HYDROLOGICAL MODELLING APPLICATIONS FOR WATER RESOURCES MANAGEMENT IN THE MKOMAZI CATCHMENT

by

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PREFACE

The experimental work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, from January 1998 to December 2000, under the supervision of Professor Roland E. Schulze.

These studies represent 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.

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ABBREVIATIONS

BBM	Building Block Methodology
BEEH	The School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, South Africa
BMP	Best Management Practice
CCWR	Computing Centre for Water Research
CMA	Catchment Management Agency
CSIR	Council for Scientific and Industrial Research
CV	Coefficient of Variation
DRIFT	Downstream Response to Imposed Flow Transformations
DWAF	Department of Water Affairs and Forestry
EFR	Estuarine Flow Requirement
FDC	Flow Duration Curve
FRD	Foundation for Research and Development
FSL	Full Supply Level
GCM	General Circulation Model
IFR	Instream Flow Requirement
IHA	Indicators of Hydrologic Alteration
ISCW	Institute for Soil, Climate and Water
IWR	Institute for Water Resources, University of Rhodes, Grahamstown, South Africa
IWRM	Integrated Water Resources Management
MAF	Mean Annual Flow
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MED	Median Annual Runoff
MMTS	Mkomazi-Mgeni Transfer Scheme
NWA	National Water Act
QC	Quaternary Catchment
RVA	Range of Variability Approach
SC	Subcatchment
SRA	Streamflow Reduction Activity

WISA	Water Institute of Southern Africa
WSAM	Water Situation Assessment Model

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ABSTRACT

Predictions that water shortages will constrain economic growth in South Africa by 2025 have led to increased concerns among water resource managers that there is a need for comprehensive water management strategies. To this extent the new South African Water Act requires that water resource allocation be approached in a more equitable and conservative way than in the past in order to sustain water resources for catchment development. This includes protection of the water resource base by the setting aside of a health Reserve for basic human needs and for the ecological functioning of rivers.

At a time when water resource management is shifting from the practice of large dam construction to reconciling water demand with water supply in more holistic strategies, the Mkomazi Catchment in KwaZulu-Natal provides an opportunity to investigate some of the major issues that dominate contemporary water resource management. Presently (2001), there are no impoundments on the Mkomazi River and the catchment is generally underdeveloped. These factors have provided the impetus for the Department of Water Affairs and Forestry's proposed inter-basin transfer scheme to use the surplus flow in the Mkomazi Catchment to augment the water resources of the neighbouring Mgeni system.

Impact-of-land-use and development scenario studies, using the *ACRU* agrohydrological modelling system, were performed to simulate the impacts of (a) baseline land cover, (b) present land use, (c) the first phase of the Mkomazi-Mgeni Transfer Scheme and (d) potential climate change on the hydrological dynamics of the Mkomazi Catchment. The results indicate that the change from baseline land cover conditions to present land use conditions has little impact on the *annual* water resources of the Mkomazi River. This is especially so in the upper catchment where there is little anthropogenic development and from where the planned inter-basin transfer will be made from the proposed Smithfield Dam. Although the impacts of commercial forestry and irrigation in the middle and lower catchment impose local stress on streamflow generation, they do not detract substantially from the main downstream flows. Evaluation of the impacts of the proposed Smithfield Dam on *annual* streamflow generation revealed that there is more than sufficient water in the upper Mkomazi Catchment to sustain the inter-basin

transfer under present climatic conditions. However, under potential climate change the *median annual* Mkomazi streamflows at the estuary could be reduced by 46% if the dam was constructed, compared with a 22% reduction under present climatic conditions. The impacts of catchment development on the seasonal low flows within the Mkomazi Catchment indicated that those areas which are already heavily utilised by afforestation and, particularly, by irrigated land use are unlikely to be able to support any further large scale commercial agricultural development, even under present climatic conditions.

Water management strategies for the Mgeni system will impact on potential water allocation within the Mkomazi Catchment. The results of the impacts studies were used to assess the water demand of the major water-use sectors and the availability of streamflows for further allocation was assessed. Present total annual water demands of Mkomazi streamflows is minimal. Even allowing for the environmental demand in the Mkomazi Catchment, as identified by the Building Block Methodology during an instream flow requirements workshop, as well as the first phase of the inter-basin transfer, there would be surpluses of 66%, 43%, 42% and 45% of streamflows, respectively, at the four instream flow requirement sites on the Mkomazi River.

The results of the Mkomazi instream flow requirements workshop were revisited to assess the achievability of the recommended flows within the *ACRU* generated daily time series of streamflows for each of the scenarios simulated, at the each of the four instream flow requirement sites on the Mkomazi River. The results confirmed the need to ascertain the Mkomazi River's natural flow variability, and to assess how much alteration is likely under development of the Mkomazi Catchment. The Indicators of Hydrologic Alteration and Range of Variability Approach methodologies were used to determine which components of the streamflow regime would be most impacted by the inter-basin transfer. Hypothetical, yet realistic, upper and lower management target thresholds were applied to determine the range of variation experienced by the streamflow regime of the Mkomazi, under both pre- and post-dam construction conditions, and to evaluate a preliminary assessment of the characteristics of the streamflow regime required to meet environmental sustainability.

The issues raised by potentially conflicting water uses within catchments in South Africa have indicated that any approach to address the increasing complexity of water resource problems, and the management thereof, requires effective hydrological modelling.

1 GENERAL INTRODUCTION

The factors affecting the availability of water resources in South Africa are numerous and diverse. Water supply is constrained, not only by the temporal and spatial distribution of rainfall and high evaporation rates, but also by increasing competition for the limited resources from expanding industrial, agricultural, commercial and domestic water use sectors. This competition for water is exacerbated by population growth and mobility, and by deteriorating water quality as a consequence of intensification of water use and from environmental water requirements.

Conventionally, the solution to water supply problems included the construction of dams and inter-basin transfer schemes (Gillham and Haynes, 2000). However, these practices are becoming increasingly criticised, not only for their inherent social and environmental impacts, but also for their singular approach to often complex and inter-connected issues. A potentially viable alternative to augmenting water supply is the implementation of water demand strategies that focus on increasing the efficiency of water use by consumers. Even where there is limited scope for such strategies, water demand management can delay the need for expensive, engineered structures. Nonetheless, demand management strategies to reduce bulk supply, such as repairing leaks, progressive tariffs and waste water recycling, generally incur additional expense for water users and these measures carry limitations.

Matching water demand with water supply for river basin sustainability requires good river basin management. Furthermore, the effective management of water resources in South Africa, in meeting demands imposed by both societal and environmental systems, requires the adoption of an integrated procedure to promote equitability for all interested and affected parties and for the sustainability of the water resource. To this extent, the Department of Water Affairs and Forestry (DWAF) recognises and accepts the necessity of an integrated management approach in South Africa, based on catchments as the *logical* representation of hydrological units (DWAF, 1996).

Increasingly, there has been a paradigm shift from providing water supply to integrating the planning and management of water resources to account for conflict and competition for water among irrigated agriculture, forestry, domestic supply, industry and the environment, with the economic, social and environmental costs as well as benefits of water management decisions. More specifically, contemporary trends in integrated water resources management (IWRM) focus on the holistic nature of ecosystems, recognising the interactions between land use and the aquatic environment. For this reason, the main purpose of this dissertation is not to explore the broad issues relating to the current state of best IWRM practice in terms of governance and policy, but rather to focus on the impacts of land use, climate and catchment development on the hydrological regime and the implications for river health and aquatic ecosystems. These studies are undertaken for the 4383 km^2 Mkomazi Catchment in KwaZulu-Natal through the setting up of a readily applicable hydrological modelling system for the catchment.

Concerns have been raised that water shortages in South Africa could limit economic growth and lead to a national crisis in South Africa by 2025 (Gillham and Haynes, 2000). This factor, together with the belief that the existing water legislation was inappropriate to South Africa's climatic and societal conditions, led to the restructuring of the nation's water law in the late 1990s. More specifically, policy makers recognised that economic development had previously been unequally distributed within the nation as a result of limited land access and water rights. The National Water Act No. 36, 1998 (NWA, 1998) is perceived by water managers to be far-sighted in its fundamental concept of shifting water management from meeting water demand, to water allocation for sustainable water resource allocation. The general issues of concern in water resources management and planning in South Africa are briefly reviewed in Chapter 2.

Decisions made to ensure an equitable water allocation must now also meet the provision of the National Water Act, 1998 (NWA) that appraises the environmental reserve as having priority over any other water user, other than that for basic human needs. Environmental requirements for rivers are now more stringent than in the past and their quantification is needed in order that water managers can account for this water demand in their management plans (Hughes, 1999a). The development of instream flow methodologies, both internationally and nationally, to assess the flow requirements of aquatic biota and ecosystems is discussed in Chapter 3. Particular focus is directed to the locally developed Building Block Methodology (BBM), which originated in two major South African workshops on instream flow requirements in 1987, and its derivatives for the assessment of the environmental reserve.

Chapter 4 introduces the case study catchment, *viz*. the Mkomazi located in KwaZulu-Natal and with distinct water resource issues. The Mkomazi Catchment is presently (2001) economically and socially underdeveloped and consequently the Mkomazi river system is generally in good ecological condition. This factor, together with regional water authority plans to impound the Mkomazi River for water transfer to the Mgeni system (DWAF, 1998a) provides a unique opportunity to assess the impacts of land use, climate and development on this catchment's hydrological dynamics.

Constraints imposed by the shortcomings of inadequate databases together with, frequently, limited time permissible for determining the availability of water resources, have resulted in water managers requiring tools which assist in their decision making processes. Water resource managers therefore need support from reliable modelling systems that integrate a variety of tested techniques, in order to make sound decisions.

Chapter 4 therefore also focuses on the application of the *ACRU* agrohydrological simulation model (Schulze, 1995a) to meet this challenge and presents the development of an installed modelling system for the Mkomazi Catchment for potential use by water resource managers. The case study continues in Chapters 5, 6 and 7 with the assessment of various water management scenarios of streamflow generation within the Mkomazi Catchment. The individual water demand of each of the principal water use sectors in the Mkomazi Catchment is quantified in Chapter 8 and an assessment is made of the streamflows available for further allocation.

In terms of the NWA, DWAF has initiated a Water Situation Assessment Model (WSAM) for the evaluation of water availability. The environmental demand is potentially substantial for many catchments and under the provisions of the NWA the granting of any potential water use licences will be subject to the requirements of this demand being met first. There is therefore a defined need, nationally, to quantify the environmental reserve. The final case study Chapters 9, 10 and 11 examine the instream flow requirements for the Mkomazi River in terms of the BBM workshop process (described in Chapter 3), the extent of alteration of the natural flow regime of the Mkomazi streamflows and preliminary management targets for the Mkomazi ecosystems.

The limited availability of water resources for different water use sectors presents one of the most challenging issues arising from the implementation of effective management and potential future development of South Africa's catchment areas. Sound hydrological modelling has been identified as a major determinant of whether the impacts of proposed catchment developments limit or exceed the capability of the natural resource base to meet water demand. Thus the overall aim of this dissertation is to describe the development of an installed hydrological modelling system for the Mkomazi Catchment that can be readily applied by water managers to assess catchment development issues.

Underpinning the success of any water resource management system is the identification of potential issues and areas of concern, as well as the needs and aspirations of the principal catchment stakeholders. This is all the more relevant when considering the provision in the NWA that some water must be set aside as an environmental reserve to protect the ecological functioning of rivers and the resource base itself (Hughes, 1999a).

Therefore, to summarise, the specific objectives of this dissertation are to:

(a) identify the issues that are distinctive to the Mkomazi Catchment

(b) highlight the processes available for the protection of environmental flows in the Mkomazi

(c) ascertain the impacts of land use, climate and proposed catchment development (specifically the inter-basin transfer to the Mgeni Catchment) on streamflow generation and the availability of streamflows for further allocation within the Mkomazi Catchment , and then to pay particular attention to

(d) assessing the alteration of the natural streamflow regime at the Mkomazi instream flow requirement sites, as a result of anthropogenic development, with a view to

(e) ascertaining preliminary management targets to sustain the integrity of Mkomazi aquatic ecosystems, all to

(f) determine the role that hydrological modelling can provide for the effective management of the available Mkomazi Catchment water resources.

Every catchment possesses a unique set of attributes, problems and complexities. While the Mkomazi Catchment is no exception, it is anticipated that the approach described could go some way to the determination of a generic methodology to assess not only the availability of catchment water resources, but also the impacts of potential development in sub-humid regions of southern Africa.

The following table provides a structure that associates the specific objectives listed above with the salient issues identified in this dissertation and is provided as reference guide to the chapters that address each particular topic. It is evident from the table that many of the Mkomazi Catchment issues are inter-linked and a number of the chapters address several of these issues simultaneously.

Table 1.1 Structure of the dissertation showing the association of the specific objectives with the salient issues identified for the Mkomazi Catchment as well as the chapters that address each particular topic

<table>
<tr><td colspan="6">General Introduction
(Sets the scene and identifies issues, aim and specific objectives)</td></tr>
<tr><td colspan="6">Specific objectives, salient issues and relevant Chapters</td></tr>
<tr><td>Objective a</td><td>Objective b</td><td>Objective c</td><td>Objective d</td><td>Objective e</td><td>Objective f</td></tr>
<tr><td>Water resource management requirements (Chapters 2, 4, 5, 6, 7, 8, 9, 10 and 11)</td><td>Instream flow assessment and methodology (Chapters 2, 3, 9, 10, and 11)</td><td>Baseline land cover for equivalent water use comparisons (Chapters 4, 5, 6, 7, 8, 9, 10 and 11)</td><td>Assessing hydrological variation in streamflow regimes (Chapters 2, 3, 9, 10 and 11)</td><td>Instream flow requirements (Chapters 2, 3, 8, 9, 10, 11)</td><td>Modelling applications and scenarios for water resources management (Chapters 3, 4, 5, 6, 7, 8, 9, 10, and 11)</td></tr>
<tr><td>Water sector demands and resource availability for allocation (Chapters 2, 8)</td><td>NWA and the Environmental Reserve (Chapters 2, 3, 4, 8, 9, 10 and 11)</td><td>Land use impacts (Chapters 4, 5, 6, 7, 8, 9, 10 and 11)</td><td>Impacts of hydrological variation on aquatic ecosystems (Chapters 2, 3, 9, 10, 11)</td><td>Restrictions imposed by inadequate ecological / hydrological data (Chapters 3, 9, 10 and 11)</td><td>Establishing confidence in modelling applications: verification studies (Chapters 4 and 5)</td></tr>
<tr><td>Land use impacts (Chapters 4, 5, 6, 7, 8, 9, 10 and 11)</td><td>Methodologies available / or applied for South African Rivers (Chapters 3, 8, 9, 10 and 11)</td><td>Streamflows under different climatic conditions (Chapters 4, 7, 8, 9, 10, 11)</td><td>Linking the historical streamflow record to habitat conditions and river health (Chapters 2, 3, 9, 10 and 11)</td><td>Setting management targets for sustainable development (Chapters 3, 4, 5, 6, 7, 8, 9, 10, and 11)</td><td>Recommending catchment management strategies for sustainable development (Chapters 3, 9, 10 and 11)</td></tr>
<tr><td>Inter-basin transfer (Chapters 4, 6, 7, 8, 9, 10 and 11)</td><td>Building Block Methodology workshop process (Chapters 3, 8, 9)</td><td>Inter-basin transfer (Chapters 4, 6, 7, 8, 9, 10, 11)</td><td>Impacts of land use change on the natural flow regime (Chapters 2, 3, 4, 5, 6, 8, 9, 10 and 11)</td><td>Recommending catchment management strategies for sustainable development (Chapters 3, 9, 10 and 11)</td><td>Monitoring the efficacy of management targets and strategies (Chapters 3, 9, 11)</td></tr>
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<tr><td colspan="6">Discussion
Relevance and inference of the studies</td></tr>
<tr><td colspan="6">Conclusion
Brings entire discussion to a conclusion, focussing on the extent to which the specific objectives were addressed</td></tr>
</table>

2 GENERAL ISSUES OF CONCERN IN WATER RESOURCES MANAGEMENT AND PLANNING

2.1 Introduction

Water has been described as a major limiting factor to economic growth within South Africa (Gillham and Haynes, 2000). The provision of water for human needs is constrained by temporal and spatial distribution of rainfall and high evaporation rates and it has been assessed that only 0.5% of South Africa's hydrological cycle is exploitable as a water resource (Kriel, 1985). Given that the quantity of rainfall and groundwater within the cycle is more or less constant, increased water consumption as a result of increased demand from industrial, agricultural, commercial and domestic water use sectors will at some stage result in demand overtaking supply (Day, [2000]).

During the past century the solution to the inequitable spatial distribution of surface waters resulted in the construction of large state dams and numerous small private farm dams. Huge feats of engineering were carried out within South Africa to transfer water from relatively water-rich catchments to catchments that lacked adequate supplies to meet demand (*e.g.* from the Tugela to the Vaal). However, the NWA recognises that there are limits to the development of large dams and inter-basin transfers and promotes more conservative practices with which to address the problem of reconciling water demand with water supply.

This chapter briefly reviews some of the more dominant issues of water resources management within South Africa. The climatic characteristics associated with the availability of water will be described, followed by a discussion of the water supply and demand management strategies ratified by the NWA. Finally, the issues relating to the protection of the water in river courses will be introduced as an innovative approach to the management of water resources.

2.2 Spatial Distribution of Southern Africa's Available Water Resource

Southern Africa (defined here as South Africa, Lesotho and Swaziland) is, generally, a semi-arid region, subject to uneven spatial distribution of rainfall and runoff generation, variability of river flows and drought as well as flooding, both of which are exacerbated by the impacts of human activity through changes of land use. Overall, runoff from southern Africa constitutes only 9% of the total rainfall, whilst 91% of all precipitation evaporates (Whitmore, 1971). The runoff to rainfall ratio in the region is low when compared with the world average of 35% and even the relatively wet province of KwaZulu-Natal has a runoff ratio of only 16.5% (Schulze, 1997).

The factors that influence runoff patterns vary from region to region as a consequence of the climatic regime (rainfall intensity and distribution as well as temperature), land use and soil characteristics. The spatial distribution patterns of median annual runoff of the 1946 inter-linked, officially designated Quaternary catchments in the region are presented in Figure 2.1. The runoff patterns indicate the spatial contrast between low runoff producing areas in the west and north, with one third of the region generating less than 10mm of runoff, and the zone of relatively high runoff extending from the Western Cape mountains through the former Transkei, parts of Lesotho, the province of KwaZulu-Natal, Swaziland and Mpumalanga (Schulze, 1997).

The variability of runoff from year to year presents uncertainties to the assured supply of water resources. Generally, the region is characterised by a very high coefficient of variation (CV) of annual runoff (Figure 2.2). Even areas with relatively reliable runoff generation have inter-annual CVs close to 40%, whereas some 20% of the region has a CV of runoff greater than 160% (Schulze, 1997). Thus, major dams in the region's catchments have to be designed with full storage capacities often considerably greater than the storage capacity of the MAR, to ensure a dependable yield of resources in periods of drought.

