The 15 land use categories identified from the LANDSAT TM coverage in the Upper Blyde River catchment were re-classified into 5 broad classes, or hydrological response units (HRUs), as discussed in Section 7.1, according to their typical hydrological responses (Table 7.2).

The hydrological attributes, *viz.* water use coefficient (CAY), interception loss (VEGINT), fraction of roots in A-horizon (ROOTA) and coefficient of initial abstraction (COIAM) were derived for present land use and IAPs based on the COMPOVEG database and derived values of hydrological characteristics in consultation with technical experts at the School of BEEH. The monthly hydrological variables and attributes used for each land use category in the *ACRU* model are shown in Table 7.3 and Table 7.4. The following assumptions were made for the hydrological attributes in the following HRUs:

- Grass and thicket: assumed to be natural vegetation and values were assigned from Acocks' North Eastern Mountain Sourveld;
- Agriculture: dryland, irrigated and subsistence farming lumped together as irrigated mango and citrus;

- Commercial plantations: intermediate age pine, intermediate site preparation, depth of the B-horizon was increased by 0.25 m according to *ACRU* guidelines;
- Dense invasive alien trees: assumed to be 90% pine and 10% natural vegetation;
- Medium invasive alien trees: assumed to be 50% pine and 50% natural vegetation
- Sparse invasive alien trees: assumed to be 20% pine and 80% natural vegetation
- Dense invasive alien shrubs: assumed to be 90% scrub and 10% natural vegetation
- Medium invasive alien shrubs: assumed to be 50% scrub and 50% natural vegetation
- Sparse invasive alien shrubs: assumed to be 20% scrub and 80% natural vegetation
- Riparian zone: designated a unique vegetation type in each scenario.

Table 7.2 *ACRU* Hydrological Response Units: Blyde River catchment

***ACRU* Hydrological Response Units**	**LANDSAT TM 1996 land use categories**
Natural vegetation: Grassland and thicket	Unimproved grassland Thicket and bushland Degraded thicket and bushland Urban/built-up land: residential
Natural vegetation: Indigenous forests	Forest Forest and Woodland Degraded: forest Degraded: forest and woodland
Agriculture: Mango and Citrus	Cultivated: permanent-commercial dryland Cultivated: temporary-commercial dryland Cultivated: temporary- semi-commercial/subsistence Cultivated: permanent-commercial irrigated Cultivated: temporary-commercial irrigated
Commercial plantations	Forest plantations
Invasive alien plants: Sparse trees Medium trees Dense trees Sparse shrubs Medium shrubs Dense shrubs	Not identified in LANDSAT categories Working for Water coverages
River channel: Riparian zone	Not identified in LANDSAT categories
Dams	Water bodies

A utility called *CreatemenufromGIS* is used to create a menu that includes each hydrological response (land use) unit (HRU) present in each sub-catchment. Therefore, the *ACRU* menu for the initial 30 sub-catchments for the Blyde River catchment (Figure 7.1) was expanded to a menu containing between 137 and 265 HRUs dependent on the land use scenario applied. As input, the utility requires the original *ACRU* menu (30 sub-catchments), a file containing vegetation information i.e. CAY, VEGINT, ROOTA and COIAM for each hydrological response unit and the GIS intersection file that contains areas each land use per sub-catchment. Thus, the unique hydrological response of each HRU in each sub-catchment is simulated separately before being accumulated as generated runoff for each sub-catchment (Figure 7.4). Once this menu has been expanded it can be used to run the *ACRU* model. If a category is not represented in a sub-catchment, it was not included as part of the subset for that particular sub-catchment. The resultant modelling system had a total of 265 linked HRUs. This further subdivision enables modelling of hydrological responses of different land uses as separate units and scenarios of change can be undertaken with relative ease. The results obtained from using this method are more hydrologically correct than simply area-weighting land use and obtaining one runoff answer, as discussed in Section 4.2 (Horan *et al.*, 2000). For the purposes of assessing the impacts of IAPs in this study, the riparian zone is considered as a separate HRU.

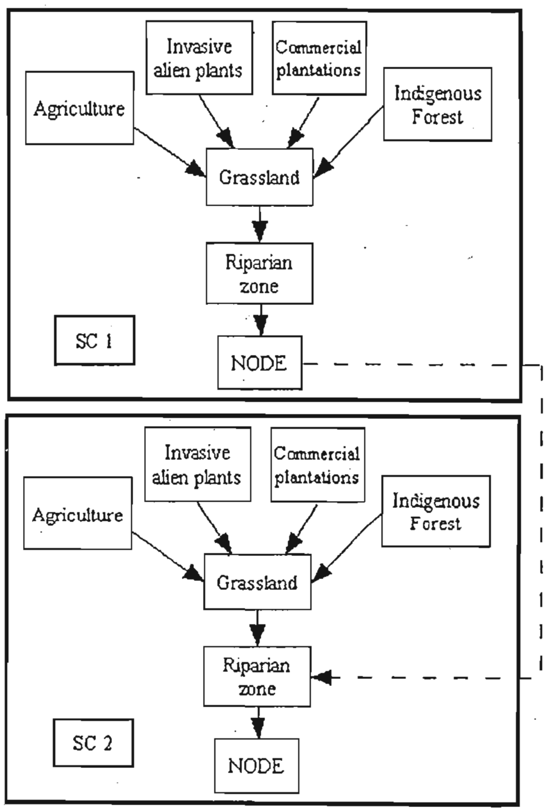


Figure 7.4 Sub-sub-catchment configuration of upstream sub-catchment contributions and routing of hydrological response units within sub-catchments.

In order to be able to determine the impact of changes in land use, one has to make a comparison against the natural, baseline, conditions of a site. This approach uses the Acocks' (1988) Veld Types (Figure 6.5) as the baseline vegetation representation. The sub-catchment boundaries for the Blyde River catchment were overlaid onto the Acocks' Veld Types coverage to determine the area (percentage) of each land type in each sub-catchment. Five veld types were found in the catchment: North-Eastern Mountain Sourveld, Lowveld Sour Bushveld, Lowveld, Arid Lowveld and Mixed Bushveld, each with its own hydrological attributes represented by the variables CAY, VEGINT, ROOTA, COIAM and percentage surface cover (PCSUCO). These were represented in a separate *ACRU* model configuration setup in the same way as that described above, i.e. each unique Acocks' Veld Type is represented as a separate HRU in the model configuration.

7.2.5 Modelling the riparian zone

The riparian zone is the lowest lying area in a catchment's topography and movement of water through the landscape results in high soil moisture levels in this area. The hydrological response parameters of the riparian sub-sub-catchment (HRU) have been adjusted so that the *ACRU* model can simulate the hydrological processes in each zone accurately. In order to represent the movement of water through the topography of the catchment, the user is able to configure the model in such a way that water is routed between HRUs. When simulating the hydrological response of the riparian zone, *ACRU* routes all contributing areas' surface flows into the channel (riparian zone) and baseflows are routed from the contributing areas to the riparian zone as subsurface flows which increases the soil moisture, making more water available to vegetation. If the soil profile becomes saturated to the soil surface, excess water is added to the stormflow contribution (Schulze and Pike, 2003). All hydrological response units in the catchment are routed to the grassland HRU and then through the riparian zone, as well as any contributing upstream catchments (Meier, 1997). Thus, only the grassland HRU contributes to additional moisture in the riparian zone (Figure 7.4). In this configuration, the baseflow and stormflow generated by the riparian zone are combined and routed through the channel downstream as streamflow.

Table 7.3 Monthly *ACRU* model input variables for pristine land cover (Acocks' veld types) in the Upper Blyde River catchment

Land cover	Variable	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
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
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
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
ARID LOWVELD	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80
	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	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
MIXED BUSHVELD	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75
	VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80
	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

Table 7.4 Monthly *ACRU* model input variables for present land use in the Upper Blyde River catchment

Land cover	Variable	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Grass and thicket	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	1.60	1.60	1.60	1.60	1.40	1.40	1.40	1.40	1.40	1.60	1.60	1.60
	ROOTA	0.85	0.85	0.85	0.90	0.90	1.00	1.00	1.00	0.90	0.85	0.85	0.85
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	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
Indigenous 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
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	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
Commercial plantations	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	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
	ROOTA	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	SMDDEP	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	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
Agriculture	CAY	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	VEGINT	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	ROOTA	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	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
Dense alien trees	CAY	0.80	0.80	0.80	0.78	0.68	0.66	0.66	0.66	0.68	0.79	0.79	0.80
	VEGINT	2.86	2.86	2.86	2.86	2.84	2.84	2.84	2.84	2.84	2.86	2.86	2.86
	ROOTA	0.76	0.76	0.76	0.77	0.77	0.78	0.78	0.78	0.77	0.76	0.76	0.76
	SMDDEP	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	COIAM	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.34	0.34
Medium alien trees	CAY	0.78	0.78	0.78	0.70	0.60	0.48	0.48	0.48	0.60	0.75	0.75	0.78
	VEGINT	2.30	2.30	2.30	2.30	2.20	2.20	2.20	2.20	2.20	2.30	2.30	2.30
	ROOTA	0.80	0.80	0.80	0.83	0.83	0.88	0.88	0.88	0.83	0.80	0.80	0.80
	SMDDEP	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	COIAM	0.28	0.28	0.30	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.30	0.28

Sparse alien trees	**CAY**	0.76	0.76	0.76	0.62	0.52	0.30	0.30	0.30	0.52	0.71	0.71	0.76
	VEGINT	1.74	1.74	1.74	1.74	1.56	1.56	1.56	1.56	1.56	1.74	1.74	1.74
	ROOTA	0.84	0.84	0.84	0.89	0.89	0.98	0.98	0.98	0.89	0.84	0.84	0.84
	SMDDEP	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
	COIAM	0.22	0.22	0.26	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.26	0.22
Dense alien shrubs	**CAY**	0.80	0.75	0.62	0.51	0.50	0.43	0.43	0.43	0.46	0.52	0.75	0.80
	VEGINT	2.05	2.05	2.05	1.96	1.85	1.76	1.76	1.76	1.85	1.96	2.05	2.05
	ROOTA	0.81	0.81	0.81	0.81	0.81	0.82	0.82	0.82	0.81	0.81	0.81	0.81
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	COIAM	0.29	0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.29
Medium alien shrubs	**CAY**	0.78	0.75	0.68	0.55	0.50	0.35	0.35	0.35	0.48	0.60	0.73	0.78
	VEGINT	1.85	1.85	1.85	1.80	1.65	1.60	1.60	1.60	1.65	1.80	1.85	1.85
	ROOTA	0.83	0.83	0.83	0.85	0.85	0.90	0.90	0.90	0.85	0.83	0.83	0.83
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	COIAM	0.25	0.25	0.28	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.28	0.25
Sparse alien shrubs	**CAY**	0.76	0.75	0.74	0.59	0.50	0.27	0.27	0.27	0.50	0.68	0.71	0.76
	VEGINT	1.65	1.65	1.65	1.64	1.45	1.44	1.44	1.44	1.45	1.64	1.65	1.65
	ROOTA	0.85	0.85	0.85	0.89	0.89	0.98	0.98	0.98	0.89	0.85	0.85	0.85
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	COIAM	0.21	0.21	0.26	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.26	0.21
Riparian zone	**CAY**	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80
	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	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	SMDDEP	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Dam	**CAY**	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	VEGINT	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	ROOTA	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	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

In order to determine the total riparian zone within the catchment, the rivers captured from 1: 50 000 topographical map sheets were buffered to 30 m on each side, as discussed in Sections 3.3.2 and 5.1.1, using the buffering facility available in the ArcInfo Geographical Information System (ESRI, 1996; Figure 7.5). This process yielded a network of polygons 60 m wide following the river patterns. The area of these polygons was then calculated for each sub-catchment by overlaying the polygon coverage with the digital sub-catchment boundaries of the Blyde River catchment. The resultant polygon theme was overlaid with the coverage of IAPs and their areas and density class were calculated per sub-catchment (Table 7.4). These values are used in the *ACRU* menu in the riparian zone sub-routine.

To facilitate the estimation of the hydrological impacts of IAPs in the riparian zone, it was necessary to run six separate "scenarios", i.e. one for each IAP classification unit (Section 5.4) assuming 100% infestation of that class in the riparian zone, because there is not an option to simulate more than one vegetation type within this unit. Once the results are obtained an area weighting can be applied to the actual extent of IAPs in the riparian zone in order to determine the impacts at current infestation levels.

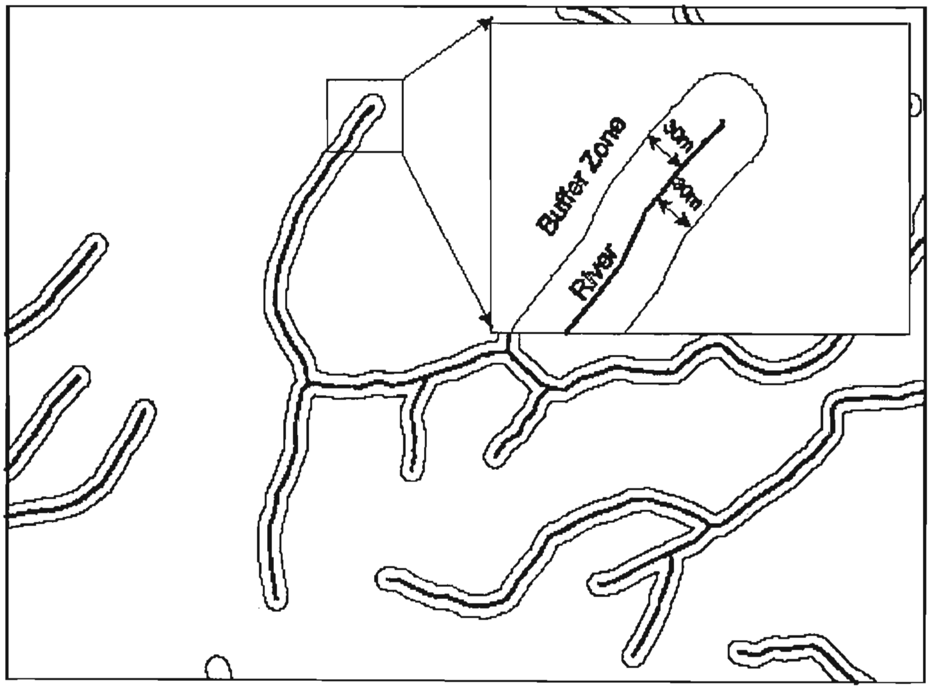


Figure 7.5 The 30m buffer zone generated by ArcInfo on the rivers depicted on the 1:50 000 topographical mapsheets (Horan *et al.*, 2000)

Table 7.5 Total calculated riparian zones, invaded area and percentage infestation by IAPs in the Upper Blyde catchment study area.

UPPER BLYDE RIVER CATCHMENT	Total calculated riparian zone (km^2)	Total IAP area (km^2)		
		Sparse	Medium	Dense
1	5.797			
2	6.937			
3	2.544			
4	3.626			
5	6.762		0.000	0.002
6	10.129	1.430	0.763	1.491
7	10.548	1.586	0.447	1.207
8	5.909	1.027	0.399	0.428
9	8.382	1.065	0.133	0.004
10	5.013	0.763	0.038	0.046
11	5.361	0.504	0.252	0.093
12	0.421	0.037	0.033	0.003
13	7.774	0.951	0.091	0.039
14	4.133	0.296	0.013	0.001
15	9.774	0.885	0.379	0.096
16	4.150	0.252	0.030	
17	2.056	0.121	0.000	
Total area (km^2)	**99.316**	**8.917**	**2.578**	**3.410**
Percentage infestation %	**15.01%**	**8.98%**	**2.60%**	**3.43%**

7.2.6 Streamflow information

Eight streamflow gauging weirs were identified in the Blyde River catchment. Observed streamflows for these gauging weirs on the Blyde River and its tributaries in the catchment were obtained from the DWAF. These were daily flows in primary data format (m^3/sec). The streamflow files were converted to *ACRU* single format (mm/day) for input to the model using the sub-catchment areas. These data were then checked for missing records (these are given a value of -99.900 M in the output file) and these were discarded. This process was repeated for each of the gauging weirs in the catchment and a continuous period of observed data was collated for each weir. It was then necessary to determine a concurrent period for which all the weirs in the catchment had observed data as well as rainfall records. Four weirs were deemed suitable for further use (Section 7.3), these being:

- B6H001 in sub-catchment 9;
- B6H003 in sub-catchment 11;
- B6R003 in sub-catchment 18 (Blyderivierspoort Dam);

- B6H005 in sub-catchment 19.

7.2.7 Abstractions and impoundments

Mining in Pilgrim's Rest abstracts directly from the Blyde River in the upper catchment at a rate of approximately 193 $m^3.day^{-1}$ in a period of 1 month, i.e. 5 790 $m^3.month^{-1}$ (Baskis, 2003, personal communication). The pipeline serving the BRID abstracts water directly from the Blyderivierspoort dam for irrigation of cultivated land at an allocation of 9 980 $m^3.ha^{-1}.yr^{-1}$ (Ravenhill, 2003, personal communication). The Blyderivierspoort Dam (Figure 6.1 and Figure 6.2) is the only major dam in the study area. There are numerous small farm dams located in the lower catchment.

7.3 Verification of Modelled Streamflows from the Upper Blyde River Catchment

Verification was carried out according to *ACRU* guidelines (Smithers and Schulze, 1995a) which specify a methodical procedure to interpret and improve simulations through a series of checks, *inter alia*, checking input data and information: rainfall, MAR and streamflow, annual reference potential evaporation; interpretation of monthly totals of observed and simulated streamflow output; interpretation of statistical comparison and acceptable objectives; important rules of checking and adjusting model parameters and checking general and monthly trends. The statistical functions and procedures that were used to verify the simulated values obtained from the *ACRU* model were:

- Comparison of the sum of total observed and simulated values;
- Comparison of accumulated monthly totals of daily streamflow for simulated and observed values;
- Correlation coefficient: Pearson's r;
- Coefficient of determination (r^2);
- Coefficient of efficiency, which measures the degree of association between observed and simulated values; and
- Coefficient of agreement, which indicates the degree to which the model's predictions are error free.

Monthly totals of simulated daily streamflow values were compared to observed data from two streamflow gauging stations, *viz.* B6H001 with an upstream catchment area 511.67 km^2, and B6H003 with an upstream catchment area 94.24 km^2 (Figure 7.3). The period for verification of simulated streamflow was chosen as 1995-2000, as this was the period in which there was available streamflow record and also the period for which the most recent land use classifications are available (CSIR, 1996; WfW, 2002). Thus, for the verification study, it was assumed that the present land cover was representative of the simulation period. The verification exercise was carried out using the input parameters for each sub-catchment obtained from various sources as described Section 7.2. The results from these inputs was checked and, in consultation with technical experts at the School of BEEH and according to the guidelines provided in the *ACRU* manual, manual adjustments were made to selected parameter values (Schulze, 2003, personal communication) in order to improve the simulations obtained.

7.3.1 Verification of simulated streamflows on the Blyde River (B6H001)

Gauging weir B6H001 lies at the outlet of sub-catchment nine and has a catchment area of 511.67 km^2. Flow records from this station are available from 1959-2000, although there are some records missing during the simulation period. There are seven rainfall driver stations in the catchment with more than 15 years record. There are some missing data in the streamflow record early in 1996 and in June 1997, but these missing values were discarded for the statistical analysis, for which 69 data points representing monthly totals of daily data for the period 1995-2000, were used.

The results for simulated streamflows at B6H001 illustrate an under-simulation of streamflow by the *ACRU* model (Figures 7.6 – 7.8, and Table 7.6), especially during periods of peak flows in 1998, 1999 and 2000. Seasonal trends are simulated relatively well with slight over-simulation during winter months. *ACRU* is not generating enough baseflow - possibly an indication that the depth of the B-horizon is too deep. There does not seem to be a substantial phase shift and the general trend is captured well.

In terms of general trends for an acceptable simulation, the difference between observed and simulated values should be no more than 10% (Smithers and Schulze, 1995a). The results obtained for the simulation at B6H001, indicate a difference of more than 30%.

This can be attributed to a number of reasons. First, because it is an operational as opposed to a research catchment, it is possible that observed data (rainfall and streamflow) recorded in the catchment may be less accurate than one would require for a study such as this, as measuring equipment and data capture methods are not maintained to the high standards demanded in research catchment experiments. Second, simulations could be improved by adjusting soil-water budget parameters. This, however, would not be a hydrologically justifiable unless a detailed soil survey for this catchment has been carried out. Third, more detailed soils information from ISCW (Idema, 1989) could have been used. However, experience in the School of BEEH has highlighted some shortcomings in the hydrological interpretation of this soils information (Pike 2003). This is currently not available for use in this study. In light of the shortcomings above, the simulation obtained can only be accepted on the basis that further research needs to be carried out on soils and soil parameters in this catchment. Such an assessment was beyond the scope and budget of this project. Thus, the *ACRU* model configuration for this catchment was accepted for further analysis of the impact of IAPs, with the recognition that these analyses need to be based on relative rather than absolute values of streamflow.

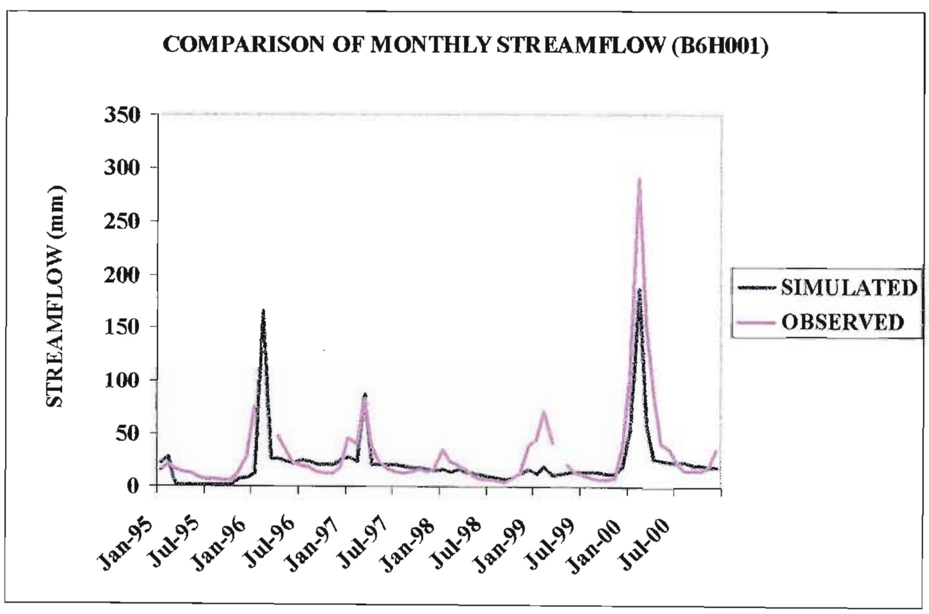


Figure 7.6 Comparison of monthly totals of daily streamflow (1995-2000)

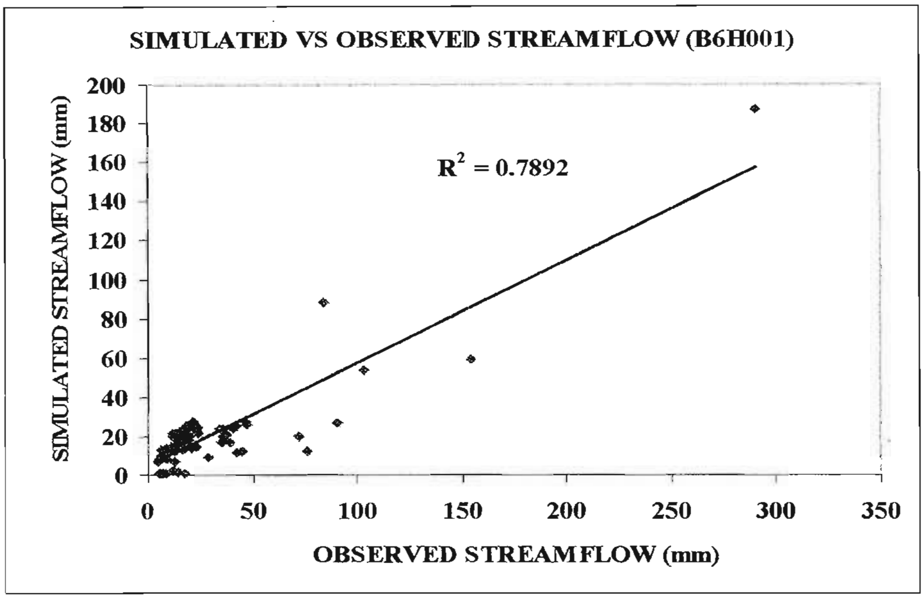


Figure 7.7 Scatter plot monthly totals of daily simulated versus observed streamflow (1995-2000)

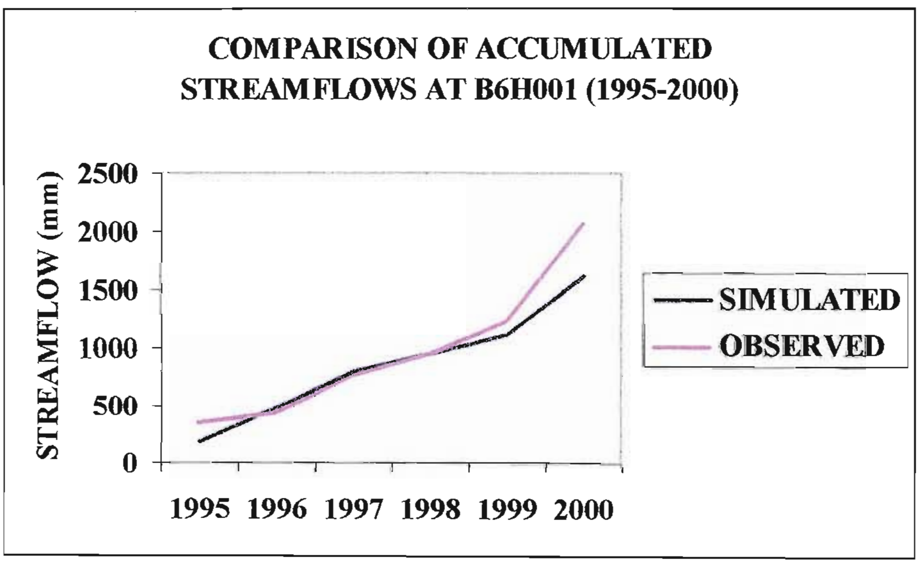


Figure 7.8 Comparison of accumulated streamflows (1995-2000)

Table 7.6 Statistical analysis of monthly totals of daily observed and simulated streamflows on the Blyde River (B6H001)

CONSERVATION STATISTICS	
Sum Observed Values	2071.83
Sum Simulated Values	1417.25
Mean Observed	30.03
Mean Simulated	20.54
% Difference Between Means	31.59
% Difference Between Variances	65.02
% Difference Between Standard Deviations	40.86
% Difference Between Coefficients of Variation	13.54
% Difference Between Skewness Coefficients	-18.40
REGRESSION STATISTICS	
Correlation Coefficient - Pearson's r	0.89
Regression Coefficient (Slope)	0.53
Regression Intercept	4.77
Coefficient of Determination - R^2	0.79
Coefficient of Efficiency	-0.01
Coefficient of Agreement	0.94

7.3.2 Verification of simulated streamflows on the Treur River (B6H003)

Gauging weir B6H003 at the outlet of sub-catchment 11 has a catchment area of 94.24 km^2 and observed streamflow records are available from 1959-2001. There are two rainfall driver stations located in the catchment, both of which have a record of 44 years. There are some missing data in the streamflow record in the second quarter of 1996, but these missing values were discarded for the statistical analysis and 70 data points were used.