The total surface runoff in South Africa has been estimated at being close to 50 000 million m^3 per annum and although some 75% of domestic demand in certain rural areas is supplied from boreholes, there are few major aquifers in South Africa (Stoffberg *et al.*, 1994). Thus, the physical limitations associated with high temporal and spatial variability

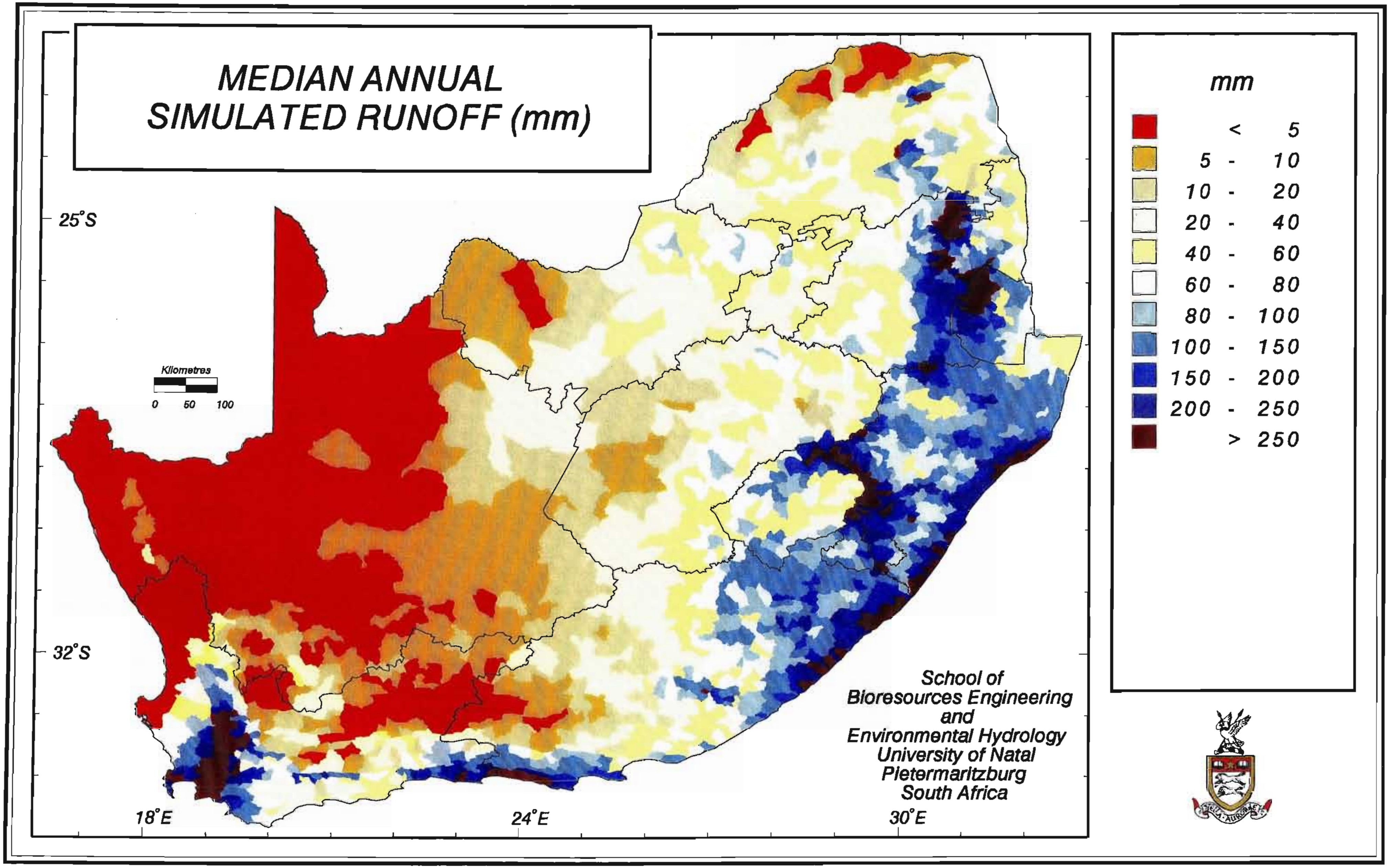

Figure 2.1 Median annual simulated runoff (mm) in southern Africa (Schulze, 1997)

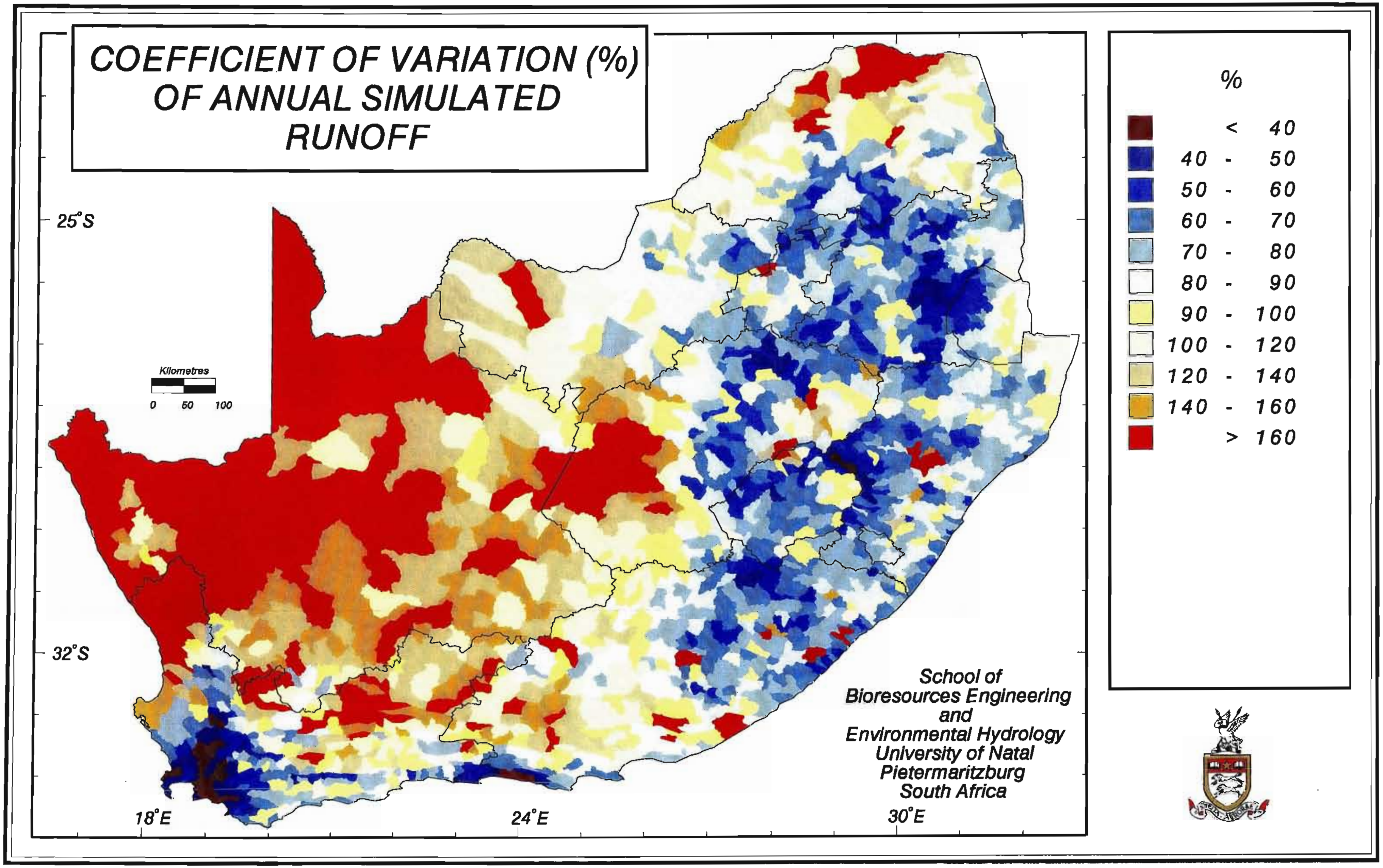

Figure 2.2 Coefficient of variation of annual simulated runoff (%) in southern Africa (Schulze, 1997)

of surface and groundwater resources call for sound management practices to safeguard the availability of adequate water supplies.

2.3 Managing Catchment Water Resources

The distribution and variability of the region's MAR largely control the availability of land for agriculture, development and recreational activities. The limited availability of water resources amplifies the complexities, costs and uncertainties associated with effective management of sustainable water supply for the various water use sectors and for potential development. Population growth, aspirations for improved living standards and economic development not only place high priority and increasing demands on the scarce water resource, but can also impact detrimentally on the resource base, both quantitatively and qualitatively, thereby resulting in even further constraints.

2.3.1 Water resources management

The DWAF has advocated catchment management as the best way to manage water resources to meet human needs in a sustainable way (DWAF, 1996). This basic premise has been embraced by the National Water Act (NWA, 1998) which promotes integrated water resources management (water allocation plans, control, development, management, conservation, and protection and use of water resources) at a catchment scale (NWA, 1998). The implications of this concept are that land uses within catchments will also be regulated (WISA, 2000). The new legislation provides for the declaration of Streamflow Reduction Activities, defined as the water use by any activity that reduces streamflow when compared to the runoff from natural vegetation (NWA, 1998). Presently (2001), forestry plantations are the major contenders for runoff reduction activity and there is great sensitivity associated with the regulation of the impact of this sector on water resources.

The present political administration in South Africa has provided the opportunity to address some of the inequities associated with the water rights and water allocation that prevailed under the previous government. The NWA overhauled previous water legislation and provides for a transformation of the water management system from an essentially private system to a public rights system or licensing system (WISA, 2000). The new water policy treats all water within the hydrological cycle as a common resource (Gillham and Haynes, 2000) and, as such, is subject to water resources management that ensures equitable allocation. This concept is manifest in the extent to which stakeholders within catchments are now empowered to decide how to use their water. Catchment Management Agencies (CMAs), the representatives of catchment stakeholders, are mandated under the NWA to identify pressing catchment issues and to formulate and adopt strategies to address them (WISA, 2000). WISA (2000) provide the example that water users within a catchment could decided whether to invest in the eradication of alien plants to increase river system yield or to augment supply by the construction of new water storage, depending on which provides the best value for money.

However, the new water policy also recognises that water resources augmentation with the construction of large dams and inter-basin transfers to increase the yield of river systems has limited potential in South Africa. Few technically suitable sites remain for the construction of large new dams in South Africa, although a few are in the planning stage. A potential water scheme has been proposed to transfer water from the underdeveloped Mkomazi Catchment in KwaZulu-Natal to the neighbouring Mgeni Catchment, where local resources have been all but exhausted (Gillham and Haynes, 2000). This particular proposal has been highlighted as a long-term strategy for the augmentation of water resources in the Mgeni Catchment and will be discussed in Chapter 4.

There is therefore, a need to develop more conservative and protective approaches, by all major water use sectors, to manage available water resources. This will require knowledge of how much water is available and an understanding of how to assure access to the water that is required (WISA, 2000). These uncertainties will be explored for the Mkomazi Catchment in Chapters 6 to 11.

2.3.2 Water demand management

Notwithstanding the devastating impacts of AIDS, the greatest social and environmental problems in developing countries emanate from continued and rapid human population expansion and the poverty associated with too few resources to meet human daily needs. Despite the poor living conditions in many southern Africa cities, pressures on urban populations have been exacerbated by an influx of people leaving rural areas where employment opportunities and living conditions are even worse. Water resource managers in rural and urban areas alike are faced with immense problems in supplying the basic human health requirements to majority of the population.

Where local water resources have been fully utilised, water demand management is a viable strategy for those catchments for which the rate of growth of demand from domestic and industrial growth is projected to increase. However, to be successful, this has to be achieved without reducing the required water supply or compromising economic growth. The principle methods of meeting this challenge are to improve water supply efficiency, increase water use efficiency, raise water tariffs, withdrawal of service for non-payment and addressing waste water treatment (Gillham and Haynes, 2000). Gillham and Haynes (2000) cite the example of Durban Metropolitan Council implementing a strategy incorporating these methods to reduce a loss amounting to 30% of their total consumption. However, it is likely that the consequence of these measures will only meet deficits in the short to medium term. Umgeni Water, the regional bulk water supplier to the Durban Metropolitan Council considers the provision of additional dams and inter-basin transfer in the region (*cf.* Chapter 4) to be the only viable long-term solution.

Reconciling water supply with water demand has become a urgent water management issue in that the more water is utilised by the human population, the less there is available for natural ecosystems (Day, [2000]). While the NWA advocates that nobody owns the water, the new water policy recognises that the water in rivers forms the resource base and belongs to the river itself. The first priority of allocation from this water is a human health "reserve" to meet basic drinking and washing water (*cf.* Section 2.5.3.1). Subsequently, an ecological, or environmental, "reserve" will be conserved to sustain the aquatic and riparian ecosystems (*cf.* Section 2.5.3.2). Under the provisions of the NWA, the granting of any potential water use licences will be subject to the requirements of these reserves (together termed the "Reserve") being met first.

2.4 Maintaining River Health and Aquatic Ecosystem Integrity

As South Africa's water resource is subject to ever increasing user demands associated with increased population growth, social aspirations and economic development, there is growing concern that the stress placed on the country's rivers has already led to a deterioration in water quality and of habitat and aquatic species richness. Water resource development projects such as the building of major dams are anthropogenic modifications to the natural flow regime and as such any proposed dam building programme requires assessment of its impact on the river's health.

Flood-mitigation dams attenuate peak discharges, which would otherwise overflow the riverbanks and spill onto the floodplain (Gordon *et al.*, 1992). Reservoirs built and used for irrigation abstraction or domestic supply modify the natural flow regime by storing water from high streamflow events and through the release of water at high peak user demands. Modifications in the frequency, timing and duration of floods can eliminate the biological cues required to initiate spawning or migration as well as reduce access to areas used as spawning sites (Richter e*t al.*, 1997). Increases in the frequency or duration of high flow levels can disturb benthic organisms, which require less velocity in stream flows for survival (*cf.* Chapters 10 and 11).

2.4.1 Instream flows

Instream flows are those river waters which are retained in their natural setting, as opposed to those which are diverted for offstream use such as industry, agriculture and domestic supply (Gordon *et al.*, 1992). Karim *et al.* (1995) have described the term "instream " as a misnomer in as far as flows in a river are also required for maintenance of wetlands, estuaries and floodplains. In this context the flows are not strictly "instream". However, they are crucial to the maintenance of aquatic ecosystems. Notwithstanding this consideration, instream flows are essential determinants of channel morphology, riparian and aquatic flora and fauna, water quality, estuarine inflow and sediment transport (Estes and Orsborn, 1986).

In a number of countries, water resource projects that impact on instream flows are subject to evaluation of the provision of flows for the maintenance or enhancement of riparian habitat or aquatic organisms. Such flows are often referred to as environmental flows and their function is to sustain river ecosystems. In South Africa the issue of environmental flows was first addressed in 1987 through two major workshops (Ferrar, 1989; Bruwer, 1991). Simultaneously, there was a change in DWAF policy from that of the provision of water on demand to that of integrated and holistic management of the water resource (King and Louw, 1998). By 1994, DWAF 's attention to water quality management and water for the environment had become key policy issues with the recognition of the aquatic environment as the base part of the resource and requiring protection if potential water resource development projects were to be sustainable (DWAF, 1994).

2.4.2 Disturbance to the stream ecosystem

Regulation of streamflows through impoundment affects both the hydrology and the morphology of the stream channel. The alteration of streamflows through anthropogenic interference and the resultant impacts on aquatic ecosystem integrity becomes more pronounced as the predictability of the hydrograph declines (Gore *et al.,* 1992). Gore *et al.* (1992) further postulate that the significance of this factor is more critical for arid and semi-arid river systems where the greatest change will result from even small alterations to streamflows.

2.4.2.1 Impacts of disturbance on aquatic ecosystems

Changes in the natural streamflow regime can lead to alterations in those stream substrate conditions under which the biota have evolved (Gordon *et al.*, 1992). Such changes could impact adversely for indigenous river species if, for example, a shortened spring runoff [in European rivers] were to reduce the period for selected fish spawning and egg incubation (Newbury and Gaboury, 1988; cited by Gordon *et al.*, 1992). Alternatively, changes in the natural streamflow regime could impact favourably for introduced species. For example, Davies *et al.* (1988; cited by Gordon *et al.*, 1992), found that a decrease in the inter-annual variability in a river system in Tasmania, Australia resulted in increased populations and more stable age structures in the brown trout, *Salmo trutta L.* The species, having been introduced from England, was better adapted to a less variable flow regime.

Changes in habitat as a result of modification of streamflows can impact on specific life stages of aquatic biota. Unless fish have access to backwaters, pools or low velocity refuges during high flows, there is the possibility that fish eggs maybe carried downstream by the higher velocities (Newbury and Gaboury, 1988; cited by Gordon *et al.*, 1992).

Changes in hydraulic conditions can also impact on aquatic community structure. Increased velocities and shear stresses affect the hydrodynamic river shape (Scarnecchia,

1988) and therefore have the potential to alter aquatic species diversity. Scouring can result in the removal of riffles, which aerate flows, as well as the reduction or elimination of shelter by the removal of undercut banks and overhanging vegetation. In general the substrate becomes unstable, reducing benthic invertebrate production (Statzner and Higler, 1986; cited by Gordon *et al.*, 1992).

2.4.2.2 Modification to flushing flows

In unregulated rivers the channel is maintained by periodic flooding (Gordon *et al.*, 1992). Diversion of water from a river does not usually impact on the frequency and duration of floods or flushing flows (also termed freshes). Conversely, impounding or diverting a large proportion of the natural river flow can have significant impacts on the flow and sediment transport regime of a river (Jowett, 1997). Any change in the timing, magnitude and frequency of high flows can impact on the channel shape as well as the substrate composition and arrangement (Gordon *et al.*, 1992). A reduction in streamflows, as a result of upstream impoundment, can lead to vegetation encroachment, siltation and channel narrowing, all of which impact on the river's physical habitat. In spite of some of the negative impacts of disturbance to the steam ecosystem, a level of disturbance which provides environmental heterogeneity, while still facilitating the establishment of communities, is necessary to maintain optimum stream biotic diversity (Ward and Stanford, 1983; cited by Gordon *et al.*, 1992). Periodic flooding (flushing flows) can help create and maintain such variability in the channel substrate and for this reason is regarded as being of crucial consideration in any instream flow assessment (*cf.* Chapters 9, 10 and 11). There is also a need to provide for flushing flows in an instream flow recommendation in order to mitigate against the deposition of fines and to maintain the existing channel characteristics (Gordon *et al.*, 1992).

2.5 Legislation to Protect the Water Resource

The protection of water resources encompasses all instream resources and uses, including their development, management and control (NWA, 1998). The concept of protection of water resources predisposes that there is a method to measure, or determine, levels of protection for that resource. Legislation can prescribe the guidelines for the specified level of environmental protection (Jowett, 1997). The NWA (1998) makes provision for the protection of water resources. Parts 1, 2 and 3 of Chapter 3 of the NWA deal with a series of measures which, together, are intended to secure the level of environmental protection sought. The following sub-sections briefly describe those measures.

2.5.1 Classification system

Part 1 of Chapter 3 of the NWA (1998) provides for the development of a national classification system for water resources by the Minister of Water Affairs and Forestry (hereafter referred to as the Minister). In terms of the NWA, it is intended that the system should provide guidelines and procedures for determining different classes of water systems and in respect of each class, *inter alia*, establish procedures for determining the Reserve (*cf.* Section 2.5.3). As well as the provision for the Reserve, the intention of this legislation is the assurance that riverine resources are sustained at a "desired future state", to be known as a "management class". The management class of any river, or section thereof, depends on the protection objectives for that river reach.

2.5.2 Protection objectives

As stated by Beecher (1990; cited by Jowett, 1997), instream flow management should have clear and measurable objectives (*cf.* Chapter 11). However, the level of protection sought may allow the objective to vary with the relative value of the water resource. Aspirations to maintain a river in near pristine conditions will lead to a high classification, whereas progressively lower classifications will be acceptable for rivers which need not, or cannot, be maintained in such good condition. Having established a classification system the Minister is required, in terms of Part 2 of Chapter 3 of the NWA (1998) to use the system to determine the class and resource quality objectives of all, or part, of every significant water resource. The objectives determined may relate to, *inter alia*, the Reserve, the instream flow, the characteristics and quality of the water resource and the instream and riparian habitat as well as the characteristics and distribution of aquatic biota.

2.5.3 The Reserve

Part 3 of Chapter 3 of the NWA (1998) provides for a part of the water resource known as the Reserve. The Reserve is, in principle, a health reserve and refers to both the quantity and quality of the water in the resource, which will vary according to the class of the resource. It is a requirement of the NWA that the Minister determines the Reserve for all, or part, of any significant water resource. In terms of Part 3 of Chapter 3 of the NWA (1998), the Reserve is defined as comprising of two parts *viz*: the basic human needs reserve and the ecological reserve.

2.5.3.1 Human needs reserve

Primarily, the basic human needs reserve provides for the fundamental water requirements to sustain the lives of those individuals served by the water resource. This component includes drinking water and washing water for food preparation and for personal hygiene. The water allocation for individuals has been assessed as being 25 litre per person per day, to be provided within 200 m of the dwelling (Roberts, 1998, pers. comm.). However, this quantity may be increased in the future to 50 litre per person per day and could possibly also include an amount reserved for subsistence farming.

2.5.3.2 Ecological reserve

The ecological reserve, also referred to as the environmental reserve, is defined as the water required for the protection of the aquatic ecosystems of the water resource (NWA, 1998). Thus the ecological reserve provides for that quantity of the water resource required to keep the interacting biological and physical river processes functioning. Moreover, the premise of the ecological reserve, in terms of the NWA, 1998, is that any future utilisation of the country's water resources depends on sustaining the ecosystem goods and services that these water resources provide.

2.6 Measurement of Aquatic Environmental Protection Objectives

The level of aquatic environmental protection provided by instream flows can range from enhancement at the upper end of the scale to species survival at the lower end (Beecher, 1990; cited by Jowett, 1997). However, as stated by Jowett (1997), the goal of non-degradation of instream resources can only be achieved if there is no change to the natural flow regime. Because of the inherent difficulties of measuring environmental goals with biological response, both temporally and spatially, it is evident that the objectives of environmental protection for water resources should be implemented by more practical procedures (Jowett, 1997). This factor has led to the development of instream flow assessment methods to meet the goals of protection for the aquatic environment (*cf.* Chapter 3).

2.7 Conclusions

This brief overview has focused on some of the more urgent issues in contemporary water resource management. The temporal and spatial availability of water resources in southern Africa and the evolution of its allocation to different water use sectors resulted in conflict in the past. However, the revised South African legislation has placed a new dimension on water resource management through the promotion of integrated water resource management as a legislated catchment management strategy. This water law addresses the allocation of water in ways that attempt to ensure sustainable economic and social development, while protecting the resource base itself.

* * * * *

The following Chapter focuses on the links between river health and river flow and describes the evolution of instream flow assessment methodologies, internationally and nationally. The setting aside of the environmental reserve as a water allocation for the management of the resource base has prompted considerable new research within South Africa in recent years and Chapter 3 concludes with a review of the methods currently available and employed to do so. The challenge of assigning management targets to maintain variability within hydrological regimes will be revisited in Chapters 9, 10 and 11 as a conclusion to the Mkomazi case study, which is described in Chapters 4, 5, 6, 7, and 8.