The graphical results (Figures 7.9-7.11) for simulated streamflows at B6H003 indicate a good simulation and general trend of observed values. The seasonal trends are accurate with no significant phasing effects. Peak flows are frequently under-simulated, but fall in phase with observed values. Low flows appear to be slightly over-simulated (baseflow retention too high).

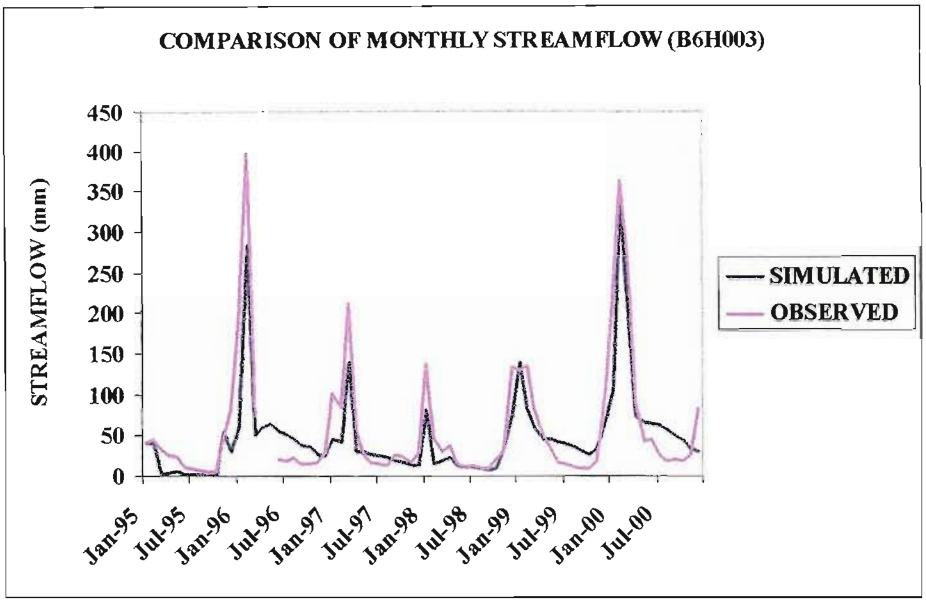


Figure 7.9 Comparison of monthly totals of daily streamflow (1995-2000)

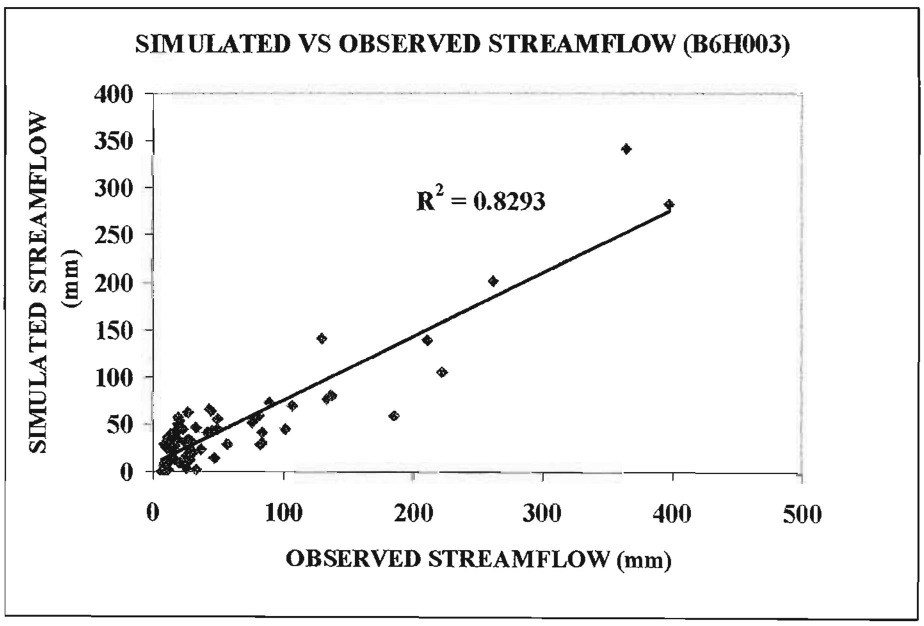


Figure 7.10 Scatter plot of monthly totals of daily simulated versus observed streamflow (1995-2000)

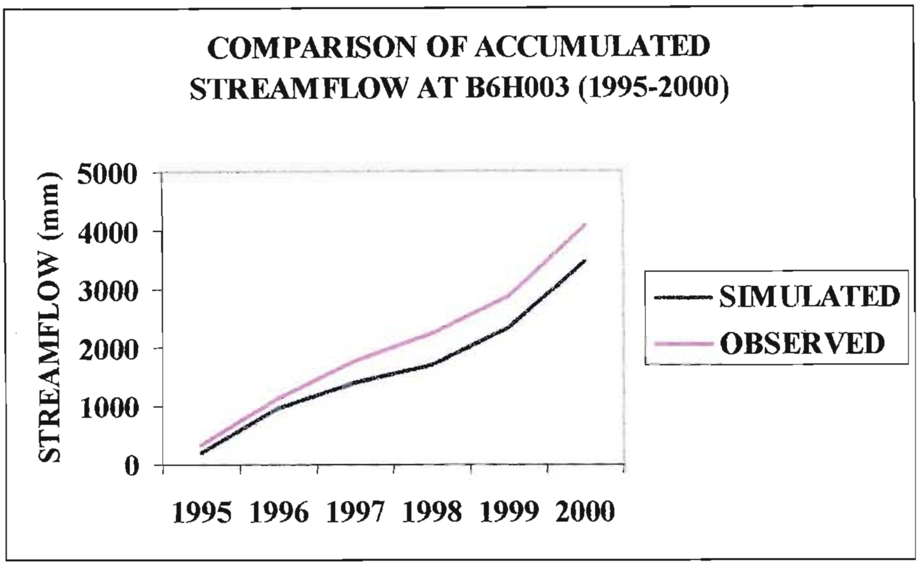


Figure 7.11 Comparison of accumulated streamflows (1995-2000)

As stated above, for an acceptable simulation the difference between observed and simulated values should be no more than 10%. The results obtained for the simulation at B6H003 indicate a difference of 18% (Table 7.7). This is markedly better than the simulation obtained at B6H001 and can most likely be attributed to the fact that the Treur River catchment is a smaller catchment and therefore more likely to have more homogenous land use and soils. Once again, simulations could be improved by altering soil water budget parameters, this however would not be hydrologically justifiable without having carried out a detailed soil survey for this catchment and hence having no field data on which to verify such changes is available. The simulation obtained therefore can be accepted as an imperfect, but a good, representation of general trends and further analysis of IAP impacts need to be based on relative rather than absolute values.

The overall underestimation of simulated streamflows from both B6H001 and B6H003 could be rectified by reducing the depth of the B-horizon. It appears that rainfall early in the season results in a fast runoff response which may be caused by a "push-through" mechanism, i.e. a small rainfall event combined with water sitting in the weir is recorded as high streamflow.

Table 7.7 Statistical analysis of monthly totals of daily observed and simulated streamflows on the Treur River (B6H003)

CONSERVATION STATISTICS	
Sum Observed Values	4078.56
Sum Simulated Values	3342.09
Mean Observed	58.27
Mean Simulated	47.74
% Difference Between Means	18.06
% Difference Between Variances	45.76
% Difference Between Standard Deviations	26.35
% Difference Between Coefficients of Variation	10.12
% Difference Between Skewness Coefficients	-24.23
REGRESSION STATISTICS	
Correlation Coefficient - Pearson's r	0.91
Regression Coefficient (Slope)	0.67
Regression Intercept	8.67
Coefficient of Determination - R^2	0.83
Coefficient of Efficiency	0.60
Coefficient of Agreement	0.95

7.3.3 Concluding comments

Although the trends of simulated streamflows were well modelled on both the Blyde River ($r = 0.89$ and $r^2 = 0.79$) and the Treur River ($r = 0.91$ and $r^2 = 0.83$), the statistics present substantial differences. Discrepancies such as these are inevitable in simulation modelling exercises and can be attributed to several problems (Schulze, 1995):

- Errors in streamflow or rainfall data records;
- Rainfall values not representative of the sub-catchment;
- Averaging of soil properties across large sub-catchments;
- Assumptions associated with changes in land cover;
- Quality of data in research versus operational catchments.

Although these simulations could have been improved by following an intensive calibration process, it was felt that there was no hydrological justification for such an exercise, and the *ACRU* model simulations were accepted as the best possible for the available input data. Furthermore, it is recognised that the poor verification may allow hydrological analyses of relative differences between IAP scenarios, but exact estimates of streamflow differences are unlikely to be accurate.

This chapter presented a detailed methodology for the configuration of the Upper Blyde River catchment as well as obtained and prepared extensive input information for the *ACRU* hydrological model. Although verification of simulated streamflows resulted in substantial statistical differences, the general trends of estimated streamflows were found to be acceptable simulations of present hydrological responses in the catchment. The problems that were encountered have been noted and, as such, highlight the recurring difficulties surrounding hydrological simulation modelling. It was determined that the *ACRU* model, despite the discrepancies, can be used to simulate the relative hydrological response of change in land use in the Upper Blyde River catchment with confidence.

8. MODELLING HYDROLOGICAL RESPONSES TO INVASIVE ALIEN PLANTS ON STREAMFLOW IN THE UPPER BLYDE RIVER CATCHMENT

Following the verification of streamflow output, and the consideration of the associated complexities surrounding hydrological modelling, daily streamflows were simulated using the *ACRU* model for 17 sub-catchments of the Upper Blyde River catchment for the period 1960-2000. The focus of this study is to assess the impacts of invasive alien plants (IAPs) on mean annual runoff, seasonal runoff and low flows in the Upper Blyde River catchment.

8.1 Modelling Hydrological Responses of Different Land Use Scenarios

Hydrological responses simulated for a catchment in pristine condition under present climatic conditions assumes that the catchment is entirely covered by natural vegetation represented by the vegetation described by Acocks' (1988) Veld Types. This provides a baseline against which streamflow from other scenarios can be compared. The appropriate hydrological variables were adjusted in *ACRU* to account for the different hydrological characteristics of natural vegetation cover (Table 7.3). This was used as a basis for comparison of the impacts of present land cover on the hydrological responses in the Upper Blyde River catchment.

A summary of the present land cover represented by the LANDSAT images (CSIR, 1996) and IAPs (WfW, 2002) in the Upper Blyde River catchment, sub-catchments 1-17 in Figure 7.1, is as follows:

- 58.93% natural vegetation;
- 27.44% commercial plantations;
- 5.38% IAPs of varying density;
- 3.81% agriculture (of which 40% is subsistence farming);
- 3.91% indigenous forest and woodland;
- 0.53% urban/residential.

Approximately 15 %, equivalent to 99.32 km^2, of the Upper catchment is defined as the riparian zone based on a 30 m buffer strip on each side of a river. The 30m buffer area is used as a guideline to define the edge of the zone of wetness. It is not, however, an exact measure of the riparian area. In the absence of a detailed soil survey, it is an effective measure used to delineate this area for input to a hydrological model and to be able to account for different hydrological processes taking place therein. The Upper Blyde riparian area is dominated by natural vegetation cover, followed by commercial plantations and IAPs and a small area is covered by agriculture (Figure 8.1). Although the CSIR mapping did not explicitly account for riparian areas in their methodology, these land uses are unlikely to encroach all the way to the river channel.

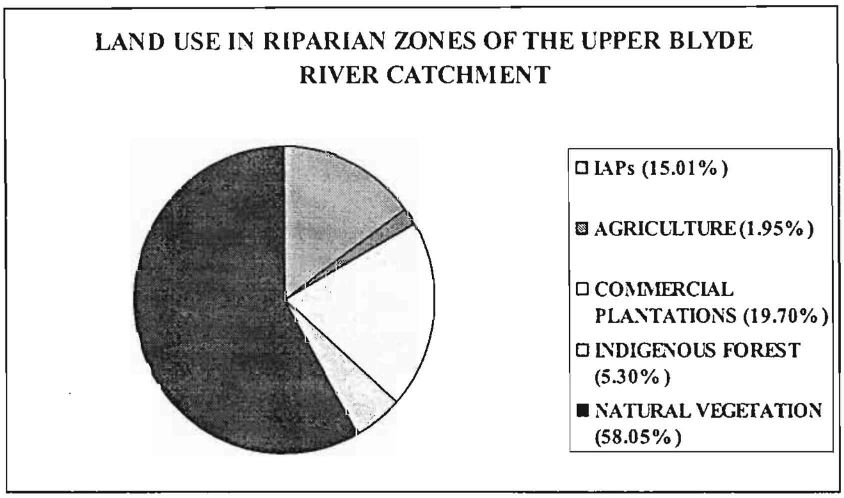


Figure 8.1 Summary of riparian land use in the Upper Blyde River catchment

The following assumptions were made when modelling the catchment response to riparian and non-riparian IAPs:

- Present land use is considered to be existing land use in the catchment derived from CSIR (1996) LANDSAT images and coverages of IAPs from WfW;
- Cleared riparian zones were considered to be covered by Acocks' Veld Type common to the area, i.e. North Eastern Mountain Sourveld;
- Total clearance of IAPs considered riparian zones to be covered by the dominant indigenous veld, and non-riparian areas to be covered by the dominant CSIR (1996) land cover.
- Land cover datasets were assumed to be accurate, noting that these were not compiled for a riparian-specific study;

- The riparian zone was calculated as a 30 m buffer strip on either side of a water course throughout the catchment although more rigorous methods of defining this zone exist, based on soils and topography.

The hydrological responses were simulated for the following catchment land use scenarios, focussing on IAP infestation in the riparian zone:

- Catchment in pristine condition based on Acocks' Veld Types;
- Present land use, sparse riparian invasive trees;
- Present land use, sparse riparian invasive shrubs;
- Present land use, medium riparian invasive trees;
- Present land use, medium riparian invasive shrubs;
- Present land use, dense riparian invasive trees;
- Present land use, dense riparian invasive shrubs;
- Present land use, cleared riparian zone;
- Total clearance of IAPs from riparian and non-riparian habitats.

An area weighting of existing vegetation to the means and low flow estimates for each riparian vegetation scenario was applied in order to obtain the streamflow values for existing vegetation in the riparian zone (Table 8.1). Once these values were obtained it was possible to plot the streamflows of present land use against those of the baseline vegetation (Figure 8.2).

Table 8.1 Existing areas and percentage areas of riparian vegetation in the Upper Blyde River catchment.

EXISTING VEGETATION	Area (km^2)	% area
Dense invasive shrubs	0.009	0.009
Dense invasive trees	3.40	3.42
Medium invasive shrubs	0.07	0.07
Medium invasive trees	2.51	2.53
Sparse invasive shrubs	4.53	4.60
Sparse invasive trees	4.39	4.42
Natural vegetation	84.42	85.15
TOTAL	**99.14**	**100%**

The results are expressed in million ($x10^6$) m^3 at the catchment level and sub-catchment level, focussing on two key rivers contributing to the Blyde River, the Treur and Kadisi

Rivers. Results are presented graphically for Acocks' Veld Types, present land use (calculated), riparian clearance and total clearance of IAPs. Tabulated results of all catchment land use scenarios are provided for 10, 33, 50 and 90 percentile levels as well as MAR.

8.2 Results of Modelling at the Catchment Level: the Upper Blyde River Catchment

The results of modelling hydrological impacts of IAPs on catchment streamflow are presented in Figures 8.2, 8.3 and 8.4 and Table 8.2 for Acocks' Veld Types, present land use with dense riparian trees, riparian clearance and total clearance of IAPs. The long term trend of accumulated streamflow (Figure 8.2) shows a clear indication of the relative differences in long term yield in the Upper Blyde River catchment between pristine conditions (Acocks' Veld Types), cleared scenarios and dense infestation of trees in the riparian zone. Land cover under Acocks' vegetation produces the most runoff, followed by land totally cleared of IAPs and IAPs cleared from the riparian zone. Over time, the difference between cleared scenarios and dense infestation becomes larger, indicating that the accumulated hydrological impact of IAPs on catchment streamflow becomes greater over time. Although much of the Upper catchment is under natural vegetation cover, forming the Blyde River Canyon Nature Reserve, commercial plantation forests account for approximately 27% of the upper catchment area having widespread implications for streamflow reduction, further compounded by IAPs in riparian and non-riparian habitats.

Analysis of mean monthly catchment streamflow under different land cover (Figure 8.3) clearly shows the seasonal trends. The influence of reduced precipitation in the dry winter months is evident from April to November when total monthly flow drops to less than 20 million m^3 and the increases in streamflow with summer rainfall from December to February. Estimated runoff from Acocks' land cover is consistently higher than all other land use scenarios, as may be expected from pristine conditions. Streamflow reduction caused by IAPs in the landscape and in the riparian zone (present land use) is evident when compared to scenarios of both riparian and total clearance of IAPs. Clearing of IAPs from the riparian zone appears to be especially important during the winter months because the relative difference from total clearance is marginal, indicating that IAPs in the riparian zone have a greater impact on streamflows than landscape IAPs alone. The impacts of IAPs will be explored in further detail at the sub-catchment level in Sections 8.3 and 8.4.

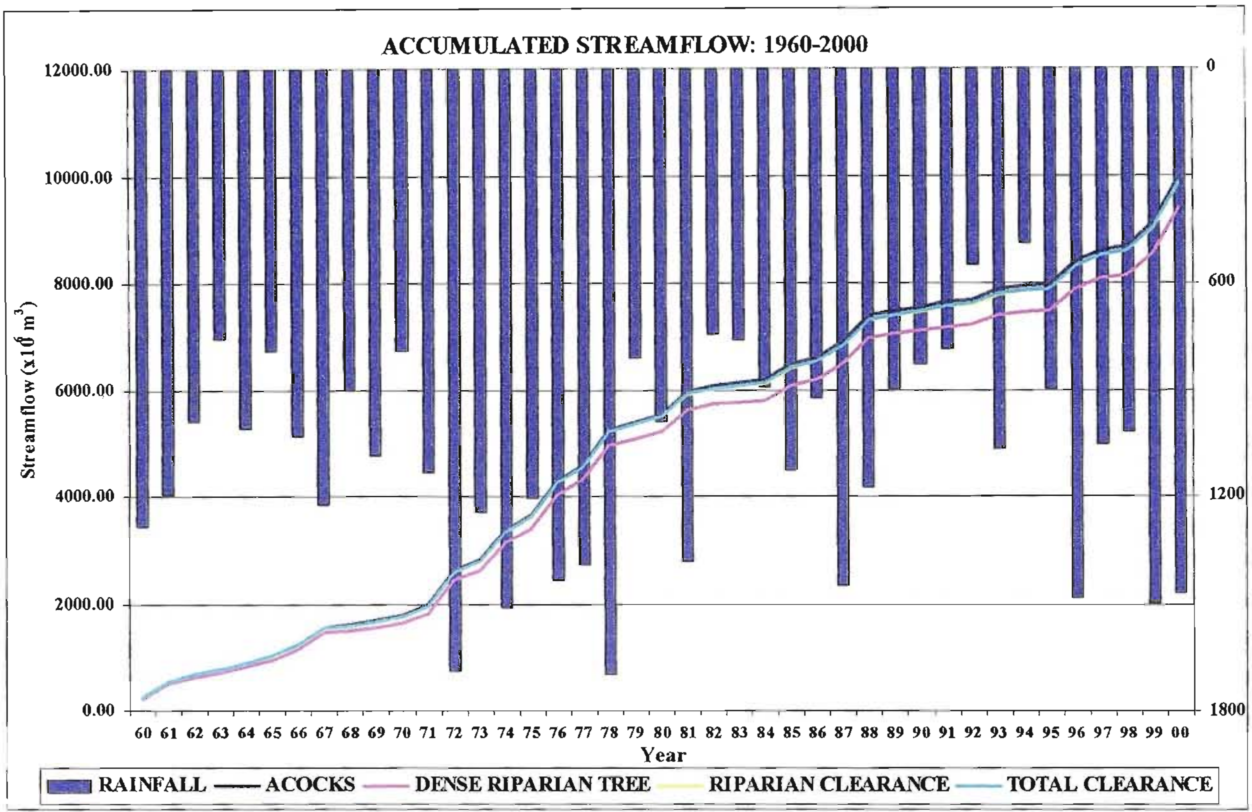


Figure 8.2 Accumulated annual streamflow for 1960-2000 in the Upper Blyde River catchment

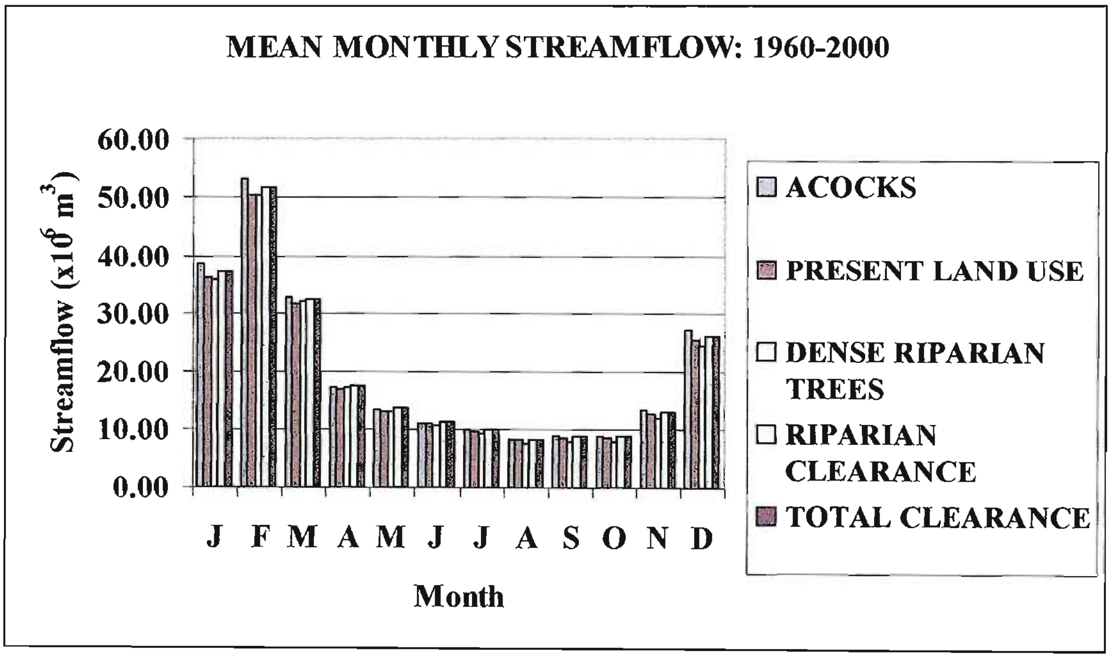


Figure 8.3 Mean monthly streamflow trends in the Upper Blyde River catchment

Analysis of monthly 10% exceedance levels, i.e. monthly flows for the driest year in ten (Figure 8.4), highlights the lowest monthly flows during the dry winter months (May-November) during which low flows are less than 0.5 million m^3 for all land use scenarios. The increase in streamflow resulting from clearance of IAPs from the riparian zone is evident and in some cases, even more than total clearance specifically during winter months. A possible explanation for land totally cleared of IAPs producing less streamflow than riparian clearance alone, specifically from July to October, may be the influence of existing commercial plantation forests in the Upper catchment. More detailed analysis of low flow periods are discussed at the sub-catchment level for the Treur and Kadisi Rivers in the next section of this chapter.

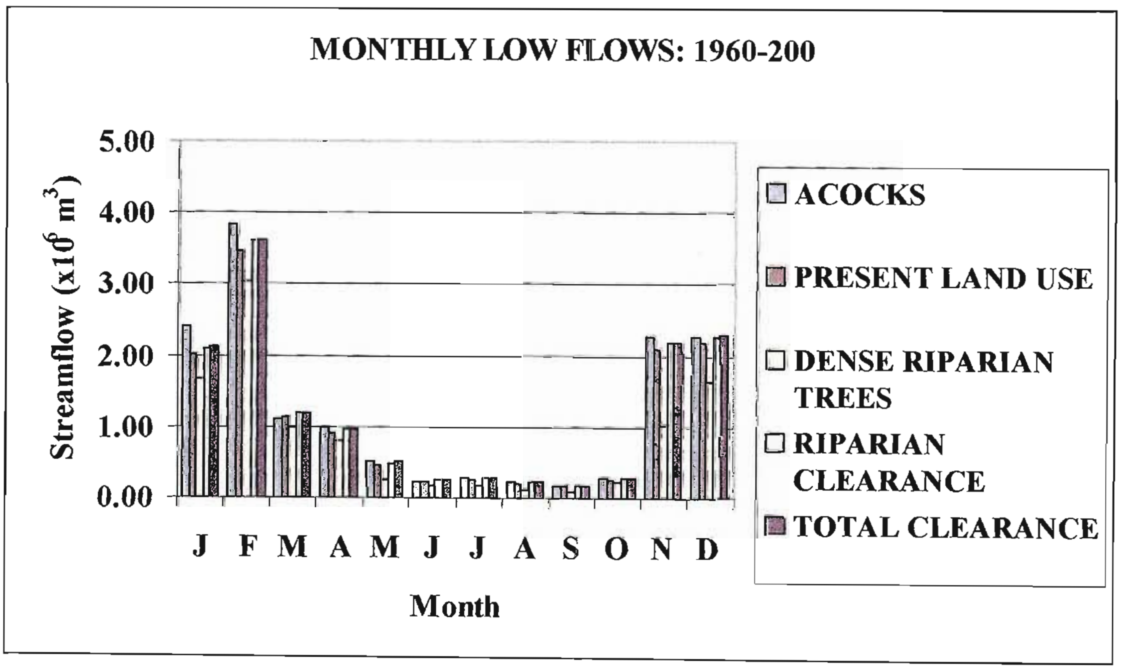


Figure 8.4 Monthly low flows in the Upper Blyde River catchment

Table 8.2 presents the annual monthly streamflow statistics at the 10th, 33rd, 50th and 90th percentiles representing the non-exceedance of streamflow. These estimations provide a good indication of the likely impact of different land use scenarios – specifically the impacts of varying densities of IAP infestation in the riparian zone - on streamflows from the Upper Blyde River catchment. Dense invasive trees in the riparian zone have the greatest reduction in streamflow during normal years, followed by the present riparian infestation and medium invasive trees. During low flows, dense invasive trees in the riparian zone cause the greatest reduction in streamflow, followed by medium invasive trees and present land use.