3 PROCEDURES TO INCLUDE THE ENVIRONMENTAL RESERVE IN WATER RESOURCES PLANNING

3.1 Introduction

Rivers are not only sources of freshwater as a renewable resource, but also structurally and functionally complex, diverse and dynamic ecosystems (Tharme, 1996). However, as described in Chapter 2 pressure on South Africa's rivers to sustain the scale of development required to meet the needs of increasing demand on the resource has led to concern over the river flow patterns required for the survival of aquatic species and wildlife habitats. The extent to which the natural flow regime can be altered without detriment to these valued ecosystems has led to the founding of the concept of instream flow requirements of rivers. These requirements are determined by instream flow assessments, which are performed to determine the quantity of water that must remain in the river system to sustain the integrity of the aquatic habitat at an acceptable level or desired state (referred to as management class in South Africa, *cf.* Section 2.5.1).

In the late 1980s the national contingent of aquatic scientists began to develop expertise in instream flow assessment in response to the need to provide recommendations for river flows (Tharme and King, 1998). Studies for the evaluation of the impacts of water resource projects, such as major dam impoundments, on aquatic ecosystems have increased over recent years, particularly since the promulgation of the NWA, as described in Chapter 2. Since aquatic ecosystems are best preserved and maintained under pristine streamflow conditions, it has become a requirement by the Department of Water Affairs and Forestry (DWAF) that any proposed water resource development project be subject to an instream flow assessment to ascertain the "natural" flow conditions.

Knowledge of the relationships between river morphology, flow related conditions, aquatic ecosystems and habitat are crucial to sound instream flow methodologies and ultimately to effective water resource planning if the goal of providing protection to the environment is to be achieved. Different instream flow assessment methods arise from the different environmental goals and levels of protection that may be sought. In this Chapter, the evolution of instream flow methodologies will be described. Whilst no comparison will be made of the various international approaches of instream flow methodology, focus will be directed to the processes commonly adopted to include the environmental reserve in water resources planning in South Africa.

3.2 Instream Flow Assessment

The aim of instream flow assessment studies is to ascertain the flow requirements of particular riverine species and to identify the timing, duration and magnitude of the flows required to secure maintenance of the population. Since indigenous species have evolved life stages and cycles in response to the natural flow regime, the best recommendation for instream flow requirements is one which mimics nature and includes variability in terms of historical patterns of high, low and zero flows (Gordon *et al.*, 1992). In this respect, instream flow requirements can be defined as being those streamflows which are essential to maintain a river's natural resources at desired or specified levels (Karim *et al.*, 1995).

3.3 The Development of Instream Flow Methodologies Internationally

Intrinsically, the determination of the instream flow requirements of rivers arose from the legal necessity to recognise and consider the aquatic environment both formally and explicitly (Karim *et al.*, 1995). The initial development and application of formal methodologies for determining instream flow requirements was instigated by legal policies in the USA. Consequently, the techniques for determining instream flow requirements were principally developed in the USA (Karim *et al.*, 1995). The first documented study for assigning instream flow requirements was performed for the Colorado River in the USA below the proposed Granby Dam site by the US Fish and Wildlife Service in the late 1940s (Tharme, 1996). However, because a number of different agencies, both federal and state, were involved in water resources management during the next three decades, the culmination was the development of instream flow methodologies which were considered not to address the issues in an holistic approach.

Initially, the evaluation of instream flows was aimed at the protection of the instream habitat for fish and wildlife. However, latterly the emphasis has shifted to interdisciplinary water resource planning (Tharme, 1996). The assessment of the instream flow requirements of rivers in Britain, Australia and New Zealand was initiated in the 1980s (Tharme, 1996).

3.4 Quantitative Instream Flow Assessment Methods

Implicit in any instream flow assessment is the need to assess and mimic natural river conditions. The major determinant of river channel shape, besides geology, is the streamflow regime (Jowett, 1997). River width, water depth and velocity all increase with discharge, although the relationships for both water depth and velocity with discharge are less well defined. Mosley (1992; cited by Jowett, 1997) presents the average relationships, derived over normal to high flows as:

$$W \alpha Q^{0.5} \qquad D \alpha Q^{0.4} \qquad V \alpha Q^{0.1}$$

where W is the average width, Q the discharge, D the average water depth and V the average velocity.

The slope of the relationship can, however, change if there is an abrupt change in the channel geometry, corresponding to inflection points of width to flow, or depth to flow curves (Mosley 1992; cited by Jowett, 1997), as would be the case when, for example, a river overflows onto its floodplain. Whilst points of inflection for width, depth or habitat with discharge are well defined for rivers of moderate gradient in well defined channels, these relationships are more complex in braided rivers (Jowett, 1997). Additional braids are formed with increasing discharge, resulting in increasing width and usable habitat (Mosley, 1982). Notwithstanding this factor, the point of inflection is considered to be a principal determinant in instream flow assessment.

The development and application of methodologies for determining instream flow requirements has led to the recognition of three distinct categories of flow assessment methods, *viz.*

(a) according to historical flow regime,
(b) channel hydraulic geometry and
(c) habitat rating (Karim *et al.*, 1995; Jowett, 1997).

Whilst all three major categories of quantitative instream flow assessment methods aim to maintain the aquatic environment, each focuses on different stream characteristics, such as flow, wetted perimeter or physical habitat (Jowett, 1997). However, all methods assume that the proportion of the flow, wetted perimeter or physical habitat prescribed as a level of protection mimics the character of the stream environment (Jowett, 1997).

To a certain extent some methods incorporate the assumption that there is a linear relationship between the quantity of flow and the condition of the stream, inferring that there is a cut-off level, or minimum flow, below which aquatic ecosystems would be degraded (Jowett, 1997). However, as concluded by Jowett (1997) this assumption is unfounded as some methods indicate that environmental response to flow is shown to be non-linear in as much as the relative change in width and physical habitat with flow is greater for small than for large rivers. A review of the three categories of quantitative instream flow assessment methods for selection of minimum flow is presented below. As the greater part of this review (Sections 3.4.1 to 3.4.5) is based on the paper already referred to in this section by Jowett (1997), no further reference will be made to that paper. However, it should be stressed that the assessment of flow requirements for South African rivers has shifted from the concept that aquatic ecosystems compete with other water users. Water resources managers are required to classify the management class of all water resources and to specify the quantity and patterns of flow required to sustain the aquatic ecosystem of each water resource within the management class set for it (*cf.* Section 2.5.1).

3.4.1 Historical flow methods

As expected, historical flow methods rely on existing streamflow values either recorded or modelled (*i.e.* synthesised). These methods have also been referred to as fixed percentage, or threshold, methods because they are applied with a fixed proportion of flow reduction to historical flow data of the specified river (Prewitt and Carlson, 1980; cited by Tharme, 1996). Assessment methods based on historical flows introduced the term "minimum flow". The term was implemented in the USA to restrict usage of offstream water during the low flow season, the inherent assumption being that at other times of the year instream flows would be adequate if maintained above this minimum value (Trihey and Stalnaker, 1985; cited by Tharme, 1996). In the application of historical flow methods it is assumed that the relationship between environmental response and discharge is linear (Figure 3.1).

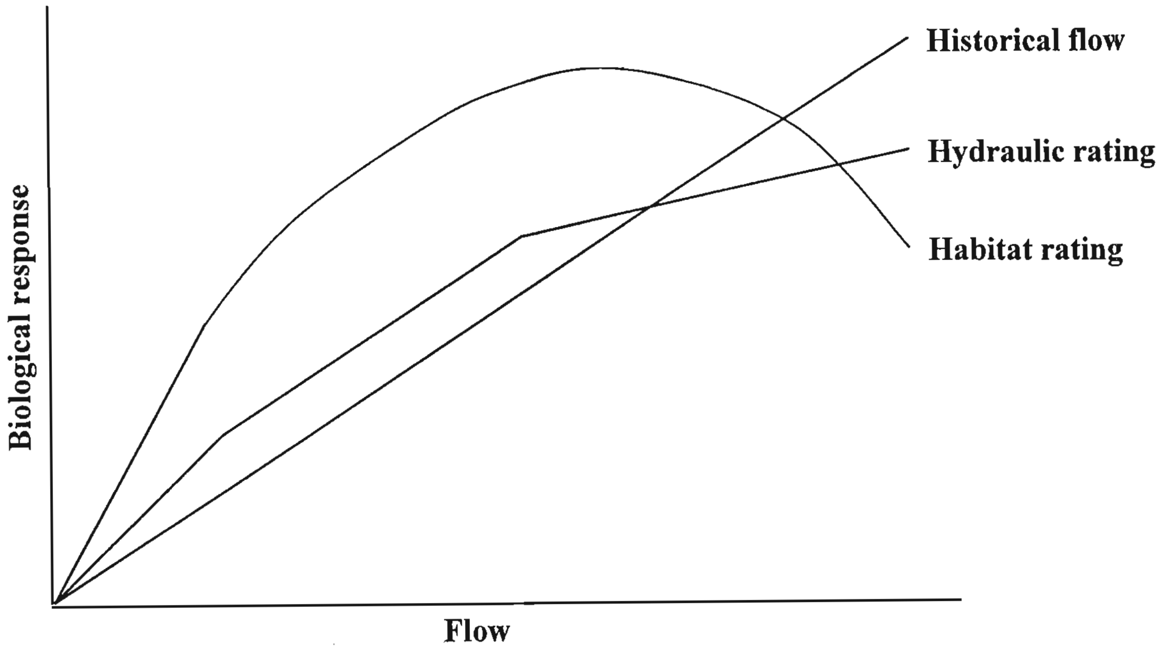

Figure 3.1 Relationships between flow and biological response for a hypothetical river, where biological response is expressed in terms of the measures used in flow assessment methods; based on historical flow methods, wetted perimeter for hydraulic methods and weighted useable area for habitat methods (after Jowett, 1997)

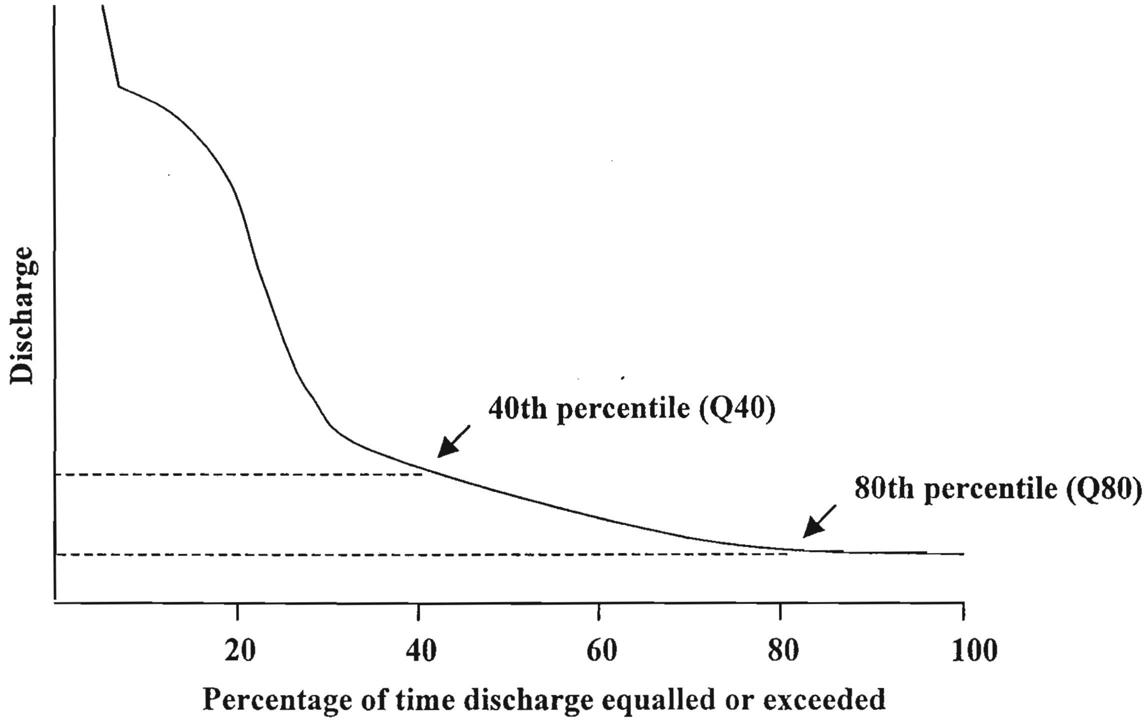

Figure 3.2 Schematic flow duration curve, illustrating some percentiles used for instream flow recommendations (after Tharme, 1996)

Tennant (1976) suggested fixed percentage values, for varying levels of environmental protection, ranging from 10% of mean annual flow (MAF) as that discharge required to sustain aquatic ecosystems at short term survival, to 200% of MAF for flushing flows (*cf.* Table 3.1). It has been suggested by Fraser (1978), that these fixed percentage values could be extended to address seasonal variation by prescribing monthly minimum flows as a proportion of monthly mean flows.

It should be noted that the values given in Table 3.1 are applicable to categories of percentage of MAF recommended for instream flow requirements for rivers in the Northern Hemisphere. However, the principle of categories of percentages of MAF for recommending instream flow requirements as an example of a methodology based on historical flows, is still valid for southern African rivers.

Table 3.1 Instream flow recommendations for fish, wildlife, recreation and related environmental resources by the Tennant method (after, Tennant, 1976).

Description of flows	**Recommended baseflow regimes (% of MAF)**	
	October - March	**April - September**
Flushing flows	200% of the average flow	
Optimum range	60 – 100% of the average flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	40%
Poor or minimum	10%	40%
Severe degradation	10% of average flow to zero flow	

Minimum flow requirements can also be recommended on the basis of a threshold flow derived from flow duration curves, or an exceedence probability of a specified low flow, as assessed from historical records and incorporating a desired level of environmental protection in the extent of the percentage. Figure 3.2 (page 27) indicates the way in which flow duration curves may be used to determine specific flow percentile(s) as instream flow recommendations. Arthington *et al.* (1992) suggested that seasonal variation could be addressed by recommending a monthly minimum flow based either on a percentage exceedence for each month or on a low flow that featured frequently in the records. This is similar to Fraser's (1978) suggestion described above, but also addresses the variability for wet seasons and floods, thereby more comprehensively mimicking the natural flow regime.

3.4.1.1 Morphological rationale

Methods based on historical flows focus on the relationship of the river channel parameters of depth, width and velocity with discharge. The effect of prescribing a percentage, or exceedence value, of historical flows as a minimum flow requirement on these parameters can be derived from the average relationships described in Section 3.4. For example, at 30% of average flow, the water velocity is $0.3^{0.1}$, or 89%, of the velocity at average flow. The effect would be similar for river width and depth. The hydraulic conditions that result from applying the same percentage minimum flow recommendation to different rivers will vary from river to river. However, the conditions that reflect the natural flow regime will be preserved, which helps to retain the morphological character of any particular river; swift rivers remain swift when compared to slowly moving rivers and large rivers remain proportionally large when compared to smaller rivers. Methods using a percentage exceedence flow also result in recommendations that maintain hydraulic characteristics in proportion to river size.

3.4.1.2 Ecological rationale

The ecological rationale inherent in historical flow methods is that maintenance of aquatic organisms is achieved by recommending a minimum flow that is within the historical flow range. Because the existing species have survived under these conditions, it is assumed that the life supporting components of food, water temperature and quality as well as habitat suitability are sufficient at such minimum flows. However, there is contention among the proponents of the application of instream flow assessment by historical methods, in that while Tennant (1976) recommends a minimum flow of 10% of MAF for any river, Arthington *et al.* (1992) state that zero flows are appropriate in Australia when rivers are ephemeral. To this extent it is proposed by Karim *et al.* (1995) that minimum flow recommendations based on historical flows should reflect all aspects of the flow regime and include seasonal patterns of flow, low flows, periods of no flow and flood flows.

3.4.2 Hydraulic methods

Hydraulic methods of assessment use changes in various parameters of the hydraulic geometry of rivers such as width, depth, velocity and wetted perimeter, with discharge to develop instream flow recommendations (Tharme, 1996). The hydraulic parameters are usually measured on single surveyed cross-sections, based on field observations and for this reason alone are more difficult to apply than historical flow methods. According to Mosley (1982), variation in hydraulic geometry with discharge can be accounted for by taking measurements at different flow rates. However, he expressed the opinion that concentration on mean values of depth, velocity and width is of little value in the assessment of instream flow in braided river channels. Perhaps it is for this reason that hydraulic methods are not commonly applied to seasonal flow assessment requirements. The most common hydraulic method applied considers the relationship between the wetted perimeter and discharge for determining minimum flow. A schematic representation of a wetted perimeter method is illustrated in Figure 3.3. This approach assumes that there is a non-linear relationship between wetted perimeter and the habitat availability and that because wetted perimeter increases with flow, the critical minimum environmental flow corresponds to a point of inflection (*cf.* Figure 3.1). It is assumed that below this discharge the wetted perimeter, and consequently the physical habitat, declines.

Tennant (1976) used the inflection point criterion to test and substantiate his postulation that stream width, water velocity and depth decline rapidly at flows less than 10% of MAF. However, Gippel *et al.* (1998) criticised the application of the point of inflection in the determination of identifying a critical minimum discharge in this manner. They (Gippel *et al.*, 1998) caution that the critical point on the curve is usually determined subjectively by eye from a graph and that the appearance of the inflection point is highly dependent on the scaling assigned to the graph axes. This anomaly can, however, be overcome by the application of appropriate mathematical techniques.

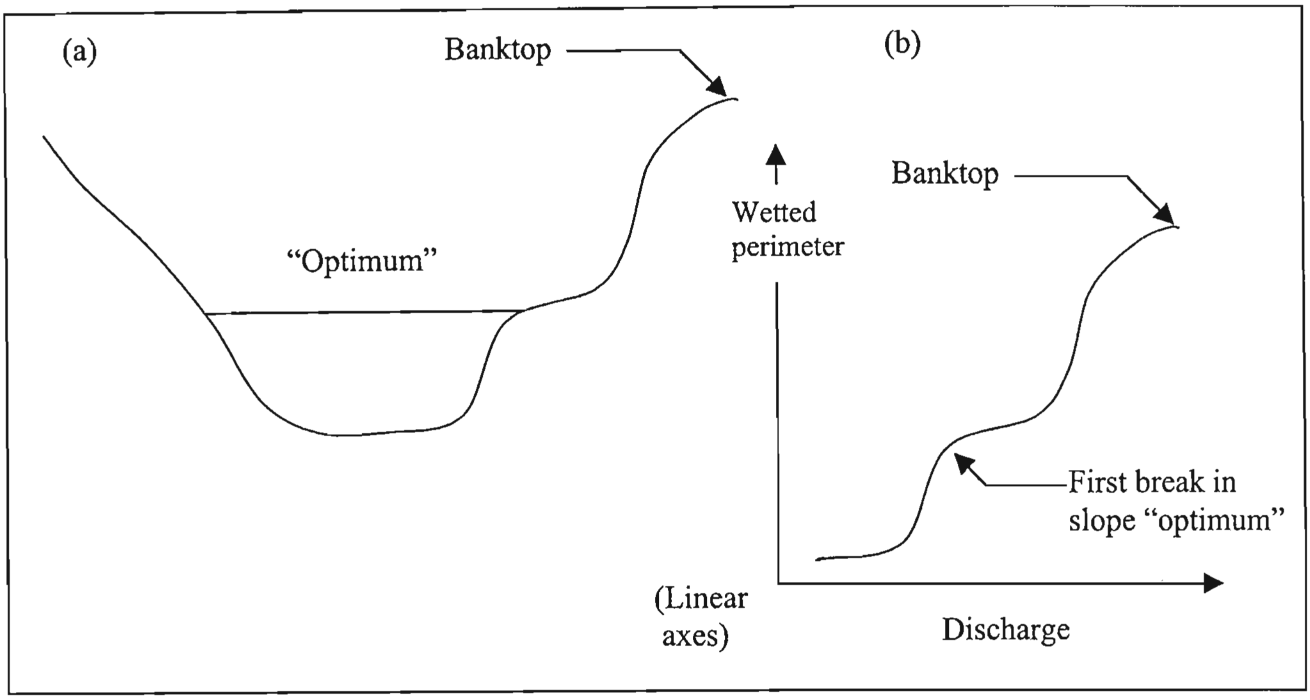

Figure 3.3 Wetted-perimeter method: (a) hypothetical channel cross-section and (b) graph of wetted perimeter *vs* discharge (after Gordon *et al.*, 1992)

A second criterion suggested for the determination of minimum flow requirements using hydraulic methods is that of percentage habitat retention. To achieve this, a percentage of width, or wetted perimeter, of the river at mean flow is identified as yielding the maximum permissible degradation and is subsequently recommended as the minimum percentage of instream flow that can be retained. However, if the minimum flow requirements were identified as a percentage of the river wetted perimeter at mean flow, and there is a linear relationship between wetted perimeter and flow, this criterion is effectively the same as a percentage of the mean flow, derived when using historical flow methods.

3.4.2.1 Morphological rationale

Because most river channels are essentially rectangular, width and wetted perimeter rapidly increase as the flow increases from zero and the channel fills with water. A point of inflection occurs where the flow just fills the base, and increase in width and wetted perimeter is restricted by the riverbanks. Thus, if based on a point of inflection, hydraulic methods identify the minimum flow that just fills the main channel.

Despite suggestions by Tennant (1976) that inflection points on rivers that are hydrologically similar would be a uniform proportion of the average flow, O'Shea (1995) applied the wetted perimeter method to 27 rivers in Minnesota in the USA and concluded that points of inflection, as a percentage of average flow, decreased with increasing river size. Some rivers exhibit more than one inflection point. Rivers with well-defined banks have one inflection point where flow just fills the channel to the base of the banks and another where flow just fills the channel to the top of the banks. Large rivers with poorly defined banks may not display any clear point of inflection because the hydraulic parameters increase smoothly with increased discharge.