Table 8.2 Annual totals of monthly statistics for scenarios of landscape and riparian IAP infestation

UPPER BLYDE RIVER CATCHMENT ANNUAL FLOW STATISTICS ($x10^6$ m^3)	**10%**	**33%**	**50%**	**90%**	**MAR**
ACOCKS	57.58	105.31	167.37	610.79	242.84
PRESENT LAND USE (LU)	51.93	101.16	159.55	589.03	232.55
RIPARIAN CLEARANCE	53.78	104.53	164.74	607.23	239.92
TOTAL CLEARANCE	53.93	104.63	164.97	607.79	240.22
PRESENT LU, DENSE RIPARIAN SHRUBS	52.71	103.96	163.67	609.23	239.51
PRESENT LU, DENSE RIPARIAN TREES	44.00	94.55	154.12	589.69	228.63
PRESENT LU, MEDIUM RIPARIAN SHRUBS	54.50	104.39	163.91	606.78	239.40
PRESENT LU, MEDIUM RIPARIAN TREES	49.11	99.49	159.32	598.02	234.14
PRESENT LU, SPARSE RIPARIAN SHRUBS	55.19	104.92	163.80	602.15	238.38
PRESENT LU, SPARSE RIPARIAN TREES	54.41	104.24	162.89	600.49	237.45

The difference in annual flows (i.e. increase or decrease) resulting from clearing IAPs from and non-riparian habitats during key flow periods is shown in Table 8.3. In particular, note the increases in streamflow when existing IAPs (present land use) are cleared: 5.42 $x10^6$ m^3 under median flows, 3.47 $x10^6$ m^3 in low flow periods and 7.66 $x10^6$ m^3 for mean annual runoff. Invasive alien trees at medium and dense cover in the riparian zone cause the greatest reduction in annual streamflow for all flow periods, but most noticeable is a 9.93 $x10^6$ m^3 reduction by dense trees and 4.82 $x10^6$ m^3 by medium trees during low flow periods. Decreases in streamflow under scenarios of sparse infestation of invasive trees and shrubs and medium invasive shrubs could be attributed to the vegetation that replaces IAPs having higher water use coefficients. The vegetation cover for the scenario of total clearance is represented by the CSIR (1996) land cover including commercial forest plantations which use water at a higher rate than sparse and medium invasive shrubs and sparse invasive trees.

Table 8.3 Differences in streamflow (x10^6 m^3) for periods of low, median and mean annual flows for different scenarios of infestation relative to scenarios of clearance

LOW FLOWS (x10^6 m^3)	RIPARIAN CLEARANCE	TOTAL CLEARANCE
PRESENT LAND USE (LU)	1.85	3.47
PRESENT LU, DENSE RIPARIAN SHRUBS	1.07	1.22
PRESENT LU, DENSE RIPARIAN TREES	9.78	9.93
PRESENT LU, MEDIUM RIPARIAN SHRUBS	-0.72	-0.57
PRESENT LU, MEDIUM RIPARIAN TREES	4.67	4.82
PRESENT LU, SPARSE RIPARIAN SHRUBS	-1.41	-1.26
PRESENT LU, SPARSE RIPARIAN TREES	-0.63	-0.48
RIPARIAN CLEARANCE		0.10
MEDIAN FLOWS (x10^6 m^3)		
PRESENT LAND USE (LU)	5.19	5.42
PRESENT LU, DENSE RIPARIAN SHRUBS	1.07	1.30
PRESENT LU, DENSE RIPARIAN TREES	10.62	10.85
PRESENT LU, MEDIUM RIPARIAN SHRUBS	0.84	1.06
PRESENT LU, MEDIUM RIPARIAN TREES	5.42	5.65
PRESENT LU, SPARSE RIPARIAN SHRUBS	0.94	1.17
PRESENT LU, SPARSE RIPARIAN TREES	1.85	2.08
RIPARIAN CLEARANCE		0.23
MAR (x10^6 m^3)		
PRESENT LAND USE (LU)	7.37	7.66
PRESENT LU, DENSE RIPARIAN SHRUBS	0.41	0.70
PRESENT LU, DENSE RIPARIAN TREES	11.29	11.59
PRESENT LU, MEDIUM RIPARIAN SHRUBS	0.52	0.82
PRESENT LU, MEDIUM RIPARIAN TREES	5.78	6.08
PRESENT LU, SPARSE RIPARIAN SHRUBS	1.54	1.83
PRESENT LU, SPARSE RIPARIAN TREES	2.46	2.76
RIPARIAN CLEARANCE		0.30

8.3 Results of Modelling at the Sub-catchment Level: the Treur River

Sub-catchments 10 and 11 are located in the eastern part of the catchment on the relatively unimpacted Treur River (Figure 8.5). The Treur River is a particularly important indicator of river health in the Upper Blyde catchment because it provides habitat to important fish and insect species (RHP, 2001). The sub-catchment has an area of 94.2 km^2, MAP is approximately 1 200 mm and the land cover (Figure 8.6) is dominated by natural grassland and thicket (62.7 km^2), commercial plantations (25.7 km^2), IAPs (5.5 km^2) and indigenous forests (0.4 km^2). The riparian zone was calculated as equivalent to 10.37 km^2 of the catchment area of which 16.1% is covered by IAPs: 12 % sparse trees and shrubs, 2.8% medium trees and shrubs, and 1.3% dense trees and shrubs.

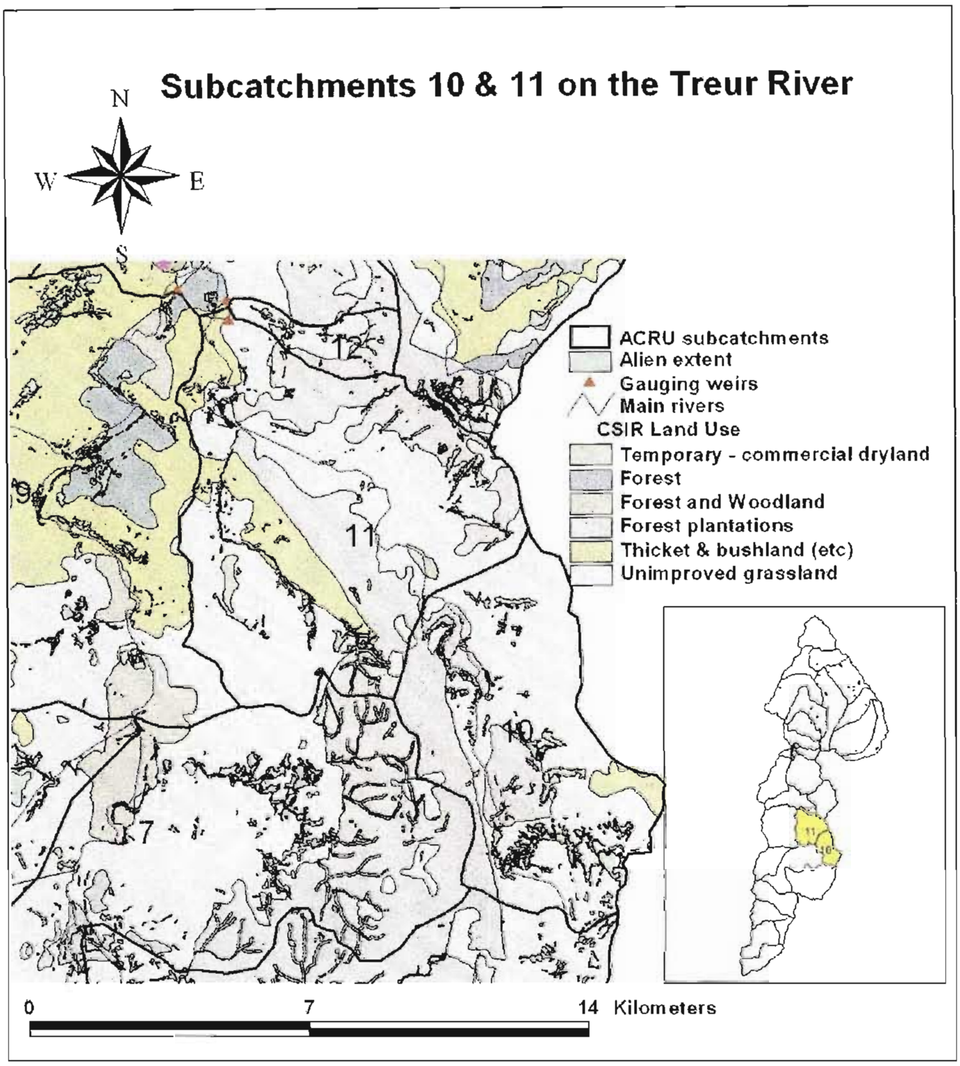


Figure 8.5 Land use and location of the Treur River sub-catchment

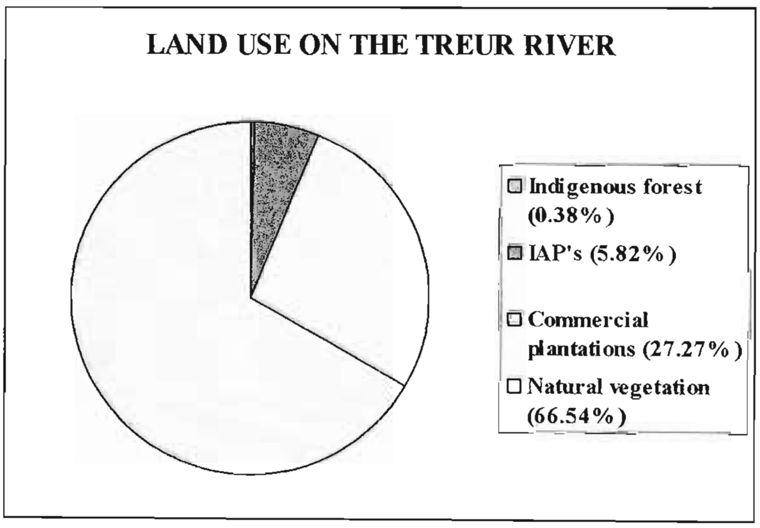


Figure 8.6 Summary of land use on the Treur River (Sub-catchments 10 and 11)

The simulated results of sub-catchment scenarios: Acocks' Veld Types, present land use (LU), riparian clearance and total clearance (riparian and landscape habitats) are presented in Figures 8.7 and 8.8. Mean daily streamflow on the Treur River (Figure 8.7) shows that the highest flows are experienced from December to March, peaking in February, and the lowest flows ($<0.0750 \times 10^6$ m^3) from April to November. The difference in flows between Acocks' and present land use and cleared scenarios appears to be small in the winter months when flows are lowest. One would expect to see bigger differences because of the influence of IAPs, specifically between Acocks' and present land use, and between present land use and scenarios of clearance because of the greater water use by IAPs compared to indigenous vegetation. It is hypothesised that IAPs would cause the greatest reduction when there is less water available. However it is possible that there may be more competition for water resources between indigenous and invasive vegetation during critical flow periods and therefore the difference in water use between the two types of vegetation would be less noticeable.

During periods of low flow at a daily level (Figure 8.8), the highest flows are experienced late in summer. The recession into winter (April to October) follows the trend of mean daily values. Winter flows are estimated at less than 0.018×10^6 m^3. The differences between the scenarios are clear at the daily level: increased flow from Acocks' Veld Types and cleared scenarios, incremental increases from present land cover to riparian and total clearance particularly during critical winter months. Streamflow from present land use is predicted to reach a minimum of 0.0055×10^6 m^3 in October to just over 0.0178×10^6 m^3 in April.

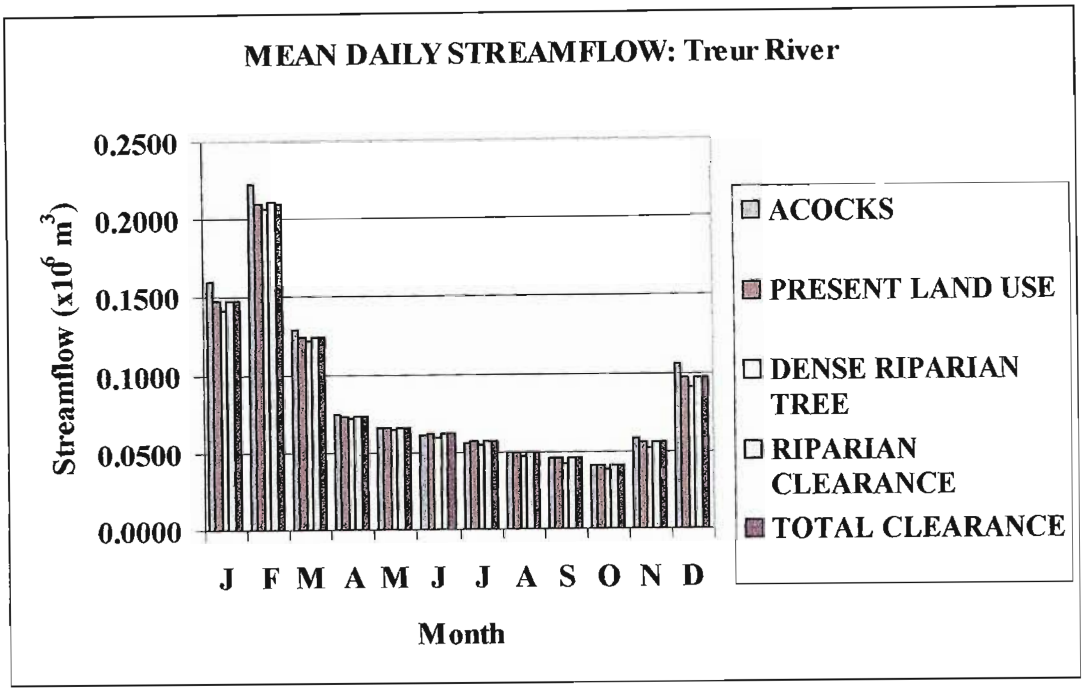


Figure 8.7 Mean daily flows on the Treur River

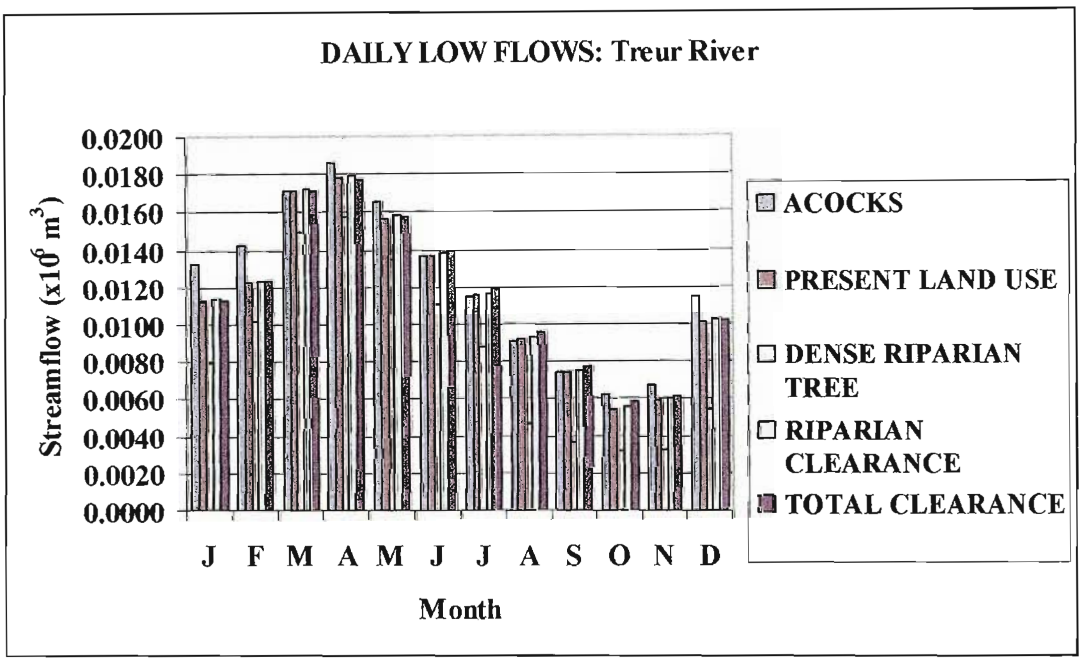


Figure 8.8 Daily low flows on the Treur River

The flow exceedance curve (Figure 8.9) provides an indication of how often a certain flow is exceeded. For all scenarios, daily flows greater than 0.09 million m^3 are experienced approximately 30% of the time. The influence of IAPs (worst case taken – dense riparian trees) is most evident when daily flows are less than 0.05 million m^3. It is interesting to note that there is a marginal difference between the daily flows for scenarios of clearance, indicating that during low flow periods total clearance of IAPs, i.e. landscape as well as the riparian zone, yields as much water as riparian clearance alone. This has important financial implications considering the cost of clearing IAPs.

Annual totals of daily flow statistics (Table 8.4) of different scenarios of IAP infestation show that invasive alien trees in the riparian zone are likely to have the greatest impact for all flow periods. Invasive alien shrubs have less of an impact in comparison to invasive trees. At the 10% exceedance level, there are consistent increases, despite being small, with flows from riparian and total clearance of existing IAPs in the order of 0.0438 million m^3 and 0.0456 million m^3 respectively. The relatively small increases in streamflow could be attributed to the fact that the riparian zone of the Treur River is dominated by sparse IAPs which have a much lower water use than higher density invasives. In addition, 27% of the non-riparian habitat is under commercial plantation forests.

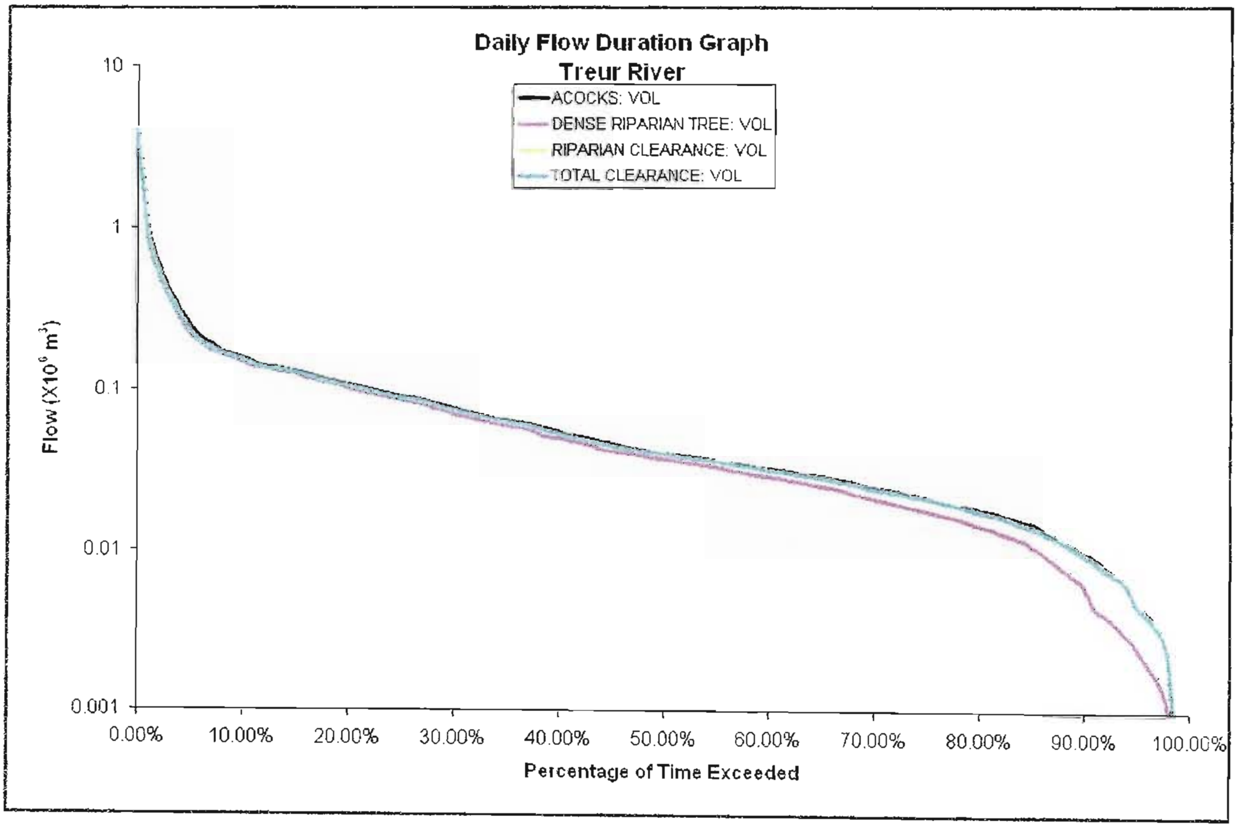


Figure 8.9 Daily flow duration curve (exceedance curve) on the Treur River

Table 8.4 Annual totals of daily statistics for scenarios of landscape and riparian IAP infestation on the Treur River

TREUR RIVER: ANNUAL FLOW STATISTICS ($x10^6 m^3$)	**10%**	**33%**	**50%**	**90%**	**MAR**
ACOCKS	11.64	21.99	24.16	62.35	32.43
PRESENT LAND USE (LU)	10.75	20.74	22.71	60.57	31.24
OBSERVED	22.88	20.72	39.15	72.63	45.40
RIPARIAN CLEARANCE	10.80	20.81	22.77	60.69	31.30
TOTAL CLEARANCE	10.80	32.64	22.68	60.67	31.24
PRESENT LU, DENSE RIPARIAN TREE	9.52	19.45	21.39	59.23	30.05
PRESENT LU, DENSE RIPARIAN SHRUB	10.80	20.86	22.75	60.81	31.32
PRESENT LU, MEDIUM RIPARIAN SHRUB	10.81	20.77	22.76	60.55	31.27
PRESENT LU, MEDIUM RIPARIAN TREE	10.24	20.16	22.10	59.78	30.68
PRESENT LU, SPARSE RIPARIAN SHRUB	10.74	20.59	22.63	60.14	31.11
PRESENT LU, SPARSE RIPARIAN TREE	10.64	20.50	22.52	60.05	31.00

8.4 Results of Modelling at the Sub-catchment Level: the Kadisi River

Sub-catchment 16 is located just above the Blyderivierspoort Dam on the Kadisi River (Figure 8.10). Most of the rural communities in the Upper Blyde River catchment live in this area and are reliant on natural resources for their livelihoods. Subsistence farming is practised in this area and much of the population lives along the river. The area has a population of approximately 814 people (Census, 2001). Owing to the dependence of the population on the river for run-of-river abstractions, analysis of low flows on this river is particularly important and relevant. The sub-catchment has an area of 57 km^2, MAP of 650 mm and is characterised by natural grassland and thicket (40.6 km^2), subsistence farming (11.04 km^2), IAPs (5.03 km^2) and commercial plantations (0.23 km^2) (Figure 8.11). The riparian zone was calculated as equivalent to 4.15 km^2 of the catchment area of which 6.8% is covered by IAPs: 6.1 % sparse trees and shrubs and 0.7% medium trees and shrubs.

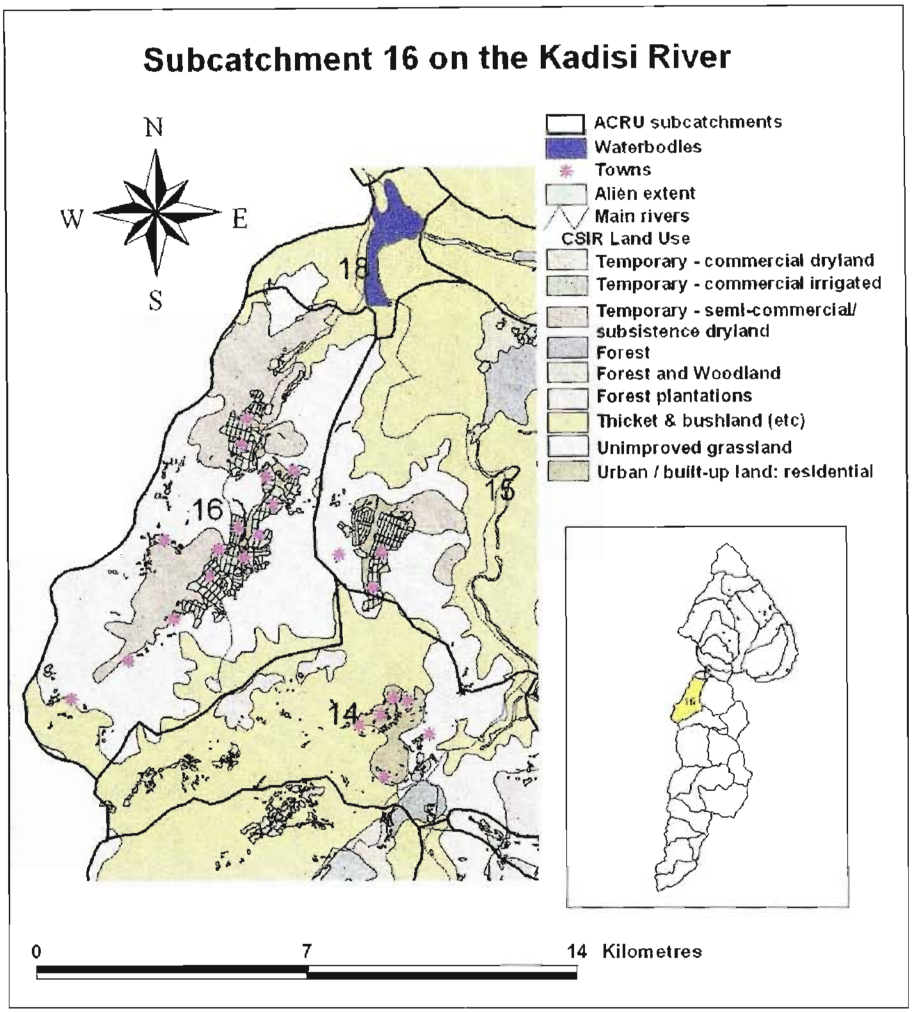


Figure 8.10 Land use and location of the Kadisi River sub-catchment in the Upper Blyde River catchment

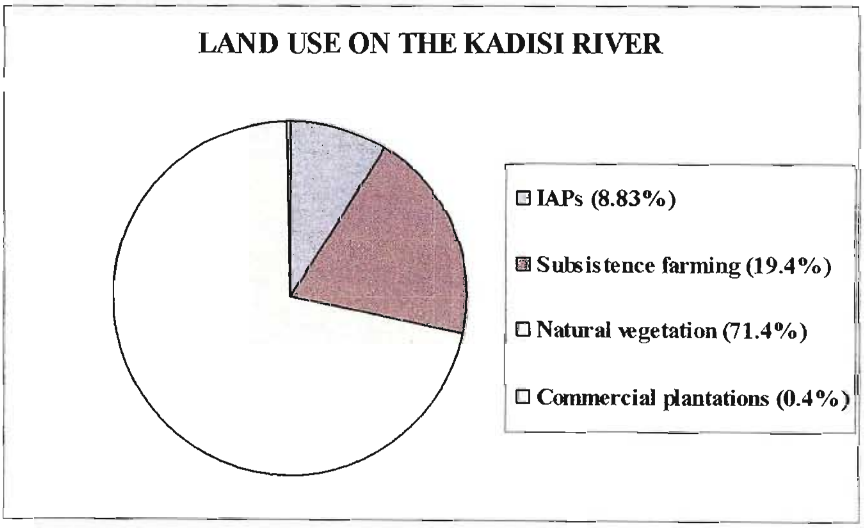


Figure 8.11 Summary of land use in the Kadisi River sub-catchment

The simulated results of sub-catchment scenarios: Acocks', present land use (LU), riparian clearance and total clearance (riparian and landscape habitats) are presented. Mean monthly daily streamflow on the Kadisi River (Figure 8.12) shows that the highest flows are experienced from January to March, peaking in February at greater than 60 000 m^3, and the lowest flows at less than 11 000 m^3 from April to November. The difference in flow between Acocks' and present land use is clear during summer months but appears to be of the same order of magnitude with all scenarios during winter months.