Similarly to historical flow methods, hydraulic methods retain some of the river character; because of the focus on the relationship of channel width with discharge, the distinction between large and small rivers is maintained.

3.4.2.2 Ecological rationale

Unlike historical flow methods, the ecological rationale of hydraulic methods considers the food producing area of the stream. River width and wetted perimeter are fundamental determinants of the presence of periphyton and benthic invertebrates (White, 1976). Adopting the inflection point as an indicator of the desired level of protection ensures that food production is maximised because it generally occurs when the flow is sufficient to maintain water across full stream width. Therefore, the ecological goal is to keep the river channel full. As in the Tennant (1976) method, hydraulic methods cannot recommend zero flow. For most rivers, application of the point of inflection results in water depth and velocity being characteristic of natural flows. Therefore, determination of these features under hydraulic methods is considered to be sufficient to sustain aquatic organisms.

3.4.3 Habitat methods

Whilst habitat methods are viewed as a natural extension of hydraulic methods, the assessment of flow is based on those hydraulic characteristics which meet specific biological requirements rather than actual hydraulic parameters. The concept of the habitat methodology is represented schematically in Figure 3.4. Habitat methods use multiple cross-sections (*cf.* Figure 3.4, a) to determine the spatial aspects of the micro-habitat of the

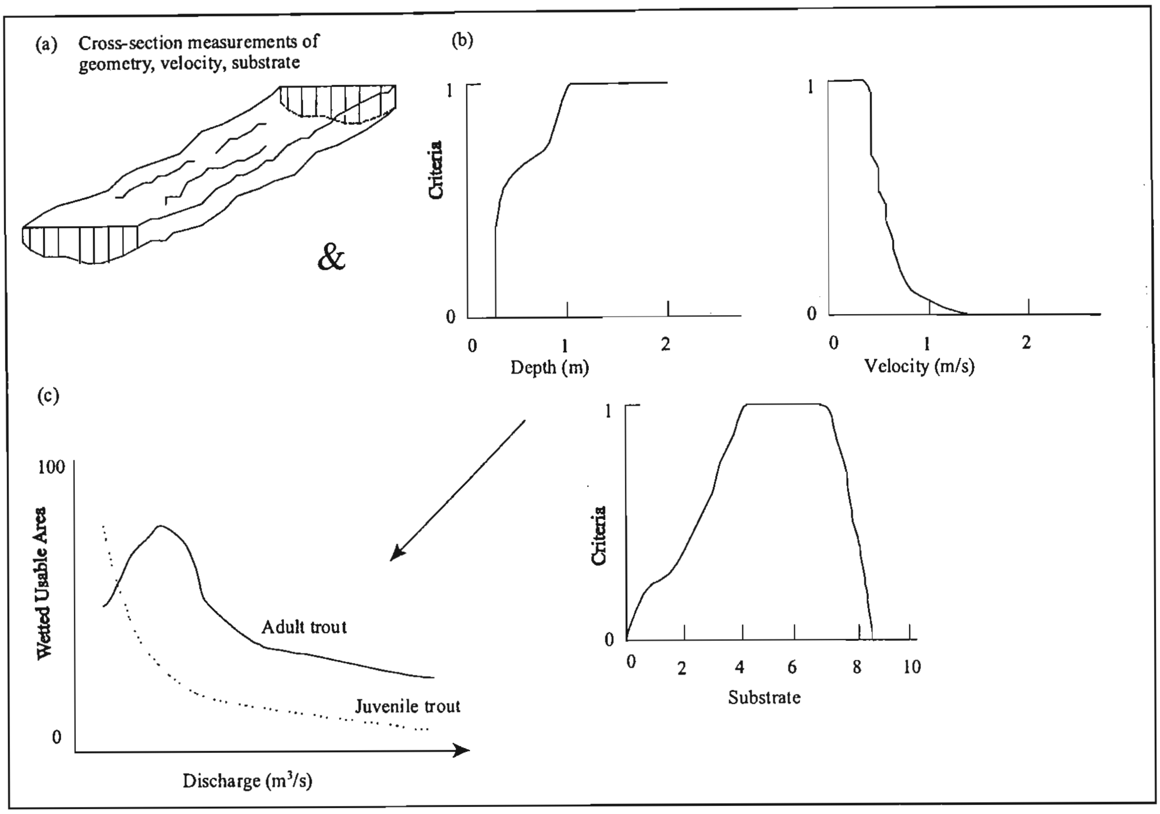

Figure 3.4 Conceptualisation of the procedures in a habitat methodology of instream flow assessment (after Gordon *et al.*, 1992)

river reach, with emphasis on quantifying the physical habitat with changes in flow (Stalnaker, 1979). Predicted values of river water depth and velocity or substrate (*cf.* Figure 3.4, b), for any reach, are compared with habitat suitability criteria to assess the area of suitable habitat for target aquatic species (*cf.* Figure 3.4, c). This can be performed for a range of flows to determine how the area of physical habitat changes with flow.

Habitat methods are considered to be more reliable and biologically defensible than any of the other flow assessment methods because they are quantitative and based on biological principles (White, 1976; Annear and Condor, 1984). The biological basis of habitat methods is a set of habitat suitability curves that can be used to identify seasonal requirements for different life stages for different aquatic species (*cf.* Figure 3.4 c). Where a decline in habitat suitability for one particular species has led to increased habitat for another species, the conflict has been addressed by the concept of habitat guilds or indicator species (Gore *et al.*, 1991). Habitat methods have been described as having the potential to offer more scope to determining flow requirements than either historical or hydraulic methods because the relationship between flow and the amount of habitat suitability is usually non-linear (*cf.* Figure 3.1). Flows can be prescribed in order to:

(a) maintain optimal levels of specified species habitat,

(b) retain a percentage of habitat at mean or average flows, or

(c) provide a minimum amount of habitat, defined either as a minimum percentage of wetted area or as a percentage exceedence value on a habitat duration curve (based on the same distribution principles as flow duration curves (*cf.* Figure 3.2), *i.e.* the percentage of time at which a specified extent of *habitat* is equalled or exceeded).

The most common method of assessing minimum flow requirements using habitat methods is to consider the point of inflection in the habitat-flow relationship as this is viewed as the level of protection at which proportionally more habitat is lost with decreasing flow than is gained with increasing flow. However, for some rivers, particularly in the low flow range (Figure 3.1), the relationship between habitat and flow for flow-sensitive species is linear. In these instances, recommendations of flow using percentage retention or exceedence for habitat are essentially the same as those of historical flow and hydraulic methods which prescribe a percentage or exceedence value for flow or wetted perimeter.

Whilst habitat methods can be used to assess seasonal flow requirements, a good knowledge and understanding of the river ecosystem is essential if any potential conflicting habitat requirements of different life species or life stages are to be resolved. The application of habitat methods in management of water resources is also pertinent to "trade-off" situations where scenarios of the incremental change in habitat can be compared with the benefits of the resource.

3.4.3.1 Morphological rationale

Habitat methods focus on water velocity and depth requirements for species survival and therefore do not take cognisance of the natural hydraulic conditions, but rather prescribe the hydraulic conditions under which particular species can be sustained. Consequently, habitat methods can recommend minimum flow requirements which are lower than naturally occurring low flows or higher than mean flows. While one set of recommended parameters of water depth and velocity may be appropriate for species survival in a particular river, it may not be appropriate for a river of different gradient where the relationship between velocity and depth would be different. In this regard, it is crucial that the flow recommendations are appropriate to the morphology of a river.

3.4.3.2 Ecological rationale

The ecological aim of habitat methods is the provision or preservation of a suitable physical habitat for aquatic organisms. Essentially, habitat methods focus on target species and their habitat preference at different life stages. However this approach may preclude other critical components of a river ecosystem. An holistic approach, which considers the requirements of the entire river ecosystem, is the solution to successful flow recommendations. Orth (1987) states that the selection of appropriate habitat suitability curves and attention to other components, such as food production, water temperature and quality is critical. Unlike historical and hydraulic methods, habitat methods focus on the water depth and velocity requirements of the target species rather than attempting to maintain the river character.

3.4.4 Assessment of periodic flows

Of the three categories of methods described, only habitat methods can be applied to assess the particular seasonal variation and flood frequency of the natural flow regime necessary to provide a specified level of protection. However, as stated by Petts (1979), impounding a substantial proportion of the natural flow regime may affect such morphological change that simple application of habitat methods may be inappropriate. Nonetheless, habitat methods can be used to assess seasonal requirements by application of habitat requirements for different life stages and activities, whereas, the natural flow regime, or a knowledge of biological requirements, can be used to construct maintenance flood flows.

3.4.5 Comparison of methods of assessing instream flows

Whilst each of the three categories of instream flow methods assess and recommend a minimum flow requirement, each method differs in its data requirements, method of selecting flow requirement, consideration of river hydraulics and ecological assumptions (Jowett, 1997). A summary of the major differences of the three assessment methods is provided in Table 3.2.

Table 3.2 Summary of major differences between historical flow, hydraulic rating and habitat flow assessment methods (after Jowett, 1997)

Attribute	**Method**		
	Historical Flows	**Hydraulic**	**Habitat**
Data Requirement	Flow record (observed or simulated)	Cross-section survey	Cross-section survey Habitat suitability criteria
Method of assessing flow requirement	% MAF or MMF % exceedence	% habitat retention Inflection point	% habitat retention Inflection point Optimum / Minimum habitat (exceedence or percentage)
Stream hydraulics	Effect on width, depth and velocity, dependent on morphology Maintains "river characteristics"	Effect on width, depth and velocity is dependent on morphology Maintains "river characteristics" with respect only to variable under consideration	Prescribed depth and velocity Potential loss of "river characteristics"
Ecological assumption	Correlation between natural flows and existing ecology	Biological activity related to wetted area	Correlation between natural flows and existing ecology
Advantages and disadvantages	Relatively straight forward step-by-step assessment Trade-off considerations not possible Flow always less than, but related to, natural conditions Precludes environmental enhancement	Not so straight-forward, some interpretation required Trade-off considerations not possible Flow dependent on channel shape Levels of protection difficult to relate to environmental goals	More complex approach; application and interpretation critical Allows trade off Flow assessment independent of natural flow Environmental enhancement potential recognised

3.5 Application of Instream Flow Assessment Methodologies

Instream flow methodologies to assess minimum flow requirements were initially developed internationally to address specific activities such as assessment of instream flows for flushing, fish migration, spawning and incubation. However, over the past four decades methodologies have evolved to identify the requirements of a variety of related functions and aspects of riverine ecosystems (Tharme, 1996).

All instream flow methodologies use one or more of the instream flow assessment methods described in Section 3.4, and in some instances sediment transport or water quality models are incorporated with existing methodologies. In 1996, Tharme (1996) completed an extensive review of international methodologies for the quantification of instream flow requirements of rivers. However, the following sections, review only those methodologies applied in southern Africa. First, the Building Block methodology, BBM (King and Louw, 1995), designed in South Africa and the most comprehensive of methodologies available will be discussed. Since 1996, a number of derivative methodologies have been developed from the BBM and these will be briefly reviewed. This chapter will conclude with a review of the emerging trends in this new science.

3.6 Instream Flow Requirements and Water Resources Planning in South Africa

In South Africa little attention was given to the instream flow requirements of even major water-providing rivers before the 1980s (Tharme and King, 1998). Although there was an awareness of the need to allocate water for environmental purposes in the late 1970s to early 1980s, it was not until 1987 that the subject of instream flow requirements for river maintenance was first addressed at a national level (DWAF, 1998b). At that time two major workshops were held by the DWAF and the Foundation for Research and Development (FRD) respectively, to address not only the issue of instream flow requirements, but also the assimilation and integration of relevant knowledge from aquatic scientists, engineers and managers (Ferrar, 1989).

3.7 The Building Block Methodology (BBM)

The rationale of the BBM is that in order to sustain the river ecosystem, some flows within the hydrological regime of a river are more critical than others. These can be identified and described in terms of their magnitude, duration, timing and frequency (Tharme, 1996). This is manifest in the fundamental concept of the BBM that natural conditions are the best cue for sustaining natural biodiversity (Hughes *et al.*, 1997). The objective of this methodology is therefore to produce recommendations that view the river ecosystem holistically. A number of assumptions are made in the methodology, based on reviews by King and Tharme (1994), Tharme (1996) and Tharme and King, 1998, *viz.*

(a) The species associated with the river can tolerate those low-flowing conditions that naturally occur often, and may be reliant on higher flows that occur at certain times, *i.e.* the species have adapted to and have become reliant on those flows that are a normal characteristic of the river.

(b) Identification of the most important components of the natural flow regime (baseflows and floods) and including them as part of the modified flow regime will promote maintenance of the rivers natural biota and processes.

(c) Identification of the flows that influence channel morphology and their incorporation into the modified flow regime will facilitate maintenance of the natural channel structure.

The BBM is therefore a combined hydrological, ecological and geomorphological approach that utilises the features important to the natural flow regime to establish a modified flow regime (Tharme and King, 1998). The modified flow regime constitutes the instream flow requirement for the river. Because the minimum acceptable value will have been determined for the flow components, the instream flow requirement specifies, temporally and spatially, the minimum quantity of water that is perceived to provide maintenance of the river at some defined desired state (King and Louw, 1998). The main procedures comprising the BBM, as identified by Tharme (1996) are summarised as:

(a) identification of a management class (previously termed "desired future state", *cf.* Section 2.5.1) for the river or its reaches,

(b) reconnaissance of riparian and river habitat characteristics and site selection,

(c) geomorphological catchment and river reach analysis and assimilation of information on the geomorphology and hydraulics at the sites identified,

(d) collection of hydraulic data at cross-sections of identified sites, including discharge, depths and velocities, with assessment of hydraulic relationships, including discharge to depth and discharge to wetted perimeter,

(e) compilation of historical record of virgin and present-day daily mean discharge information and creation of plots of time series of daily discharge and flow duration curves,

(f) compilation of flow-rated information on particular ecosystem components,

(g) assimilation of summaries of the above information in a starter document, and

(h) participation of field experts at a workshop to determine the recommended instream flow requirement of the river.

The BBM workshop process, identified as procedure (h) above, is the crux of the methodology, since the workshop participants set recommendations of river flow requirements based on the collection hydrological and hydraulic data and information coupled with their ecological expertise. However, the generation of hydrological data can be problematic. IFR sites are often some distance from existing flow measurement sites and where historical flow records do exist, they are usually impacted by upstream anthropogenic development (Hughes, 1999a). It is, however, important that the workshop participants set ecological flows that are expected to occur within the natural flow regime and considerable effort on the part of the hydrological specialist is required in the generation of representative time series of flows to facilitate these recommendations. The entire BBM can be resource intensive. The process will be revisited in Chapter 9 as a case study of the instream flow requirements of the Mkomazi River.

Recommendations of the instream flow requirement include the magnitude, timing and duration of the modified flow regime. The BBM addresses three building blocks of the modified regime, *viz.*

(a) The first addresses the magnitude of baseflows in the dry and wet seasons. Monthly values of the lowest flow, for as many years as possible, are identified for reference at the workshop. This is achieved using either some value related to the seven-day running mean or a percentile (such as the 75th or 80th) from the monthly flow duration curves (*cf.* Figure 3.2) derived from daily flow information.

(b) The second addresses the intra-wet freshes that are required for the provision of flow variability, initiation of scouring and cleansing of the riverbed. The magnitude of the freshes has been identified as being two to five times the preceding stable low flow.

(c) The third building block determines the magnitude, timing and duration of floods in the wet season (Tharme and King, 1998).

The outcome of the BBM workshop process is a recommended modified flow regime, assembled as a set of month by month low flow and high flow values ($m^3.s^{-1}$), including the duration and magnitude of the intra-wet freshes and the variations anticipated between wet, average and dry years (Hughes *et al.*, 1997; Hughes and Ziervogel, 1998). The modified flow regime addresses both maintenance flows and drought flows and the output is provided at different levels of resolution, *viz.*

(a) month by month discharges,

(b) percentages of either present, or virgin, mean annual runoff and

(c) either present, or virgin, percentage exceedence values on flow duration curves on a month by month basis.

An example of a blank IFR Table is shown in Table 3.3.

Tharme and King (1998) provide a comprehensive description of the strengths and weakness of the BBM in their review of the development of the methodology for instream flow assessments. The two succeeding sections include some of their account.

3.7.1 Attributes of the BBM

The BBM correlates to the natural long-term hydrological record and provides quantitative recommendations on the flows required. The recommended flows can subsequently be used in the design of potential water resource developments. In this way the methodology provides water managers with a preliminary quantitative assessment, endorsed by ecological motivation, that can be altered when more biological information becomes available. Tharme and King (1998) also report that the methodology can be applied for regional planning purposes to assess how much water is available for further development within a catchment or region. The concept of the BBM is relatively simple and can be easily understood by non-experts. In essence the methodology is a transparent and cross-disciplinary process that encompasses communication and understanding.

Table 3.3 Example of a blank Instream Flow Requirement (IFR) Table used in the Building Block Methodology (BBM) workshop process (after King and Tharme, 1994)

IFR SITE NUMBER:	RIVER:			PRESENT STATE:			DFS:							
IFR MAINTENANCE LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x $10^6 m^3$	% of VIRGIN MAR
Flow ($m^3.s^{-1}$) FDC % (virgin) Volume (x $10^6 m^3$)														
IFR MAINTENANCE HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$) Duration (Days) FDC % (virgin) Volume (x $10^6 m^3$)														
IFR DROUGHT LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x $10^6 m^3$	% of VIRGIN MAR
Flow ($m^3.s^{-1}$) FDC % (virgin) Volume (x $10^6 m^3$)														
IFR DROUGHT HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$) Duration (Days) FDC % (virgin) Volume (x $10^6 m^3$)														

The instream flow requirements of either all the riverine ecosystem components, or of target species only, can be addressed and as such Tharme (1996) has appraised the BBM as being an holistic approach to the assessment of streamflows. The methodology works well in both data rich situations and in cases where biological data and understanding of the particular river ecosystems are limited (DWAF, 1998b). Notwithstanding these attributes, perhaps the most pertinent recommendation is that DWAF has formally endorsed the BBM in its procedure for South African water resource projects.

3.7.2 Limitations of the BBM

In general, confidence in the output of the BBM increases in relation to the amount of available data. Although the methodology can be applied with only one set of surveyed cross-sectional hydraulic data at each instream flow requirements site, the methodology is enhanced by additional sets of such data, over a range of discharges. This confidence level is also pertinent to the length of daily average discharge records. The reliability of the methodology output is also greatly affected by the quality of either the measured or simulated hydrological and hydraulic data (Tharme, 1996). The BBM largely relies on professional judgement and field expertise, which can be construed as being subjective. The IFR sites need to be as natural as possible so that judgements on the required flows can be made with reference to the distribution of aquatic and riparian species as well as the inundation of aquatic biota. The availability of such sites is often problematic because many of the nation's rivers are already affected by land use change and development.

The methodology is still evolving and some aspects of the BBM, in particular the determination of the management class (previously termed desired future state) of the rivers, requires further investigation or verification. Furthermore, expertise in certain fields may be inadequate and some ecosystem components may have to be omitted from the instream flow assessment (Tharme, 1996).

3.8 The Need for More Rapid Methods of Assessment

Expertise in the application of the BBM became considerable in Southern Africa in the late 1980s and throughout the 1990s. However, the promulgation of the NWA and the DWAF's objective of developing a Water Situation Assessment Model (WSAM) to ascertain present-day and future availability of water resources at a Quaternary Catchment scale, has highlighted the need for more rapid methods of assessment to determine the county's environmental reserve (Hughes, 1999a). Additionally, the provision in the NWA, which stipulates that some water must be reserved for environmental purposes, contributes some urgency to the need to evaluate the Reserve. The process for determining the Reserve is not due to be published until 2003 (Mallory *et al.*, 1999). However, it became clear to the developers of the BBM, that until comprehensive BBM studies could be performed for the nation's river systems, a preliminary Reserve could suffice the planning estimates required for the WSAM.

Hughes and colleagues at the Institute for Water Resources (IWR) at the University of Rhodes responded to this need by defining a suite of assessment methodologies, based essentially on the concepts of ecological assessment inherent in the more comprehensive BBM, but with varying degrees of confidence assigned to the results. Hughes (1999a) describes four levels of reserve determination now recognised by DWAF, *viz.*

(a) ***Desktop estimate***, based on generic, regionalised values used within the WSAM and being the most rapid of the four assessments, takes only hours to complete and consequently incurs low confidence in the results;

(b) ***Rapid determination***, applying a similar technique, but incorporating some measure of ecological input and carrying a greater level of confidence;

(c) ***Intermediate determination***, a diluted version of the BBM (or similar) approach taking approximately 2 months to complete; and

(d) ***Comprehensive determination***, in the form of a detailed BBM (or similar) approach, requiring as long as 12 months to complete, but resulting in the highest degree of confidence.

Clearly the cost of any particular determination, in terms of expertise, resources, time, data and information, increases with the degree of confidence sought. In all but the comprehensive determination, this translates into the need to find more a practical approach to the generation of a time series of natural flows than running and verifying a daily rainfall-runoff simulation model. Recognising the concept that the modified regime should reflect the hydrological variation that characterises natural flow regimes, Hughes *et al.* (1998) investigated the hydrological extrapolation of past IFR results.

3.9 Variability of Flow Regimes in South African Rivers

Evaluation of past IFR results and discussions held during IFR workshops identified two major traits resulting from the BBM process. The volume of water (expressed as a percentage of MAR) required for the environmental reserve generally decreased as the management class (*cf.* Chapter 2) moved from category A to category D (Hughes *et al.*, 1998). Moreover, those rivers that have highly variable flow regimes were assessed to require a smaller portion of their mean annual flows to meet the environmental reserve than those with less variable regimes (Hughes, 1999a).

Hydrological extrapolation of past IFR results confirmed the variability of South African flow regimes by the large amount of scatter of the values of flow requirements within each management class (*cf.* Section 2.5.1). Hughes *et al.* (1998) attributed some of the scatter to "ecological noise", *i.e.* to the subjectivity inherent in the BBM workshop process, regional differences in riverine ecological processes or specific river reach ecological processes and to the differences in geomorphological characteristics. However, the main focus for Hughes *et al.* (1998) in enhancing the preliminary reserve methodology for South African rivers was to address the differences that might be as a result of the differences in the flow regimes that characterise rivers. Hughes (1999a) describes the variability of flow regimes in South African rivers in terms of:

(a) the proportion of their total flows that occurs as baseflow, as recognition of the extent of intra-annual variability and

(b) monthly, or annual, coefficients of variability (CVs), as a measure of longer term variability, including the occurrence of droughts.

Hughes and colleagues developed an index that combined a measure of the wet and dry season monthly CVs and the mean annual contribution from the baseflows, which provided some explanation of the differences arising from the differences in the natural flow regimes (Hughes *et al.*, 1998). This index has subsequently been incorporated in the desktop preliminary assessment methods described above. However, as indicated by the developers, only the most elementary of these methods (and consequently resulting in low confidence in the results) can be performed without some knowledge of the ecological processes and characteristics of the rivers being assessed.

3.10 Emerging Trends in Southern African Instream Flow Assessment: DRIFT (Downstream Response to Imposed Flow Transformations)

New approaches to performing environmental flow assessments for rivers in southern Africa are beginning to emerge which attempt to address some of the "ecological noise" identified in the discussion of the BBM process in Section 3.9. DRIFT (Downstream Response to Imposed Flow Transformations) was developed by Southern Waters Ecological Research and Consulting in South Africa for the assessment of environmental flows for the Lesotho Highlands Water Project. The methodology arose from, and is based on, the same holistic concepts as the BBM, but according to the developers (Brown and King, 2000) differs from the BBM process in three fundamental principles, *viz.*

(a) DRIFT is a scenario-based approach that can be used to assess biotic responses to potential flow regimes. The methodology was designed for application in water resources conflict resolution, whereas the BBM is prescriptive in its determination of flows to sustain a particular aquatic condition.

(b) The BBM "builds" components of a recommended flow regime, whereas DRIFT assumes present-day flows and assesses the impacts of further development on the extant regime.

(c) DRIFT is designed to assess the links between changing river condition *and* the socio-economic impacts of development on those people most at risk from the change.

As in the BBM process, DRIFT attempts to establish the link between river flow and river condition from the historical hydrological condition. The main assumption in the DRIFT process is that different characteristics of the flow regime of a river produce different responses from the aquatic ecosystem. DRIFT assesses the historical hydrological record in order to separate different types of river flow in accordance with their relevance to ecosystem functioning (Brown and King, 2000) and recognises four principle types of river flow, *viz*:

(a) normal low flows, *i.e.* the flow in a river channel outside the highflow events,

(b) freshes, *i.e.* the small floods that occur several times a year,

(c) large floods that occur less frequently than once a year and

(d) flow variability.

As in the BBM process, DRIFT requires workshop participation from different disciplines and incorporates expertise in the fields of hydrology, hydraulics, chemistry, geomorphology, botany, ecology and ichthyology. However, where the BBM process *builds* a modified regime, the DRIFT approach to recommending a modified regime is the *reduction* of various parts of the flow regime. Typically, low flows are reduced in range and consequently in variability, whereas high flows are reduced in number (Brown and King, 2000).

The DRIFT approach requires consideration of the water levels of the river at different times, *e.g.* at the low flow higher magnitude events (freshes), and converts the percentage of time that such events occur to flow duration curves. The values on the flow duration curves are converted to depths and marked on surveyed cross-sections of each river site assessed. The cross-sections used by the DRIFT approach also contain information regarding the riparian vegetation and the types of substrata present. The flow duration curves indicate how often any cross-section characteristic is exposed or inundated and the curves are used to assess the wetted perimeter provided by each water level. Consequently a link is made between the hydrological statistics and the hydraulic features of the river (Brown and King, 2000).

3.11 Conclusions Regarding the Assessment of Instream Flow Requirements for Water Resource Planning

In response to the need to provide a level of protection to aquatic ecosystems, instream flow assessment methods have been developed, internationally, to recommend the minimum flow requirements of rivers. Assessment methodologies and techniques available to predict and evaluate minimum flow needs, range from uncomplicated rule of thumb recommendations (*i.e.* application of assessment based on historical flows), thereby eliminating the necessity to perform field work, to sophisticated simulation models (*i.e.* assimilating the recommendations of a number of experts with calibrated modelling systems). Again, it must be emphasised that in terms of the NWA, 1998 the assessment of flow requirements in South African rivers must recognise that human needs are dependent on first meeting the needs of the environment as embraced by the concept of the ecological "Reserve".

While different river ecosystems call for different management decisions, the general consensus amongst instream flow requirement working groups favours models that are based on the response of aquatic organisms to changes in river flow. However, the understanding of the biological component in river ecosystems is incomplete and most methods of instream flow assessment are criticised for their inadequate consideration of certain aspects of the aquatic environment. For example, none of the instream flow assessment methods reviewed consider water quality or temperature, despite the fact that these characteristics have the potential to be greatly influenced by any modification to the natural flow regime.

New trends in flow assessment for southern African rivers remain focussed on the link between river flows and river condition. The application of historical hydrological records to identify variations in the magnitude, timing and velocity of flows provides the relationship between hydrology and ecology, whereas the link is the hydraulic characteristics of the cross sectional channel. However, flow requirements for biota are only part of a package of management decisions that must be made to properly maintain ecosystem integrity. Ideally, instream flow studies should consider the cost and benefits of all potential water resource uses so that changes in stream habitat can be balanced with other beneficial uses.

* * * * *

The following chapters assess the hydrological modelling needs for water resources management. Chapters 4, 5, 6, 7 and 8 introduce the Mkomazi Catchment in KwaZulu-Natal as a case study and describe the approach adopted for an installed hydrological modelling system in order to assess the impacts of land use change on the available water resources.

The BBM workshop process described in this chapter is revisited in Chapter 9 for the Mkomazi River to assess the appropriateness of the recommended modified streamflow regime. The assessment of hydrological alteration within ecosystems is revisited in Chapters 10 and 11 for the Mkomazi Catchment, in order to provide an indication of the preliminary management targets required to sustain some semblance of the natural variability of the Mkomazi River.

4 ASSESSING THE MANAGEMENT NEEDS OF CATCHMENT WATER RESOURCES: MKOMAZI CATCHMENT CASE STUDY

4.1 Introduction

The limited availability of water resources for different water use sectors presents one of the most contentious and challenging issues arising from the implementation of effective management and potential future development of South Africa's catchment areas. Even in relatively wet regions such as KwaZulu-Natal there is a need for effective management strategies to reconcile water demand with water supply. It has been projected that by 2008 some form of impoundment of the Mkomazi River will be required to augment the water supply in the neighbouring Mgeni Catchment to meet the water demand of the Durban-Pietermaritzburg region (Gillham and Haynes, 2000). The locations of the Mkomazi Catchment and the Mgeni Catchment, as well as the cities of Pietermaritzburg and Durban are shown in Figure 4.1.

4.2 Prior Studies and End-User Modelling Requirements

The Department of Water Affairs and Forestry (DWAF) conducted a pre-feasibility study (1997 / 1998) for proposed water resources developments in the Mkomazi Catchment for inter-basin transfer to the Mgeni System. The rationale for the study was that the water resources of the Mgeni River System, which is the main source of water for the Durban / Pietermaritzburg metropolitan area, are already fully utilised. Augmentation to the Mgeni System from the Mooi River is already taking place, with further augmentation schemes in an advanced stage of planning. In earlier studies, the Mkomazi River was identified as being the most feasible after the Mooi River to augment the Mgeni System. The Mkomazi-Mgeni Transfer Scheme (MMTS) is intended to store excess water in the upper Mkomazi Catchment in one, and possibly two, impoundment dams for transfer via pipeline to the lower Mgeni System.

Because it has historically been DWAF policy that the needs of a donor catchment should be met before consideration be given to transferring water to other catchments, a reconnaissance level basin study was conducted to determine the present and future water

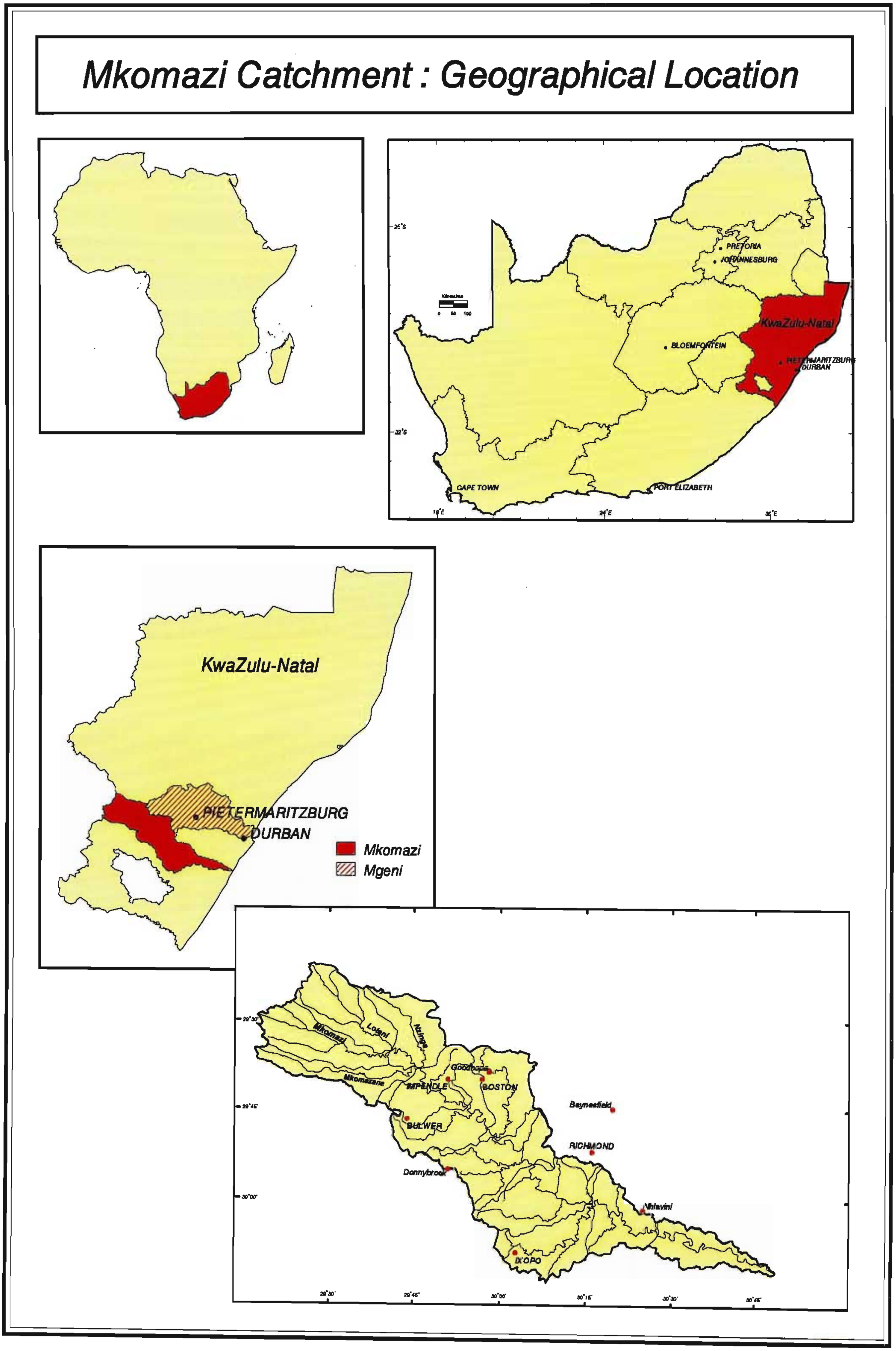

Figure 4.1 Mkomazi Catchment: Geographical location

demands within the Mkomazi Catchment (DWAF, 1998a). High, middle and low demand scenarios were assessed. However, the study was carried out at Quaternary subcatchment level with monthly time step modelling procedures. Umgeni Water, the parastatal organisation that supplies bulk potable water to the larger portion of the population of KwaZulu-Natal, has indicated that any modelling of the hydrology of the catchment would better suit their planning needs if the catchment was discretised at a sub-Quaternary level. This provision would facilitate the determination of the impacts of proposed development on the generation of streamflows at potentially critical sub-Quaternary regions. Furthermore, the potential to evaluate the streamflow regime at a daily, rather monthly, level would enhance any management decisions required to address those daily streamflow characteristics considered critical for ecological purposes, in as well as for the sustainable development of, the Mkomazi Catchment.

4.3 Objectives of the Mkomazi Case Study

The primary objective of this and the three following Chapters is to describe the approach adopted to modelling the impacts of development on the hydrological dynamics of the Mkomazi Catchment at a sub-Quaternary scale and on a daily time step. The simulation of daily flows is considered to be fundamental to adequately assess those streamflow characteristics associated with the instream flow requirements. The simulated daily streamflows can subsequently be used to generate a daily time series of flows which occurs within the natural flow range. Such a time series is critical for the effective operation of dam release rules designed to meet the needs of all catchment stakeholders and will be revisited in Chapters 9, 10 and 11.

A further important objective relates to the evaluation of the techniques applied in the data acquisition and preparation of the model menu input. The most recognised approach to achieve this is to conduct verification studies of the simulated streamflows with reliably gauged flows. Verification of the simulated Mkomazi streamflows will be addressed in Chapter 5.

It is anticipated that the assimilation of hydrological criteria into an appropriately configured daily model will result in an "Installed Modelling System" for the Mkomazi. The benefits of such a system is that analyses of development scenarios require relatively little effort and can be expected to produce reliable answers to questions posed by water resources managers.

In order to achieve the above objectives, the Mkomazi Catchment streamflows were simulated under the following land cover conditions and development scenarios:

(a) "pristine" land cover conditions, defined for the purposes of this report as Acocks' Veld Types (Acocks, 1988),

(b) present land use conditions, defined in accordance with Thompson's (1996) land classification and the interpretation of the 1996 LANDSAT TM image,

(c) present land use, but including potential future impoundments, in accordance with DWAF's MMTS and

(d) present land use, both before and after the construction of the potential impoundment, but with the climate perturbed in accordance with the climate change scenarios for a doubling of CO_2 conditions as generated by the HadCM2 General Circulation Model (excluding sulphate forcing), *i.e.* the second version of the Hadley model developed by Murphy and Mitchell (1995).

This chapter describes the Mkomazi Catchment, focusing on the current issues of concern and development and presents the approach adopted in modelling the catchment hydrological dynamics to reflect those issues.

4.4 The Mkomazi Catchment

The Mkomazi Catchment comprises the 12 DWAF Quaternary Catchments (QCs) numbered U10A to U10M and covers an area of 4383 km^2. The catchment is situated around 29° 17' 24" E and 29° 35' 24" S (Figure 4.2), stretches 170 km from 3300m altitude in the northwest to sea level in the southeast and has a Mean Annual Precipitation (MAP) ranging from 1283 to 752mm (Table 4.1). The MAP is higher in the upper, higher altitude reaches of Mkomazi Catchment (950 – 1283 mm) and consequently most of the catchment runoff is generated there (DWAF, 1998a).

The Mkomazi Catchment is characterised by steep gradients of altitude and rainfall, highly variable land uses as well as highly variable intra- and inter-seasonal streamflows. The annual water yield of the Mkomazi System under present land use conditions and consumption rates has been estimated to be 905 million m^3 (DWAF, 1998a). Despite the