During periods of low flow, estimated flows at a daily level for all scenarios are less than 2 000 m^3 which is an extremely low value (Figure 8.13). The highest flows occur in the summer months and decline rapidly into the winter months with values less than 2 000 m^3. This is of great concern because it means that the river is tending to run dry during the winter months of low flow periods. The differences between the scenarios are clear at the daily level in the summer months: increased flow from Acocks' and cleared scenarios, incremental increases from present land cover to riparian and total clearance, but less so during the critical winter months. This is an indication that baseflows are generated from large summer events and that the riparian zone routine is not working. Streamflow from the present land use scenario is at a minimum of 60 m^3 per day in September to just over 183 m^3 per day in February which is enough to irrigate approximately two hectares.

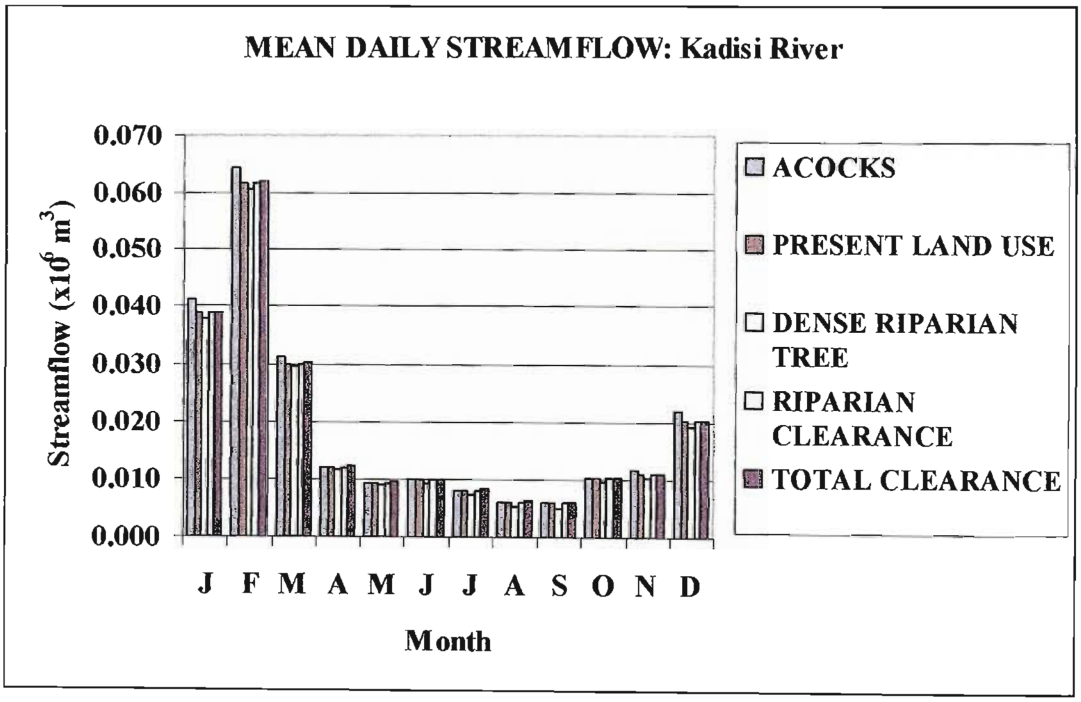


Figure 8.12 Mean daily flows on the Kadisi River

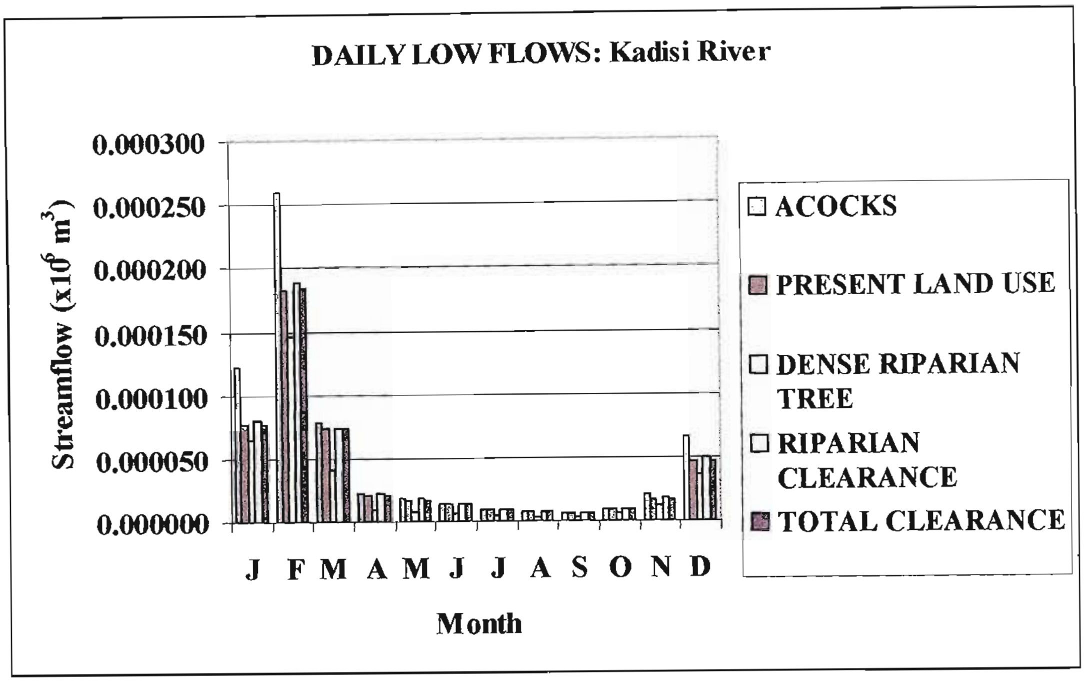


Figure 8.13 Daily low flows on the Kadisi River

The flow exceedance curve (Figure 8.14) provides an indication of how often a certain flow is exceeded. For all scenarios, daily flows greater than 80 000 m^3 are experienced approximately 5% of the time. The influence of IAPs (worst case taken – dense riparian trees) is most evident when flows are less than 10 000 m^3. At 50% exceedance, i.e. median flows, the Kadisi river flows at approximately 5 000 m^3 per day under scenarios of clearance and at 3 000 m^3 per day under the scenario of dense trees in the riparian zone. It is difficult to know how often this river runs dry because there are no observed data available for this sub-catchment.

Annual totals of daily flow statistics (Table 8.5) of different scenarios of IAP infestation show that invasive alien trees and dense invasive shrubs in the riparian zone would have the greatest impact for all flow periods. Medium and sparse invasive shrubs have less of an impact in comparison to invasive trees. At the 10% exceedance level, there is an increase of 300 m^3 after riparian clearance of existing IAPs. Total clearance increases flow by 5 000 m^3. The relatively small increases in streamflow could be attributed to the fact that the riparian zone of the Kadisi River is only invaded to approximately 6% by sparse shrubs and trees. There is extensive subsistence farming along the river and a large rural community living in the area for which run of river abstractions have not been quantified in this study, although rough estimations could be made based on the allocation of 25 litres per person per day for ± 814 people. In addition, the rare Tufa waterfall is found in the lower reaches of the Kadisi River. Considering the results obtained here, there is a need for careful consideration of water supply for both the human and environmental reserve.

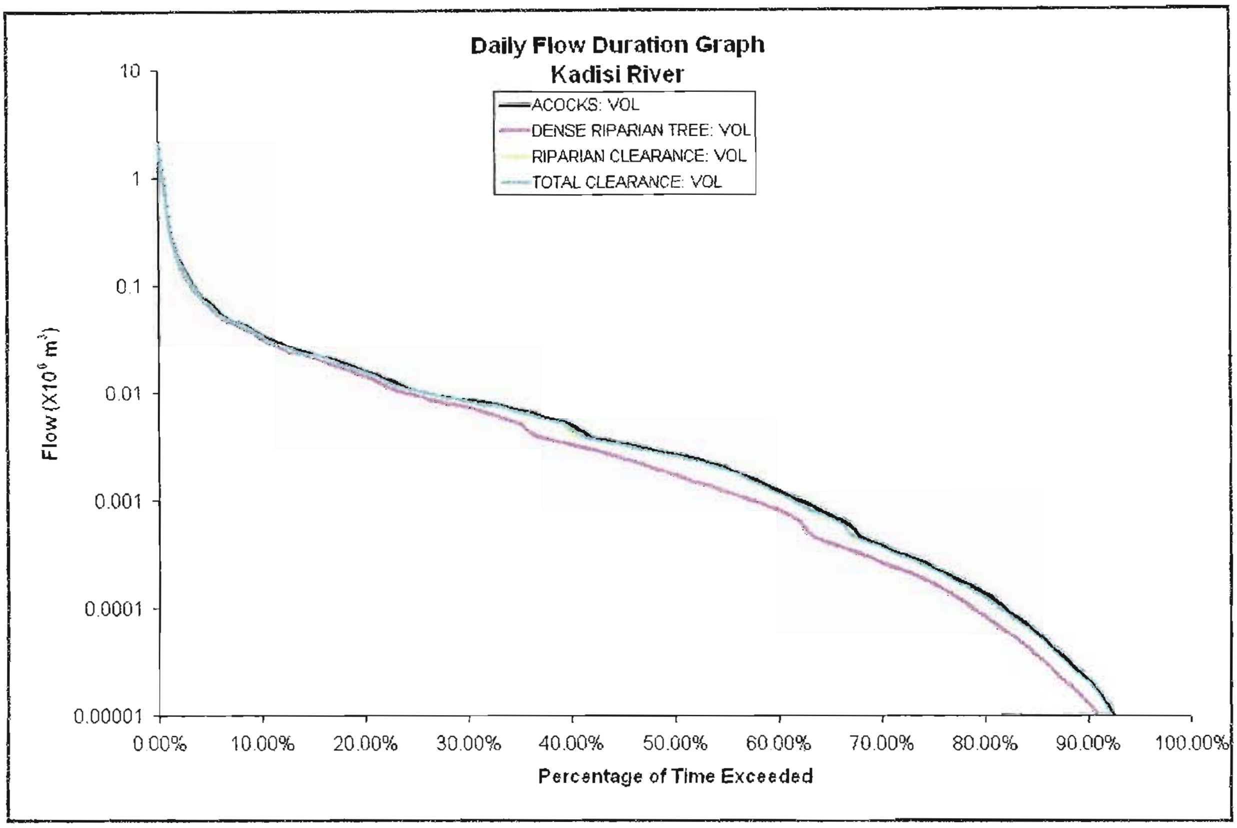


Figure 8.14 Daily flow duration curve (exceedance curve) on the Kadisi River

Table 8.5 Annual totals of daily statistics for scenarios of landscape and riparian IAP infestation on the Kadisi River

KADISI RIVER: ANNUAL FLOW STATISTICS ($x10^6$ m^3)	10%	33%	50%	90%	MAR
ACOCKS	1.2577	2.1189	3.9052	17.9178	6.9560
PRESENT LAND USE (LU)	1.1059	2.0222	3.6661	17.5636	6.7005
RIPARIAN CLEARANCE	1.1062	2.0235	3.6628	17.5666	6.7006
TOTAL CLEARANCE	1.1109	2.0366	3.6958	17.6720	6.7431
PRESENT LU, DENSE RIPARIAN SHRUB	1.0749	2.0217	3.6299	17.5551	6.6908
PRESENT LU, DENSE RIPARIAN TREE	0.9672	1.9114	3.2665	17.2537	6.4400
PRESENT LU, MEDIUM RIPARIAN SHRUB	1.1094	2.0004	3.6821	17.5556	6.7087
PRESENT LU, MEDIUM RIPARIAN TREE	0.9957	1.9648	3.4946	17.4155	6.5737
PRESENT LU, SPARSE RIPARIAN SHRUB	1.1144	2.0079	3.7371	17.5354	6.7134
PRESENT LU, SPARSE RIPARIAN TREE	1.0862	2.0009	3.6949	17.5074	6.6844

9. DISCUSSION

In this dissertation, several issues pertinent to Integrated Water Resources Management in South Africa, particularly some of those relevant to land use issues facing water managers today, have been presented. The importance of water scarcity in South Africa is highlighted in many research projects and assessments, indicating that this is a serious issue that requires some thoughtful planning. The issue of IAPs is one, in particular, that is highly relevant as they have been shown to affect catchment water resources directly and, consequently, water yield and supply to both aquatic and terrestrial environmental systems. The SEA framework, introduced in Chapter 2, provides a basis for the consideration of social, economic and environmental consequences of water management decisions. As such it may become a useful tool for ensuring South Africa's scarce water resources are used sustainably to the benefit of people and the environment. In the context of this study, the economic element of the SEA framework is not addressed, however the assessment of social and environmental elements does provide some insight into the management of water resources in the Upper Blyde River catchment for which numerous decisions regarding land use, and hence water use are currently under consideration.

9.1 Results of Modelling IAPs

There has been much debate regarding the hydrological implications of commercial plantations, themselves being trees of exotic origin. Forestry, however, is not the only land use that may cause a reduction in streamflow; others include sugar cane, other agricultural crops and IAPs, all of which could have hydrological implications that require further investigation. Whilst it is recognised that these land uses should be taken into consideration with regard to legislation pertinent to streamflow reduction activities, in particular Section 36 of the NWA. The focus of this research, however, was on the hydrological impact of IAPs in riparian and non-riparian areas of the Upper Blyde River catchment and their classification as a land use for the estimation of catchment hydrological responses using a hydrological model.

Approximately 5.38% of the Upper Blyde River catchment is infested with IAPs at varying degrees of density. Riparian zones make up approximately 15% of the catchment area, and 15% of this area is covered by IAPs at varying densities. Using the currently available version of the *ACRU* model, it is not possible to model explicitly more than one land cover with differences in densities, such as those of infestations in the riparian zone. Therefore, streamflow for present land use had to be calculated on an area weighted basis from the estimated flows for the riparian zones. Comparisons between catchment land use scenarios were made at the catchment and sub-catchment scales in order to establish general trends at a broad scale and to focus on localised impacts in key sub-catchment areas. Furthermore, it was important to determine the degree to which IAPs in the riparian zone affected catchment streamflows. In this regard, six scenarios were modelled to simulate the impact of different types of IAPs at different densities of invasion in the riparian zone. It was found in Chapter 8 that medium and dense invasive trees and dense invasive shrubs had the greatest impact on catchment, and sub-catchment streamflow.

The most important result emerging from the Upper Blyde River catchment modelling exercise was that the increase in flow from clearing riparian zones alone relative to clearing both riparian and non-riparian habitats ranged from 0.10 $x10^6$ m^3 during low flow periods to 0.30 $x10^6$ m^3 MAR (Table 8.3). This trend, i.e. flow increases after riparian clearance and total clearance, is a consistent outcome at both sub-catchment and catchment scales. Streamflow reductions estimated for scenarios of 100% infestation by different density trees and shrubs are substantial, particularly for invasive tree species and dense infestations in the riparian zone, for both mean annual runoff and low flow periods.

Analysis of daily flows at the sub-catchment level, specifically on the Kadisi River, revealed some important results (Chapter 8). Low flows were found to be extremely low. Domestic abstractions were not quantified in the model because these data were not available. Therefore, it must be noted that there could be some serious implications for water supply planning specifically during periods of low flow. Unfortunately, there are no observed streamflow data for this sub-catchment and so there is no basis for comparison of simulated results. Adopting the SEA process in the Kadisi catchment will ensure the consideration of social and community interests, and assurance of supply of water for the community for subsistence farming as well as allocation for the Reserve, particularly when considering the low flow estimates obtained and the low MAP (650mm). These are long term considerations which will have implications for maintaining supply for environmental and social purposes in future planning.

The national Working for Water programme has been instrumental in implementing control methods, with positive results, while simultaneously providing employment to members of marginalised communities in South Africa. The initiative is well supported by government and private industries alike, offering an alternative solution to contemporary social and conservation issues. Catchment experiments and process studies have revealed that the exact water use of IAPs is largely unknown, but compared to that of commercial plantations, it has been estimated to be approximately twice as high per annum, i.e. 93mm, for plantations compared with 190mm for invaded areas, according to Versfeld *et al.* (1998). Possible explanations for this include the propensity of invading species to establish themselves in riparian zones along watercourses, as well as established IAPs tending to be older than average age plantation trees, and hence have greater biomass.

The land use scenario in which IAPs are presumed to be cleared from both the landscape and the riparian zone (Chapter 8), clearly indicates the improved hydrological response of catchment streamflow. This could be seen as an argument to justify the benefits of clearing activities. However, marginal increases in streamflow at a daily level for scenarios of riparian clearance versus total clearance of IAPs may have some important financial implications for managers and land owners when considering the cost of clearing IAPs. The costs involved in consistent and maintained clearing and control are high for initial clearing, but are relatively low for sustained maintenance (Versfeld *et al.*, 1998; Le Maitre *et al.*, 2002). There are likely to be direct economic as well as ecological and social benefits from the resultant increased water yield. Ideally, total clearance of IAPs, i.e. in the landscape as well as in the riparian zone, is the ultimate goal in managing IAPs, but in cases where there are financial or other constraints (e.g. labour and time), clearing IAPs from the riparian zone should be prioritised.

Several limitations and weaknesses are recognised in the overall approach of the analysis of the Upper Blyde River catchment:

- The *ACRU* model verification showed up underestimation by up to 30%. However, despite consistent under-simulation of streamflow, as discussed in Section 7.3.8, it was felt that the model could be used for the scenario analyses used in this study, with recognition that underestimation of streamflow for all catchment land use scenarios was to be expected;

- There is a lack of high quality observed streamflow data as well as a dense network of rainfall stations at the sub-catchment level for model verification and comparison for land use scenarios;
- There is a lack of water use information, *viz.* subsistence agricultural demands and domestic requirements on the Kadisi River;
- Water use information for IAPs based on derived water use parameters in the School of BEEH requires more research and testing;
- A uniform buffer zone of 30m on either side of a river is assumed;
- The model is at present unable to simulate more than one land cover in the riparian zone – hence having to calculate flows from scenarios of IAPs with an area weighting approach;
- The streamflow reduction from commercial plantation forests was not quantified in this study and this will have further implications for overall streamflow reductions in the Upper Blyde River catchment.

9.2 IAPs as a Land Use in Hydrological Models

Using a spatially explicit method to model the hydrological response of different types of IAPs at different densities in both riparian and non-riparian habitats is a useful technique in determining the degree to which IAPs influence catchment streamflow. It is important to remember, however, that modelling only reflects ones understanding of reality and, therefore, model results must be taken for what they are, i.e. they will always be limited by our perception of reality and will never replicate nature exactly. Although the methodology and classification system presented in Chapter 5 simplifies the detailed information obtained from WfW mapping somewhat, it presents an important structure for use within hydrological models in general. Furthermore, the classification system presented has wider application in other land use sensitive hydrological models and has been applied within the HYLUC model (Calder, 2001; Gush, 2003, personal communication).This approach should be replicated and tested in other case study areas and with other land use sensitive models. In this way, this notion may contribute to the SEA framework for decision making regarding water use in catchment scale planning.

The methodology used for habitat and plant classification could very well be extended to species level detail, particularly if more accurate plant water use information becomes available. If necessary, it could also provide a framework of priority for clearing activities, *viz.* habitat to be cleared, type and density of IAP, in situations where there are financial constraints. Obviously total clearance of IAPs from South African catchments is the ideal solution. However, there are many factors affecting implementation and maintenance of clearing programmes and these need to be considered and weighed up to find a sustainable solution.

9.3 The Upper Blyde River Catchment

Having carried out a situation assessment and modelling exercise in the Upper Blyde River catchment, several issues relating to water resources have been highlighted. Apart from the impacts of IAPs in the upper catchment, irrigation, mining and the proposed sugar project (Chapter 6) warrant some future analysis. In terms of water use, the mining industry in the upper catchment uses substantially less water every year than the volumes required for irrigation and supply from the Blyderivierspoort Dam to the BRID and the Phalaborwa Water Board entitlements downstream, i.e. approximately 70 000 m^3 as opposed to 50 x 10^6 m^3. The capacity of the dam is 54 x 10^6 m^3 and the annual yield estimated by DWAF (1991) was found to be approximately 143.2 x10^6 m^3. This estimate was made in 1991 on the premise that "... there are no activities in the dam's catchment that could have any significant impact on the hydrology of the catchment...". However in the light of this study it has been established that there are, indeed, land use activities that could have significant impact on the catchment and, as a consequence, could affect the assurance of supply to downstream users.

Upstream land and water use activities will therefore have to be managed sustainably so that the dam can continue to fulfil downstream entitlements, thereby emphasising the significance of the removal of IAPs and also the implications of proposed projects such as the Blyde River sugar project. If this particular proposal is approved by DWAF, there would be a change in land use from relatively low water use to higher demands from sugar cane, resulting in increased irrigation demands in the Upper catchment. Thus, potential gains in water from the removal of IAPs could be cancelled by the increased demand on water resources for sugar cane. Furthermore, this change in land use could jeopardise the quantity of water flowing into the Blyderivierspoort Dam and subsequently downstream to the Olifants River and the Kruger National Park. It is certainly not in the interests of the conservation efforts being made to remove commercial afforestation only to replace it with sugar cane and its associated industries. One also has to consider secondary implications of the removal of vegetation, both IAPs and commercial forests, on water quality aspects such as erosion and subsequent sedimentation. In addition, water quality should be monitored because of the risk of contamination from old mining operations in Pilgrim's Rest. These are factors that have not been quantified explicitly in the context of this study, but are nonetheless very real issues of concern.

10. CONCLUSIONS AND RECOMMENDATIONS

There is no doubt that removing IAPs increases catchment streamflow. However, the results of this research suggest that future assessment of the hydrological impacts of IAPs should shift focus to critical flow periods, i.e. the low flow periods, associated impacts with regard to water quality and downstream water supply. Flow estimations on the Kadisi River were estimated to be 2 000 m^3 per day during low flow periods, and estimated domestic demands in the order of 20.00 m^3 per day to meet the minimum requirements of the human reserve. Furthermore, neither an estimate of the agricultural demands for the community, nor an assessment of the potential impacts of agriculture on the ecosystem, *viz.* soil erosion and sedimentation, was made. These issues were beyond the scope of this study. However, this raises concerns for long term supply of water to the sub-catchment, specifically during critical flow periods and warrants more detailed investigation in future.

The broad objective of the study was to perform a hydrological assessment focussed on the potential impacts of commercial afforestation and IAPs in the riparian and non-riparian areas of the Upper Blyde River catchment, as well as to develop a methodology using readily available information and data that can be applied in other studies. This was achieved by developing a generic classification system that represented IAPs as spatially explicit land use units for use with a hydrological model, and then using maps from WfW of IAP extent in the Upper Blyde River catchment. The *ACRU* model was configured for the Upper Blyde River catchment with available data and observed record of rainfall and streamflow information. It was then used to estimate streamflow under IAPs, providing comparable estimates in terms of water use, despite difficulties experienced with model verification, the riparian routines and certain input parameters. Owing to complex physical processes taking place in this zone, modelling water use in the riparian zone is a difficult exercise and requires some refinement. This could be done either within the *ACRU* model or, alternatively, with a separate model focussed on more realistic representations of these processes. It should not be overlooked, however, that the riparian zone is an important part of the landscape and needs to be considered as a part of the whole catchment in water resources assessments.

A successful planning strategy is one where research enhances the available knowledge base and finds its way into management frameworks and programmes for application in the broader context of catchment management. Programmes such as the Working for Water and Working for Wetlands should receive continued support from government and water managers alike, in order to sustain their efforts and achieve positive results. Tools used within management frameworks, such as SEA and IWRM, are vital in evaluating local scale changes on catchment water resources. Furthermore, hydrological models can be used to assess the hydrological responses of changes in land use in catchments and for identifying the potential hydrological benefits that may be derived from implementing suitable management programmes. The management of land use and water resources requires not only an understanding of their interactions, but it also requires methods through which assessments can be made with regard to future development. These methodologies are required at all development scales for their implementation to be successful. The relationship between land and water use is a complex one, and one that requires ongoing research and the successful dissemination and implementation thereof.

Recommendations for further research arising from this study are:

- Further investigation of changes in land and water use, focussed on low flow periods and aspects of water quality, particularly the impacts of soil erosion and sedimentation associated with the removal of riparian vegetation is required;
- Enhancements to the *ACRU* model with regards to riparian zone routines are necessary;
- Reasons for the sometimes poor model performance must be identified, i.e. whether it is as a result of poor quality of hydrological data inputs or model structure, and making relevant improvement to the *ACRU* model, if that is found to be the reason;
- Investigation into the water use of both IAPs and indigenous vegetation for more accurate and representative water use parameters for input to hydrological models is required; and
- The classification system for IAPs should be applied to other land use sensitive hydrological models for verification, and their wider use by incorporating methodologies into guidelines for use by WfW at national and provincial levels.

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