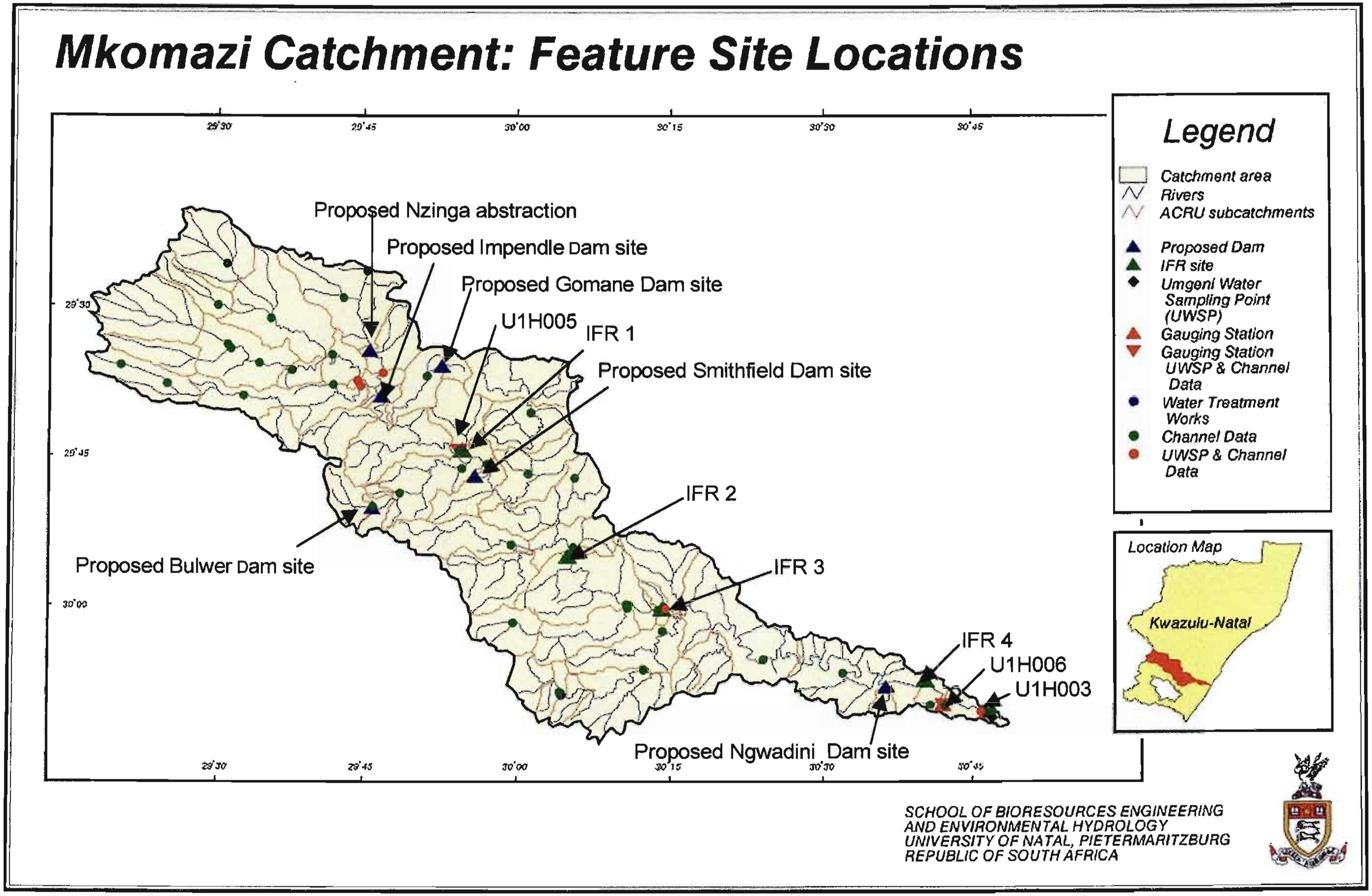

Figure 4.2 Mkomazi Catchment: Feature site locations

Table 4.1 Mkomazi subcatchment information

SC No	QC No	Area (km^2)	"Driver" Rainfall Station	"Driver" Rainfall Station Name	Mean Altitude (m)	Longitude (degree, decimal)	Latitude (degree, decimal)	MAP (mm)
1	U10B	162.91	0237606 W	Sani Pass (Pol)	2124	29.38	29.51	1107
2	U10B	63.32	0237606 W	Sani Pass (Pol)	1959	29.39	29.59	1095
3	U10B	141.69	0268359 W	Cyprus	1533	29.54	29.58	1044
4	U10B	29.22	0238132 W	Snowhill	1373	29.64	29.61	962
5	U10A	142.97	0268199 W	Highmoor (Bos)	2165	29.49	29.41	1283
6	U10A	57.76	0237731 A	Cobham, Himeville	2088	29.46	29.47	1179
7	U10A	208.01	0268359 W	Cyprus	1639	29.60	29.50	1095
8	U10D	47.09	0238341 W	Paulholme	1410	29.71	29.59	982
9	U10D	189.23	0268359 W	Cyprus	1851	29.71	29.49	1040
10	U10D	77.44	0238636 W	Impendle (Pol)	1643	29.79	29.56	946
11	U10C	93.12	0237606 W	Sani Pass (Pol)	2104	29.38	29.62	1068
12	U10C	32.87	0238132 W	Snowhill	1685	29.60	29.71	945
13	U10C	148.15	0238045 W	Himeville (Mag)	1568	29.60	29.69	951
14	U10D	29.97	0238341 W	Paulholme	1339	29.79	29.64	906
15	U10E	18.87	0238636 W	Impendle (Pol)	1680	29.90	29.60	935
16	U10E	70.94	0238636 W	Impendle (Pol)	1492	29.84	29.64	965
17	U10E	69.99	0268359 W	Cyprus	1678	29.71	29.72	1088
18	U10E	158.55	0238468 W	Bulwer (Tnk)	1310	29.81	29.72	1055
19	U10F	77.69	0238636 W	Impendle (Pol)	1435	29.91	29.68	997
20	U10F	55.13	0238468 W	Bulwer (Tnk)	1723	29.72	29.82	1073
21	U10F	24.12	0238293 W	Rockleigh	1554	29.77	29.85	988
22	U10F	9.06	0238468 W	Bulwer (Tnk)	1506	29.77	29.81	1089
23	U10F	145.82	0238806 W	Emerald Dale	1232	29.87	29.80	931
24	U10F	65.33	0238806 W	Emerald Dale	1155	29.92	29.81	897
25	U10G	136.00	0238636 W	Impendle (Pol)	1543	30.01	29.62	1003
26	U10G	106.48	0239133 W	Vaucluse	1351	30.02	29.70	947
27	U10G	116.18	0239133 W	Vaucluse	1172	30.02	29.78	970
28	U10H	137.54	0239133 W	Vaucluse	1090	30.01	29.82	980
29	U10H	117.43	0238806 W	Emerald Dale	1372	29.90	29.89	947
30	U10H	122.67	0238837 A	Emerald Dale	1260	29.95	29.96	860
31	U10H	76.55	0239472 W	Richmond (Tnk)	975	30.09	29.90	997
32	U10J	7.28	0239566 A	Little Harmony	780	30.10	29.91	876
33	U10J	76.07	0238837 W	Emerald Dale	1229	29.98	30.04	853
34	U10J	101.10	0210099 W	Ixopo (Pol)	855	30.11	30.05	844
35	U10J	211.44	0239138 W	Whitson	866	30.11	29.96	916
36	U10J	11.94	0239359 W	Naauwpoort	585	30.22	29.99	802
37	U10J	97.83	0239566 A	Little Harmony	761	30.23	29.96	938
38	U10L	23.74	0209795 W	Hancock Grange	840	30.28	30.12	778
39	U10L	56.04	0209825 A	Grange, Umzimkulu	725	30.13	30.10	758
40	U10K	48.36	0210136 A	Finchley, Ixopo	1161	30.02	30.13	888
41	U10K	29.74	0210099 W	Ixopo (Pol)	1091	30.06	30.15	810
42	U10K	30.07	0210099 W	Ixopo (Pol)	1026	30.09	30.16	819
43	U10K	143.62	0210099 W	Ixopo (Pol)	914	30.17	30.17	767
44	U10K	109.86	0239359 W	Naauwpoort	742	30.18	30.07	768
45	U10L	226.22	0239359 W	Naauwpoort	567	30.36	30.02	752
46	U10M	16.76	0211228 S	Esperanza	359	30.60	30.16	906
47	U10M	199.77	0210826 W	Sawoti	305	30.55	30.12	822
48	U10M	25.70	0211546 S	Illovo Mill	132	30.68	30.15	919
49	U10M	26.23	0211407 S	Renishaw	144	30.73	30.17	955
50	U10M	0.79	0211437 W	Scottburgh (Mun)	63	30.77	30.18	1023
51	U10M	2.30	0211546 S	Illovo Mill	95	30.77	30.18	1011
52	U10M	5.72	0211437 W	Scottburgh (Mun)	53	30.78	30.19	1053

variability of the streamflows, the Mkomazi River flows throughout the year.

The potential to store the high flows of the river system, together with the proximity of the catchment to the denser distribution of population in the Mgeni system provides the impetus for impoundment.

4.5 Issues of Concern

Presently (2001) the catchment supports commercial afforestation, extensive agriculture (principally livestock grazing and sugarcane), intensive agriculture (citrus and vegetables), subsistence agriculture as well as tourism and leisure activities. With the exception of the Sappi Saiccor paper mill at the estuary mouth and the coastal town of Umkomaas, the Mkomazi Catchment contains no major towns or industry. The distribution of rural population ranges from moderate to sparse, with greater a concentration in the lower catchment (DWAF, 1998a). Use of available water resources is therefore considered by DWAF (1998a) to be conservative. Currently, there are no major reservoirs within the catchment. However, six potential impoundment sites have been identified by DWAF. Of these six sites, four have been identified as potential development sites for the supply of piped water to rural communities. Two sites on the Mkomazi River have been identified as potential major impoundment sites (Figure 4.2) for the transfer of water from the Mkomazi Catchment to augment the Mgeni, which supplies the heavily populated and industrialised Durban / Pietermaritzburg region. These developments will impact significantly on the natural streamflow regime of the Mkomazi.

Therefore, there are potentially conflicting water issues within the catchment. Potential conflicts of water use, demand and allocation are perceived to emanate from competition arising from:

(a) environmental streamflow and estuarine flow requirements,
(b) commercial agricultural practices (*e.g.* streamflow reduction from forestry, land management practices and irrigation),
(c) urban and peri-urban water demands
(d) rural subsistence-based communities water needs and
(e) inter-basin transfers.

These issues have varying impacts on the availability of water resources under present water use as well as scenarios of future demand and supply. There is a defined need for useful guidance which allows water planners and managers faced with the interconnectedness of these issues to assess the impacts of potential development on available water resources.

4.5.1 End-user requirements

The principal beneficiary of this case study was initially perceived to be Umgeni Water, the bulk water supplier to the region. However, the NWA (*cf.* Chapter 2) makes provision for the nation's catchments to eventually be managed and controlled by CMAs (*cf.* Chapter 2), which will be mandated to represent the interests of all the catchment stakeholders. In the interim, it is more probable that the present governing water bodies will in practice be the principal stakeholders. However, there is provision for the needs of other interested and affected parties to also be addressed. In the case of the Mkomazi this will include, *inter alios*, the Environmental Task Group, Foresters' Association, irrigation boards and KwaZulu-Natal Nature Conservation Service, all of whom have needs which differ from those of Umgeni Water.

Notwithstanding these provisions, it was projected in 1996 that the Mgeni System water demand would increase from just over 250 million m^3 per annum to between 375 and 500 million m^3 in 2010 depending on the demographic scenario used (DWAF, 1998a). Beyond 2010, the projected water demand continues to rise exponentially, with expectations that the volume required in 2025 is likely to be between 650 and 900 million m^3 (DWAF, 1998a). The principal reason for the increased demand can be attributed to population growth and industrial development in the Durban Metropolitan Area. Additionally, Umgeni Water has initiated water supply schemes to deliver piped water to meet the demands of rural communities within the Mkomazi. For these reasons Umgeni Water, in association with DWAF, conducted a pre-feasibility study for the transfer of available water resources from the Mkomazi Catchment to augment the water resources of the Mgeni Catchment (DWAF, 1998a).

Two major potential impoundment sites, *viz.* Impendle and Smithfield (680 million m^3 and 170 million m^3 capacity respectively) on the Mkomazi river were initially identified (*cf.*

Figure 4.2). However, after reconsideration of the factors affecting projected water demand, it was provisionally decided by DWAF that only one dam site (Smithfield) should be developed, with the option of augmenting that development with water from another dam at the second site (Impendle) if the expected demand was exceeded.

Projected water demands are influenced by changes in climatic conditions as well as by changes in population demographics. Climate change, as a result of global increases in temperature, is expected to affect many sectors of the natural and man-made sectors of the environment (Ringius *et al.*, 1996). However, the changes in availability, quality and distribution of water are considered to be the most important consequences of climate change. The proposed Smithfield and Impendle Dams have been designed as long term management strategies for water supply and augmentation for the Mkomazi and Mgeni catchments. However, the impacts of potential climate change on the Mkomazi Catchment water resources could have implications for the effectiveness of the proposed impoundment to meet projected water demand.

Even under present climatic conditions, the impacts of different land uses and catchment development on water resources are particularly relevant in periods of low flows. Water resource managers frequently need to make decisions regarding the priority of water allocations in times of water scarcity, either in times of hydrological drought or during seasonal low flows.

The redistribution of water resources from the Mkomazi Catchment to the Mgeni Catchment will require complex design and release priority rules. This is especially the case if the scheme to augment the proposed Smithfield Dam with water released from the proposed Impendle Dam, via the river, is implemented. Furthermore, it is a legal requirement that the impoundment operating rules of the transfer scheme meet any design releases in periods of hydrological drought (Hughes and Ziervogel, 1998).

Therefore, the principal needs of Umgeni Water include the assessment of the water yield of the Mkomazi Catchment under:

(a) various land use conditions,

(b) proposed inter-basin abstractions,

(c) different flow conditions, including:

- years of flows either lower or higher than the average annual flow and
- seasonal low flows, as well as
- flows under conditions of potential climate change and

(d) different water allocation rules, including setting aside that water required to meet the environmental requirements as prescribed by the National Water Act.

4.5.2 Agricultural practices

The Mkomazi Catchment is relatively undeveloped and neither agriculture nor forestry is a major land use throughout, although they are of local importance. Furthermore, catchment topography, climate and economics constrain the diversity of agricultural practices. Water resources are not a restraint on agricultural practices, *per se*, as the catchment receives relatively high rainfall by southern African conditions. However, there are substantial, and potentially conflicting, differences between the types of farming practised throughout the Mkomazi Catchment.

The MAP of the upper catchment ranges from 1000 to > 1200 mm, (Figure 4.3). This provides conditions that can be considered conducive to those farming practices that do not require supplementary water. This factor, together with steep gradients (Figure 4.4) which exacerbate the difficulties of leading water from the river valley, has contributed to the major land uses in the upper catchment being those of ranching, especially in those areas formerly part of the KwaZulu homeland, and forestry. The main problems relating to ranching are those associated with overgrazing, which contributes significantly to disturbed soil conditions, soil transport and ultimately sedimentation of river channels and impoundments. Exotic, commercial tree plantations are the focus of a whole gamut of water related issues, ranging from streamflow reduction through interception and transpiration losses, particularly in times of low flows, to water quality problems which include excess acidity of headwaters and exacerbation of sedimentation at harvesting.

The economic and socio-political structure of the upper Mkomazi also excludes any crop husbandry other than low input commodities. As a result yields per hectare are low. The area generally has poor infrastructure, with rural populations having severely limited access to amenities and agricultural technologies.

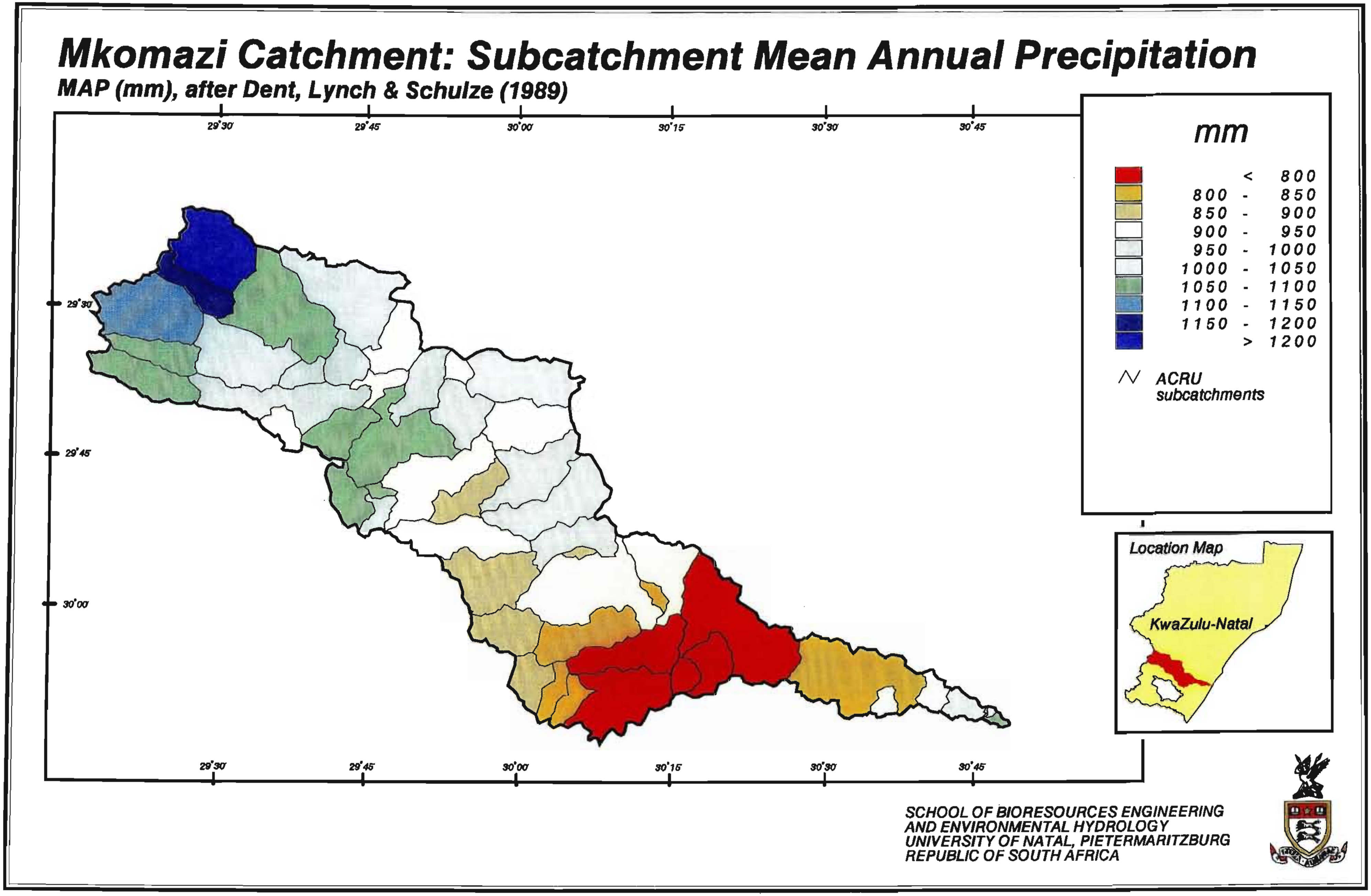

Figure 4.3 Mkomazi Catchment: Subcatchment mean annual precipitation (after Dent, Lynch & Schulze, 1989)

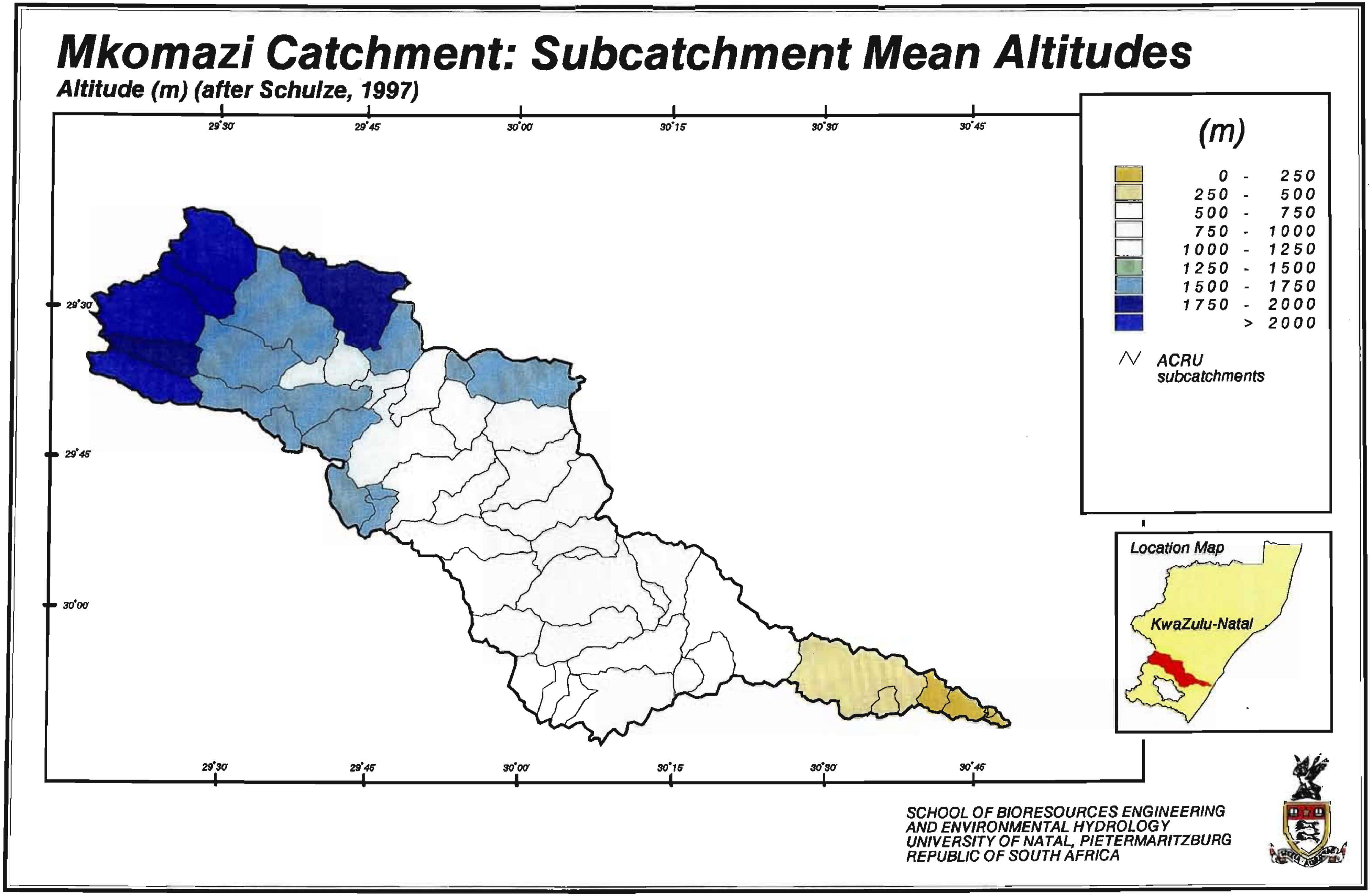

Figure 4.4 Mkomazi Catchment: Subcatchment mean altitudes (after Schulze, 1997)

The economic structure of the Mkomazi Catchment and problems of access to water become stronger downstream. Because of relatively high rainfall (950–1000mm), commercial forestry is a significant land use in the middle Mkomazi, particularly around Richmond (*cf.* Figure 4.1). The more intensive cultivation of sugarcane and horticulture are also practised in this region, despite growing conditions being marginal as a result of the incidence of frost.

The lower Mkomazi Catchment is more amenable to intensive crop farming. The economic driving forces of the lower part of the catchment are much greater than in the upper and middle catchment and consequently there is greater concentration of farm dams, together with high input crops producing high yields per hectare. Paradoxically, these practices are most prevalent in that part of the Mkomazi Catchment that receives least rainfall (less than 850 mm, Figure 4.3). Farmers in this region have compensated for this by storing excess streamflows in numerous farm dams and irrigating heavily from them. However, the consequence of the irrigation is that river flows in the affected catchments have all but ceased and there is no significant river flow in the river channels downstream of the town of Ixopo.

The socio-economic development of the Mkomazi Catchment is heavily reliant on agriculture. Therefore, it makes economic, as well as hydrological, sense to utilise the catchment hydrological dynamics to utmost potential. Determination of the different impacts of different agricultural practices on quality and availability of water resources is consequently of primary concern to catchment stakeholders.

4.5.3 Sedimentation

The principal water quality concern for the Mkomazi River is that of sedimentation. This is particularly prominent in those areas impacted by overgrazing, tillage practice and land cover clearing activities of rural subsistence populations. Together with the geology of the region, these factors have resulted in soil transport culminating in river turbidity during high flows and sediment deposits in low flows.

Hydro-geological processes are important for sustaining habitat diversity in so far as suspended materials may provide a food supply for some river biota and sediments provide refugia for different stages of aquatic life cycles. However, aquatic ecosystems depend on the processes that would occur within the sediment variability range of the natural flow regime. Excessive sediment deposition leads to encroachment of alien riparian and aquatic species in low flows, and modification of channel geomorphology in high flows (DWAF, 1998b).

The potential for soil to be transported into impoundments can have serious consequences for sediment accumulation behind impoundment walls, thereby increasing the risk of dam failure by either breaching or hindering the release of flood overflows. Equally serious are the impacts of sedimentation to the lifespan of any potential impoundment, and as such the rate of sedimentation is an important consideration in the proposal of any expensive water resources planning project.

Umgeni Water places high importance to these threats and monitors for suspended solids at three sites in the upper Mkomazi, one site in the mid Mkomazi and at two sites in the lower reaches of the river (Figure 4.2). The contributing upstream areas of these sites are provided in Table 4.2. Unfortunately, a spatio-temporal analysis of the sediment yield of the Mkomazi is beyond the scope of this dissertation.

4.5.4 Inter-basin transfers

At present there are no major impoundments on the Mkomazi River. However, the catchment has an historical mean yield of 905 million m^3 per annum (DWAF, 1998a) and there are plans to utilise this water resource. In September 1997, there were six dam sites identified for the Mkomazi Catchment. Three of these sites (Gomane, Nzinga and Bulwer, Figure 4.2) in the upper catchment have been identified as dam sites planned to alleviate rural water supply shortages and one site (Ngwadini, Figure 4.2) in the lower catchment has been identified for a proposed off-channel storage dam for the surrounding agricultural community. The remaining two sites (Smithfield and Impendle, Figure 4.2) are the focus of proposed inter-basin transfer. It is anticipated that the abstraction of water from the Mkomazi Catchment to augment the Mgeni supply system will impact on those downstream abiotic characteristics of the Mkomazi River (hydrology, geomorphology, chemistry, temperature) as well as on the responses of the ecosystem components (fish, riparian vegetation and aquatic invertebrates).

Table 4.2 Mkomazi sites of interest: Contributing areas

Site of Interest		Locality	Longitude (degrees, decimal)	Latitude (degrees, decimal)	SC No	Upstream Area (km^2)
Umgeni Water Quality Sampling Sites	**144**	Impendle	29.74	29.64	13	274.14
	145	Impendle	29.74	29.63	8	852.96
	146	Impendle	29.78	29.62	10	266.67
	147	Josephine's Bridge	30.77	30.01	36	3339.57
	125	Sappi SAICORR	30.77	30.18	49	4373.50
	125.1	Sappi SAICORR	30.78	30.19	51	4376.58
Instream Flow Requirement Sites	**IFR1**	Lundy's Hill	29.91	29.75	19	1819.43
	IFR2	Hela Hela	30.09	29.92	32	2939.01
	IFR3	Josephine's Bridge	30.23	30.02	35	3327.62
	IFR4	Mfume	30.67	30.12	47	4321.56
Gauging Stations	**U1H005**	Lundy's Hill	29.90	29.74	18	1741.74
	U1H006	Goodenough Weir	30.70	30.17	48	4347.27
	U1H003	Delos Estate	30.77	29.74	50	4374.28
Proposed Dams		Impendle	29.78	29.65	14	1423.74
		Smithfield	29.93	29.77	23	2053.57
		Gomane	29.88	29.60	15	18.87
		Nzinga Abstraction	29.76	29.58	9	189.23
		Ngwadini	30.61	30.14	46	16.76
		Bulwer	29.76	29.84	20	55.13
Water Treatment Works		Ixopo	30.07	30.15	41	78.11

However, the main consideration of this study is assessment of the changes in streamflow generation on the downstream environment, as a result of impoundment of storage water by the proposed Smithfield and Impendle Dams, with respective upstream contributing areas of 2054 km^2 and 1424 km^2 (Table 4.2).

4.5.5 Environmental streamflow requirements

The DWAF reconnaissance level basin study to determine the present and future water demand within the Mkomazi Catchment (DWAF, 1998a) has identified that environmental requirements, in the form of instream flow requirements (IFRs) are a dominant water resource consideration, requiring approximately 30% of the Mean Annual Runoff (MAR). The four IFR sites selected by the BBM workshop process are shown in Figure 4.2. The locations of all the IFR sites are downstream of either, or both, of the proposed Smithfield and Impendle Dam sites (Figure 4.2). A principal issue of concern relating to impacts of the MMTS on the catchment hydrological dynamics is that the provision of the ecological component of the Reserve will have a significant impact on the yield and operating rules of both proposed dams. The respective upstream contributing areas for the four IFR sites are provided in Table 4.2. The general consensus at Mkomazi IFR workshops regarding the Mkomazi estuarine flow requirement (EFR) is that if the IFRs are satisfied, then the EFR will also be satisfied.

4.6 Simulating the Catchment Hydrological Dynamics

The Mkomazi Catchment is characterised by diverse land uses as well as environmental and developmental issues, all of which are significant, albeit to different extents, to the various stakeholders within the catchment. The assessment of the potential impacts of any proposed development on the Mkomazi streamflows is therefore critical to the sustainable management of water resources within the catchment.

Hydrological modelling plays an integral role in the provision of reliable information for the management and planning of water resources (*cf.* Chapter 2). Agrohydrological simulation modelling, in particular, can ascertain the hydrological response(s) to land use change and the consequent impacts on the available water resources.

4.6.1 The effects of land cover and land use on hydrological systems

Whilst the hydrological response of a catchment is largely controlled by its physiographical characteristics and climatic regime, land cover and land utilisation play a vital role in the water redistribution processes. Different natural land covers and anthropogenic land uses (including commercial forestry, organised agriculture, settlement and irrigative operations) affect hydrology differently, through canopy and litter interception, consumptive water use, infiltration of rainfall into the soil, rooting characteristics, evapotranspiration and evaporation of water from the soil surface (Schulze, Lecler and Hohls, 1995). The impact of different land uses on water yield depends not only on these factors, but also on their areal extents and distributions, as well as the level of management applied. Thus, simulation modelling of the impacts of land cover and land use on catchment water resources necessitates the inclusion of those hydrological attributes associated with the above-named factors.

4.6.2 Application of the *ACRU* model

Although the *ACRU* agrohydrological modelling system has been described in great detail in Schulze (1995a), which needs not be repeated fully here, its application in simulating the impacts of land use is briefly reviewed below as it is particularly relevant to this research study.

ACRU is a daily time step, physical-conceptual model revolving around multi-layer soil water budgeting. It is a multi-purpose model (Figure 4.5) with options to output, *inter alia*, daily values of streamflow, peak discharges, recharge to groundwater, reservoir status, irrigation water supply and demand as well as seasonal crop yields. The model is structured (Figure 4.6) to be hydrologically sensitive to catchment land uses and changes thereof, including the impacts of proposed developments such as large dams on catchment streamflow, as well as to changes in climate induced by the greenhouse effect.

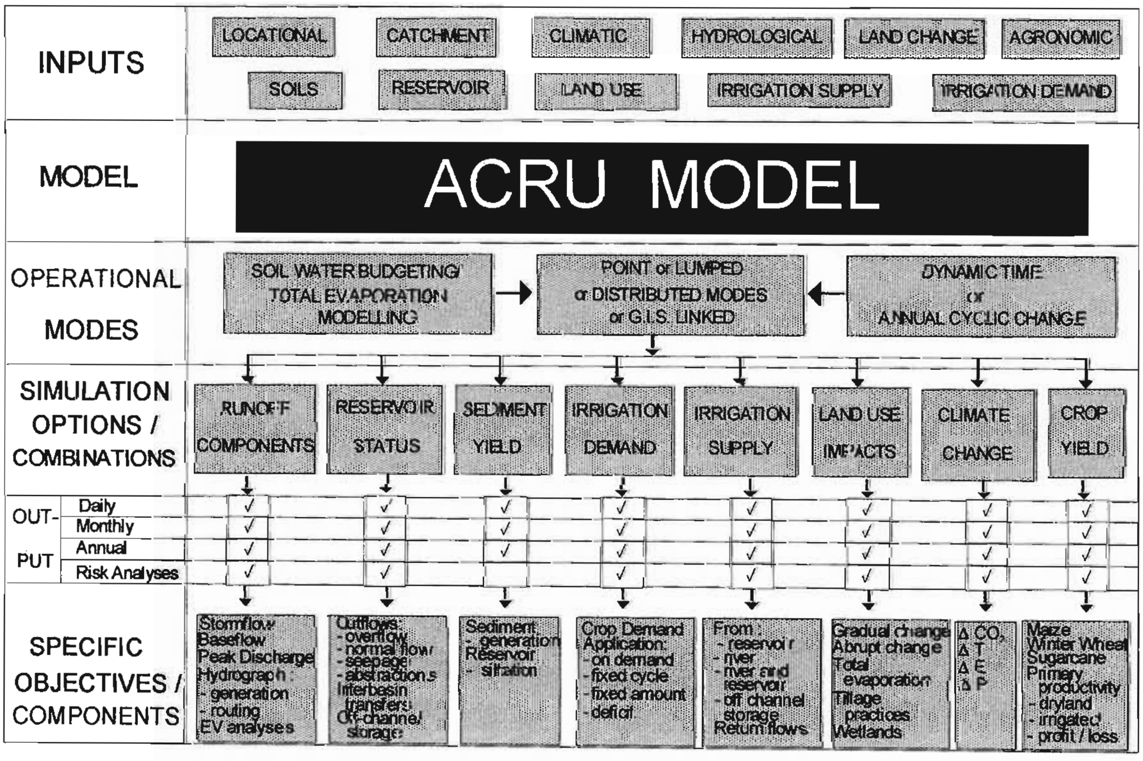

Figure 4.5 *ACRU* : Concepts of the modelling system (Schulze, 1995a)

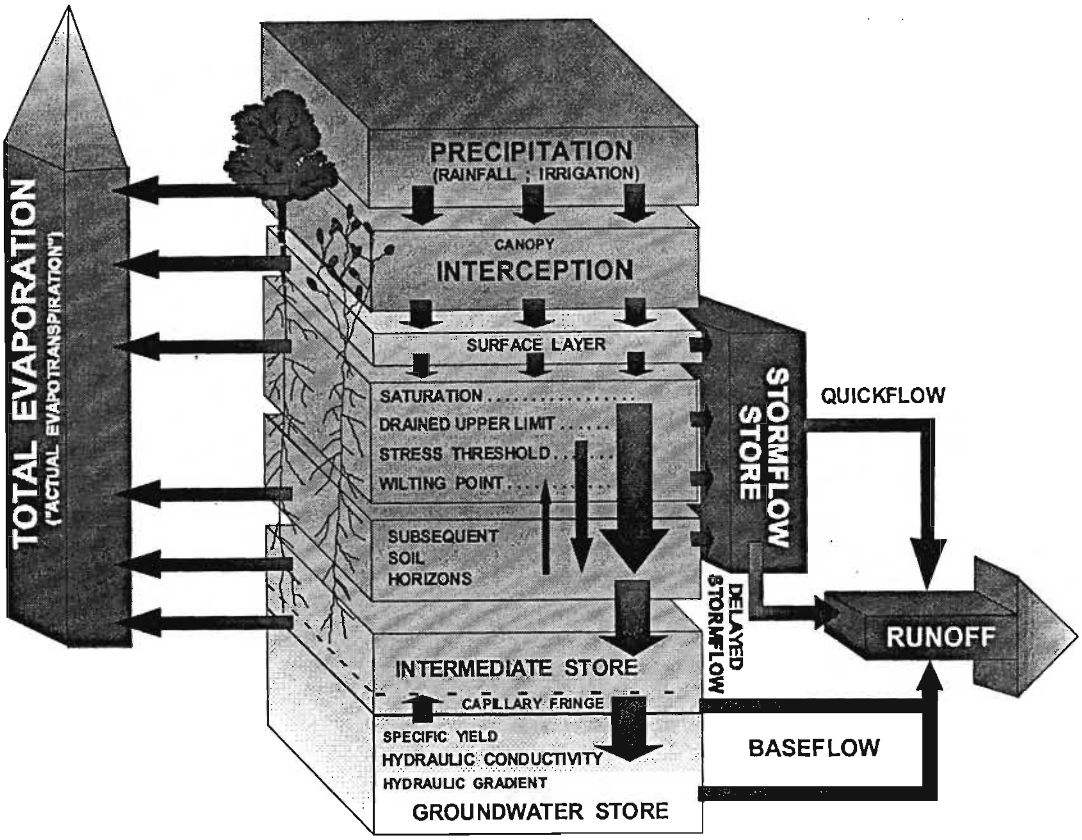

Figure 4.6 *ACRU* model structure (Schulze, 1995a)

The *ACRU* model has been designed as a deterministic model. It integrates physical catchment characteristics, rather than being a calibrated, parameter fitting model. Consequently, the output of simulated values relating to streamflows, and the associated risk analyses computed by the model, are assumed to realistically reflect actual values. This factor is essential if any reliable decisions are to be based on the model predictions. Numerous verification studies in *ACRU* have been conducted to validate that the model provides the right predictions for the right reasons. These studies have addressed all major components of the modelling system and instil credibility in the practical application of the *ACRU* agrohydrological modelling system (Schulze, 1995b).

In the context of modelling the impacts of land use, simulation of soil water content by *ACRU* at two locations with different climates, irrigation strategies and crops was found by Dent, Schulze and Angus (1988) to effectively reflect observations.

The hydrological response to changing land uses over a 30 year time period were investigated by Tarboton and Cluer (1991), who compared simulated streamflows with observed streamflows for the Lion's River subsystems of the Mgeni Catchment. The study showed that using "static" land cover for long term hydrological simulations resulted in significant underestimation of cumulative observed streamflows, whereas using the *ACRU* dynamic option, which accounts for gradual change in land cover with time, resulted in a much more accurate streamflow representation.

4.6.3 Simulating the impacts of land use with the *ACRU* model

The *ACRU* model requires input of known, or measurable, factors relating to the catchment including information on:

(a) climate (daily rainfall; temperature; potential evaporation)
(b) soils (horizon depths; soil water retention and drainage characteristics, and tillage impacts)
(c) land uses (either for baseline or current conditions; types; seasonal above- and below-ground water use related characteristics)
(d) exotic tree species planted (species distributions; extent and levels of site preparation)
(e) wetlands (capacities; surface areas; releases; abstractions)
(f) impoundements (full supply capacity; surface area at full supply capacity; spillway characteristics; surface area to volume relationships)
(g) other land use practices or water abstractions, if relevant (*e.g.* irrigation demand and supply; domestic or livestock abstractions; amounts; sources of water; seasonality) and
(h) climate change (changes in temperature, evaporation and precipitation for an effective doubling of CO_2 scenarios; C3 or C4 plant transpiration feedback).

This information is transformed in the model by considering:

(a) the climate, soil, vegetative, hydrological and socio-economic subsystems
(b) how they interact with one another
(c) what thresholds are required for responses to take place
(d) how the various responses lag at different rates and

(e) whether there are feedforwards and feedbacks which allow the system to respond in a positive or reverse direction.

The model then produces output of the unmeasured variables to be assessed; *e.g.*

(a) streamflows under different catchment conditions (from different parts of the catchment; including stormflow and baseflow on a daily basis) and low flows and

(b) risk analyses in the form of month-by-month and annual statistical frequency analyses, including flows under median conditions and for the driest / wettest flow in, *e.g.* 5 or 10 or 20 years; flow variability; low flow analyses design; peak discharges.

4.7 Modelling Requirements

The catchment hydrological dynamics were modelled with the *ACRU* agrohydrological model (Schulze, 1995a) to assess the impacts of proposed developments on the availability of water resources. The purpose of this Section is to describe the procedures adopted to ensure that the hydrological modelling of the Mkomazi Catchment would not only represent Umgeni Water's management requirements, but would also assimilate the best available data and techniques required to do so. Hydrological model criteria and parameters, as well as associated values are given, complete with descriptions of their sources and relevance.

4.7.1 Subcatchment delineation

At the request of Umgeni Water, the Mkomazi Catchment was configured to represent 52 major inter-linked subcatchments, based essentially on a division of the 12 DWAF Quaternary Catchments within the catchment. The 52 subcatchments were delineated from 1:50 000 topographical map sheets for the Mkomazi Catchment, supplied by the Surveyor General (DSLI, 1997). The main objectives of the delineation were to represent the different land use and management practices as discrete units as well as considering proposed developmental concerns within the catchment. Figure 4.7 illustrates the criteria used for discretising the individual subcatchments. The final configuration specifically includes:

(a) 2 major proposed dam sites on the Mkomazi river (Impendle and Smithfield)

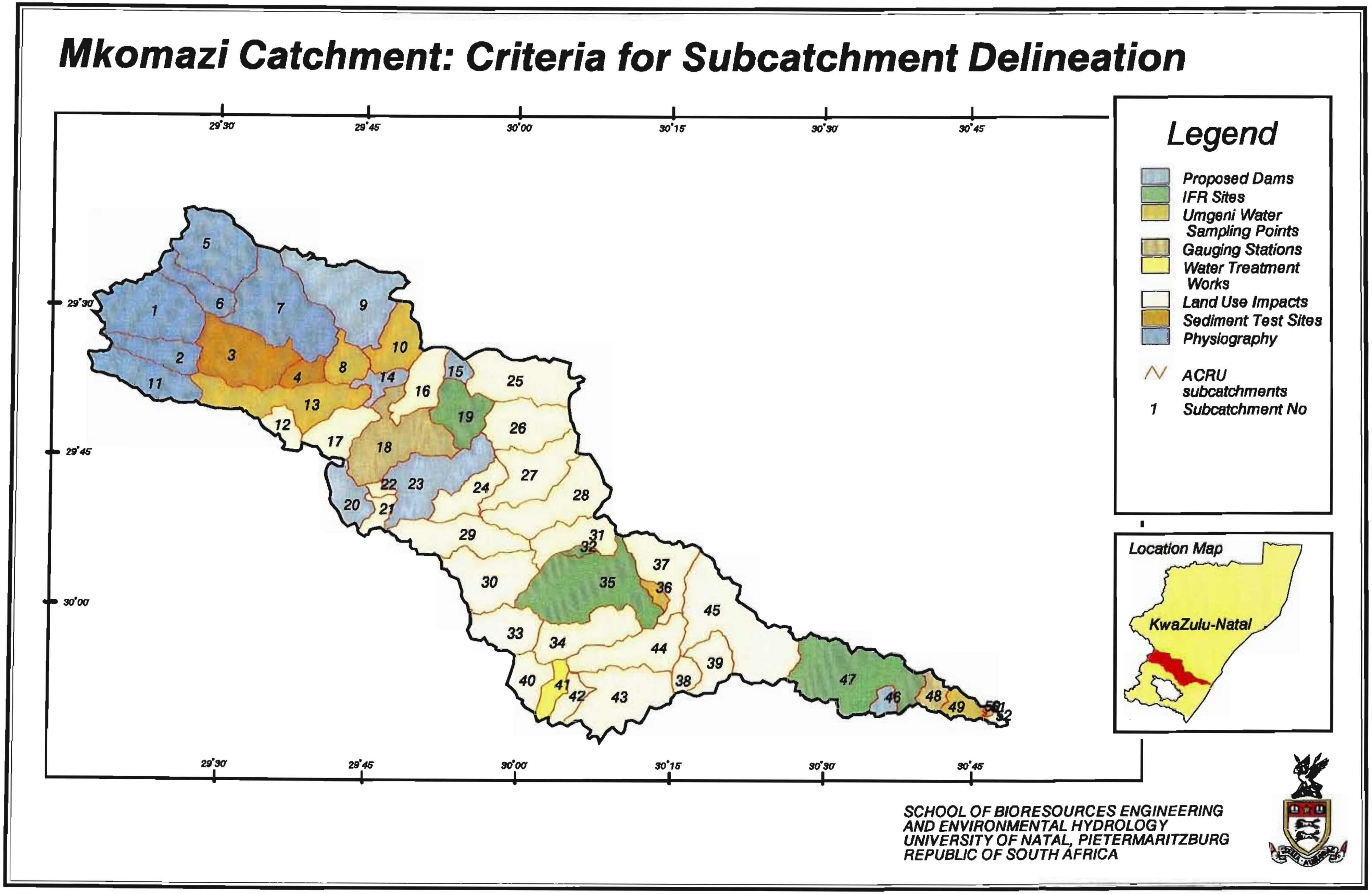

Figure 4.7 Mkomazi Catchment: Criteria for subcatchment delineation

(b) 4 proposed rural supply abstraction developments

(c) 4 Instream Flow Requirement (IFR) sites to assess the environmental water needs, all on the Mkomazi river

(d) Umgeni Water's sampling sites for water quality

(e) DWAF's streamflow gauging stations

(f) the waste water treatment works at Ixopo

(g) 3 sediment test sites which were used in collaborative research with the University of Florence in Italy, but not reported in this thesis

(h) the subdivision of the Drakensberg region on physiographic grounds because of the steep altitudinal, hence rainfall and consequent runoff gradients found there and,

(i) distinction of the different land uses which impact on hydrological responses.

4.7.2 Configuration of subcatchments into hydrological response units

The School of Bioresources Engineering and Environmental Hydrology at the University of Natal in Pietermaritzburg (BEEH) has gained considerable experience in a number of impacts-of-development projects over recent years (*e.g.* Kienzle and Schulze, 1995; Taylor, 1997; Schulze *et al.*, 1996). This has resulted in a tested subcatchment configuration (Figure 4.8) which represents the hydrological responses of not only a number of different land uses and different land management practices, but also takes cognisance of DWAF Quaternary Catchments. Nine different land use categories were identified in the Mkomazi in accordance with their anticipated hydrological responses. The categorisation is shown in Table 4.3.

The land use categorisation shown in Figure 4.8 for two subcatchments, has been applied to each of the 52 subcatchments, giving 468 linked hydrological units or cells each with their own input parameters. The benefit of this configuration is that the areal extent of each land use category, or unit, and the parameters associated with different management practices, can be altered accordingly within the configuration when the hydrology of different land use scenarios is simulated. For example, for assessment of the change in water yield from an increase in commercial plantation in a given subcatchment, the land use category of plantation (*ACRU* category 2 in Table 4.3) would be increased to represent the proposed areal extent. Correspondingly, the areal extent of the category representing the land use being converted to plantation (say, grassland, *ACRU* category 6 in Table 4.3) would be decreased by the equivalent areal extent.

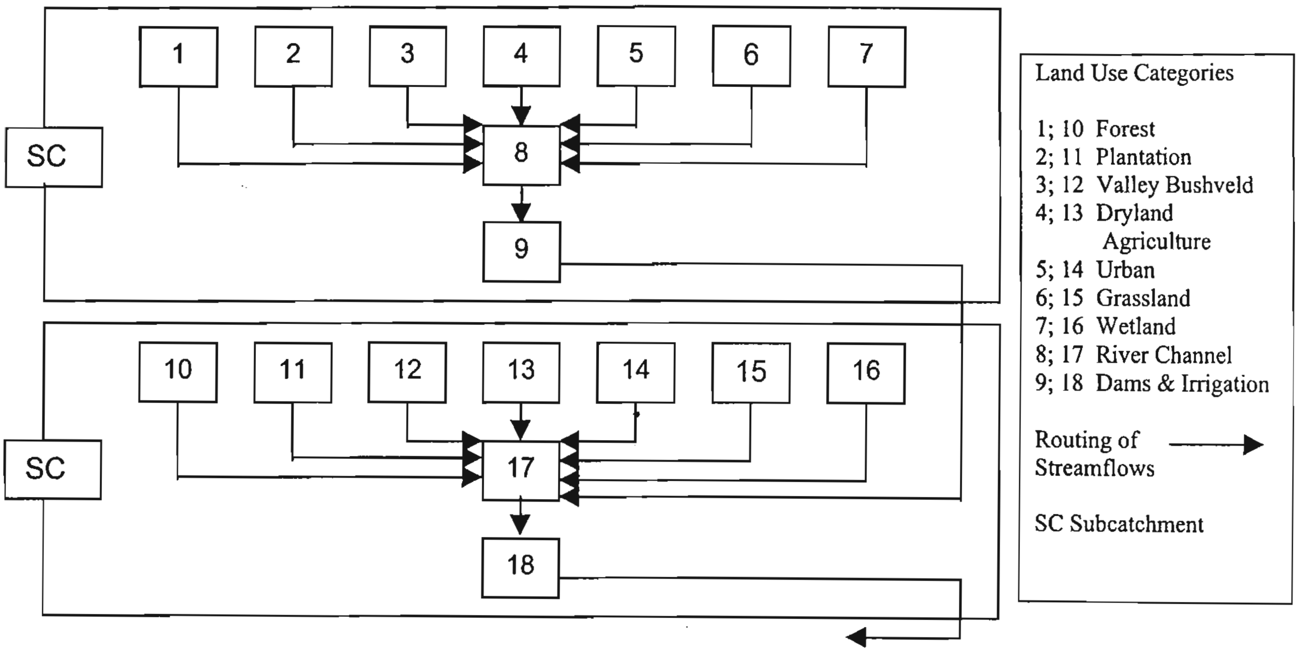

Figure 4.8 Schematic representation of the Mkomazi subcatchment and cell configuration

Table 4.3 Mkomazi Catchment: Land use categorisations

No	Categorisation used in *ACRU* model	CSIR land use classifications
1	Forest	Forest Forest & Woodland
2	Plantation	Forest Plantation
3	Valley Bushveld	Thicket & Bushland
4	Dryland Agriculture	Cultivated permanent: commercial sugarcane Cultivated temporary: commercial dryland Cultivated temporary: semi-commercial / subsistence dryland
5	Urban	Barren rock Degraded: thicket & bushland Degraded unimproved grassland Urban / built-up land: residential Urban / built-up land: residential (small holdings; bushland) Urban / built-up land: transport
6	Grassland	Shrubland & low fynbos Unimproved grassland
7	Wetland	Wetland
8	Riparian	None identified
9	Dams and Irrigation	Improved grassland Waterbodies Cultivated: temporary: commercial irrigated

A further advantage of isolating the different land uses into units or cells, is that the hydrological responses of each unit are modelled distinctly. The routing of simulated streamflows resulting from the individual categories is also indicated in Figure 4.8. In particular, the cell discretisation and inter-cell routing configuration used in the Mkomazi Catchment is indicated in Figure 4.9. The numbered configuration of the Mkomazi, by subcatchment, is shown in Figure 4.7.

4.8 Land Use

4.8.1 Land use classification

The 1996 LANDSDAT TM 1996 coverage provided by the Council for Scientific and Industrial Research (CSIR) was used as a basis for present land use input for the *ACRU* menu. The present land use, in accordance with the LANDSDAT coverage for the Mkomazi Catchment, is shown in Figure 4.10. Nineteen distinct land uses (*cf.* Table 4.3) were identified for the Mkomazi Catchment from the LANDSAT coverage using the CSIR land use classification (Thompson, 1996). Because it was considered undesirable and impractical to allocate a separate land use based sub-subcatchment to each land use identified in each of the 52 subcatchments, it was decided that the different land uses could be more than adequately represented by categorisation in accordance with their anticipated hydrological responses. This resulted in application of the nine-fold categorisation of land uses for use with the *ACRU* model, as shown in Table 4.3. Each of the 19 different land uses identified from the LANDSAT coverage using the CSIR land use classification (Table 4.3), was therefore grouped into one of the nine land use categories for modelling purposes. The distribution of present land cover and land use in the Mkomazi Catchment, as identified by the 1996 LANDSAT TM image, is shown in Appendix A, Table A1.

It was however, necessary to address the limitations of the CSIR land use classification for several of the land uses identified from the LANDSAT coverage *viz*:

(a) The CSIR land use classification does not distinguish the genera of commercially planted trees. Therefore, for the purposes of this study it was assumed that all plantations comprised pines of intermediate age and the sites prepared by pitting, since this was the genus and associated management practice most frequently observed during fieldwork in the Mkomazi Catchment.

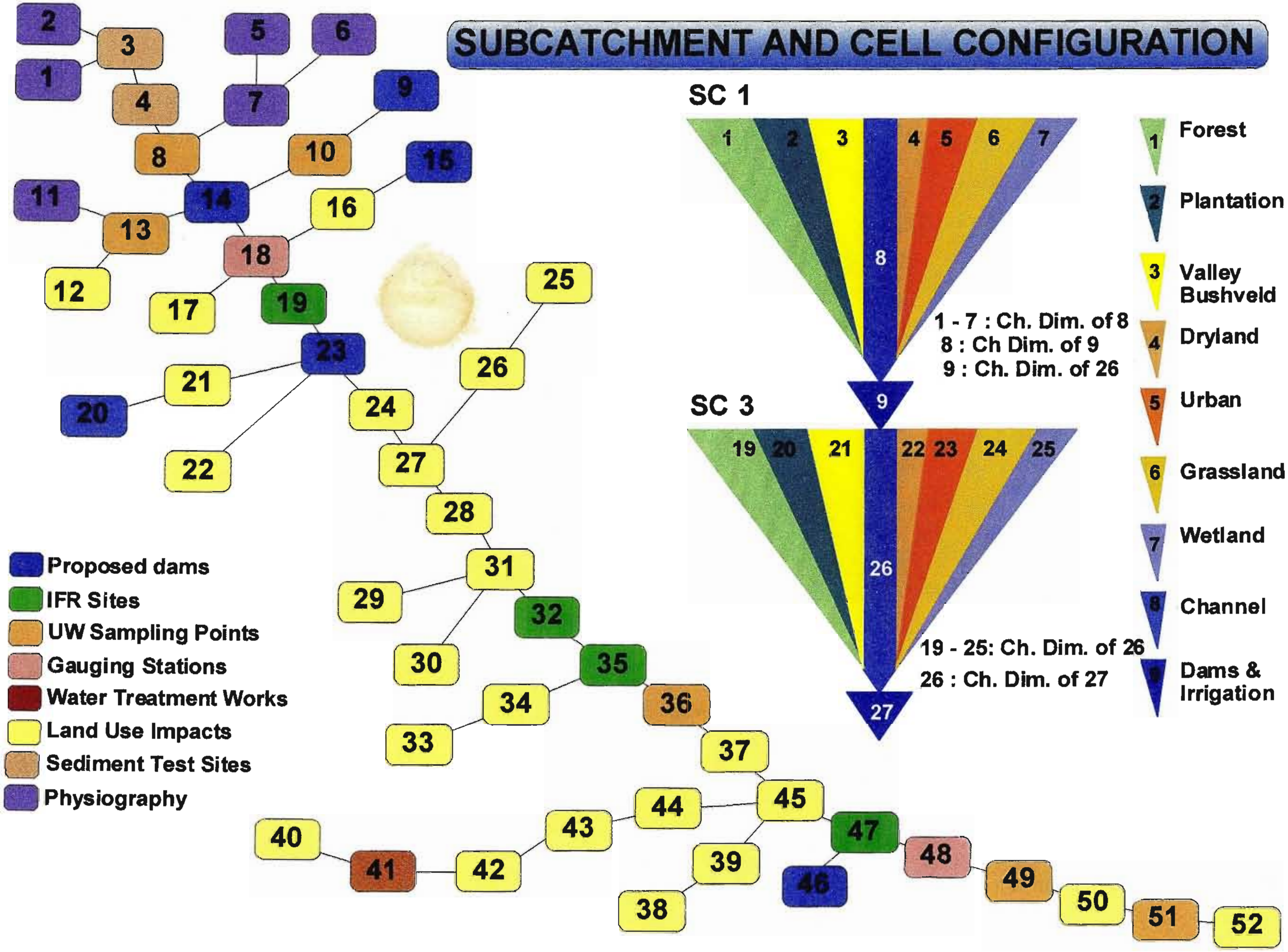

Figure 4.9 Schematic representation of Mkomazi subcatchment discretisation and inter-cell configuration

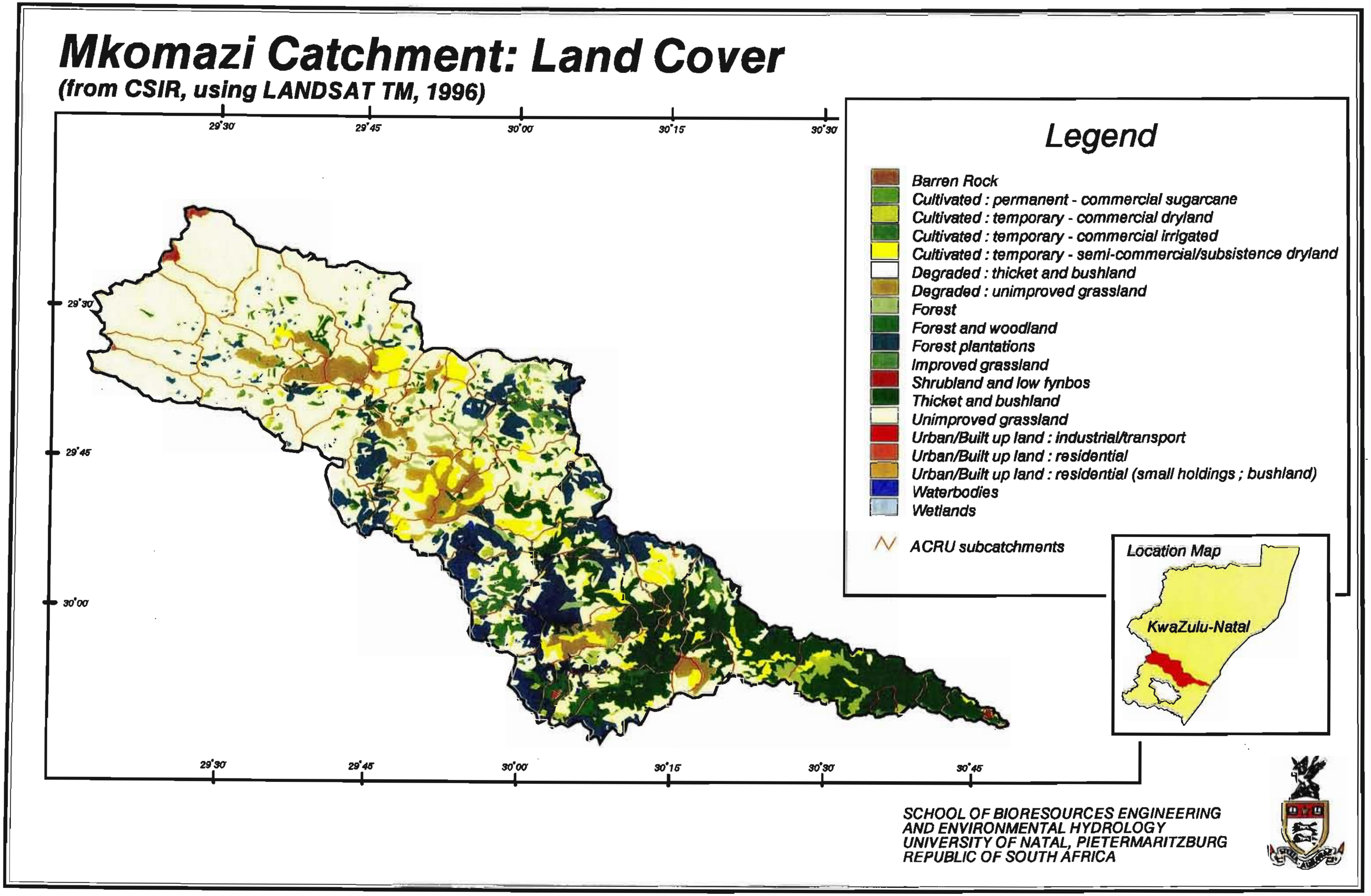

Figure 4.10 Mkomazi Catchment: Land cover (from CSIR, using LANDSAT TM, 1996)

(b) From fieldwork observations, it was considered that *improved grassland* in the catchment was pasture under irrigation.

(c) Irrigated crops in the upper Mkomazi Catchment were assumed from fieldwork observations to be cabbages planted on 1 March (and harvested 3 months later) and potatoes planted on 1 August (also harvested 3 months later). Irrigated crops in the lower Mkomazi Catchment were assumed from fieldwork observations to be citrus.

(d) The LANDSAT imagery did not capture the river channel. The *ACRU* riparian category (*cf.* Table 4.3) was assessed by evaluation of the extent of the tributaries or main river reaches within each of the 52 subcatchments. This was achieved by the application of two procedures *viz*:

  - Representative top-of-channel widths for each subcatchment were evaluated by field measurements. The sites at which the river channel measurements were assessed are shown in Figure 4.2.
  - The lengths of each subcatchment river reach were assessed from the 1:50 000 topographic map sheets for the Mkomazi Catchment (DSLI, 1997).

  Riparian wattle was found from fieldwork to be the prevalent riparian species. Where this species had made substantial invasion along the river channel, a strip 20m on either side of the river channel was configured for the model simulations.

Furthermore, in order to provide an accurate assessment of the hydrological responses of the land cover identified as *unimproved grassland* from the LANDSAT coverage using the CSIR land use classification, an Acocks' Veld Types (Acocks' 1988) coverage was overlayed with the subcatchment boundaries of the Mkomazi Catchment. This application identified which particular Veld Type(s) occurred within a given subcatchment. Where more than one Veld Type occurred, the relevant proportions were assessed and area-weighted to ensure that representative values for vegetative water use coefficients could be assigned (*cf.* Section 4.8.2). The distribution of Acocks' Veld Types (Acocks' 1988) for the Mkomazi Catchment is shown in Figure 4.11.

4.8.2 Vegetative water use

The vegetative water use by each land use within the nine land categories given in Table 4.3 was assessed using values of the water use coefficient (equivalent to the "crop"

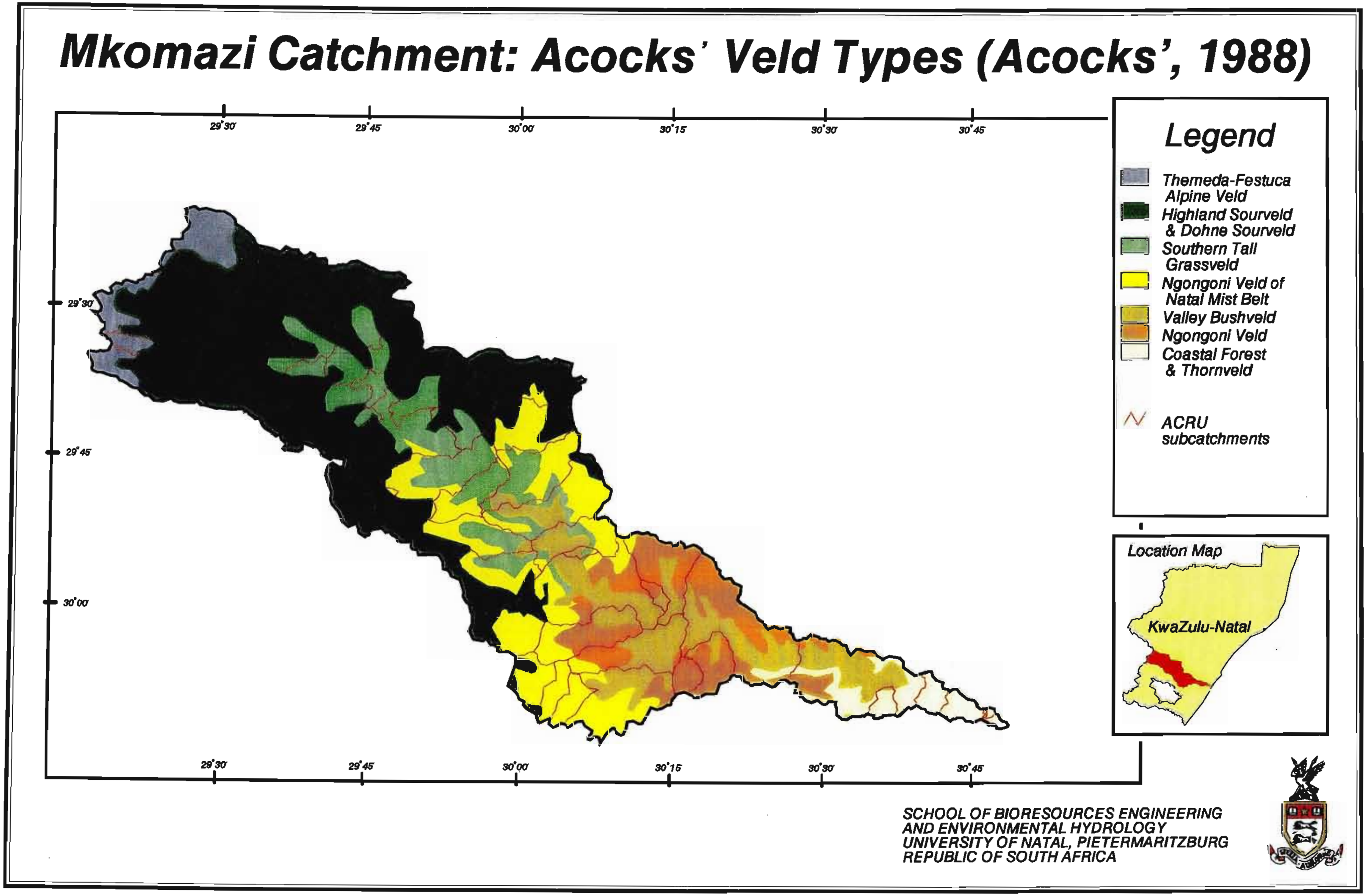

Figure 4.11 Mkomazi Catchment: Acocks' Veld Types (Acocks', 1988)

coefficient) given in Smithers and Schulze (1995) and subsequently revised by BEEH (*e.g.* Summerton, 1996; Schulze *et al.*, 1996). The hydrologically relevant vegetative characteristics of each land use include:

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

(b) a monthly consumptive water use coefficient (converted internally in the model to daily values by Fourier Analyses), which reflects the ratio of water use by the vegetation under conditions of freely available soil water to the evaporation from a reference potential evaporation (*e.g.* A-pan or equivalent), and

(c) the fraction of plant roots that are active in extracting soil moisture from the top soil, and, by implication from the subsoil horizon, in a given month, with this fraction being linked to root growth patterns during a year growing season and periods of senescence brought on, for example, by a lack of soil moisture or by frost.

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

The variables representing the consumptive characteristics of the 19 land uses identified by the 1996 LANDSAT TM image, together with those of riparian wattle (Schulze *et al.*, 1996) which was found from fieldwork to be the prevalent riparian species, were area-weighted within the respective 9 land use categories described in Section 4.7.2. The month-by-month input variables for the land use categories used in the Mkomazi Study are listed in Appendix A, Table A2.

4.9 Physical Input Variables

The assessment of the impacts of development on water resources using a physical-conceptual model such as *ACRU* requires careful consideration of those physical input parameters relating to climate, soils and sediment generation. It is particularly pertinent to apply the best available rainfall data, since this is considered to be the dominant driving force of the hydrological system.

4.9.1 Rainfall

The Mean Annual Precipitation (MAP) of the Mkomazi Catchment varies from 1283mm in the northwest to 752mm in the southeast. However, Figure 4.3 indicates the variation in the subcatchment MAP and clearly shows the driest region, as running from Ixopo through the lower Mkomazi valley to Nhlavini (*cf.* Figure 4.1).

“Rainfall is the fundamental driving force and pulsar input behind most hydrological processes” (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995). Hydrological responses, in nature and also in a daily model such as *ACRU*, are highly sensitive to rainfall input, with an error in rainfall estimation often doubling (or more) any error in runoff estimation (Schulze, 1995a; Schulze and Perks, 2000). A major effort was therefore expended to obtaining subatchment rainfall values which could be considered to be as realistic as possible, both spatially and temporally.

Ninety-two rainfall stations with daily data, in and immediately adjacent to the Mkomazi Catchment, were selected for a first assessment of their pertinence in “driving” the daily rainfall for the catchment. After infilling any missing daily data at each of the rainfall stations using an inverse distance weighting program (Meier, 1997), and for a time period extending from 1945 to 1996, the rainfall stations were screened for appropriateness as driver rainfall stations. This was achieved by applying using the CALC_CORPPT program developed by BEEH to assist in the selection of the best available rainfall station data. The final selection resulted in the 26 driver rainfall stations shown in Figure 4.12 being used in the model configuration. Each rainfall station has monthly adjustment factors input to the ACRU menu to provide a more representative subcatchment areal rainfall. The details of the selected rainfall stations are provided in Table 4.1, and the

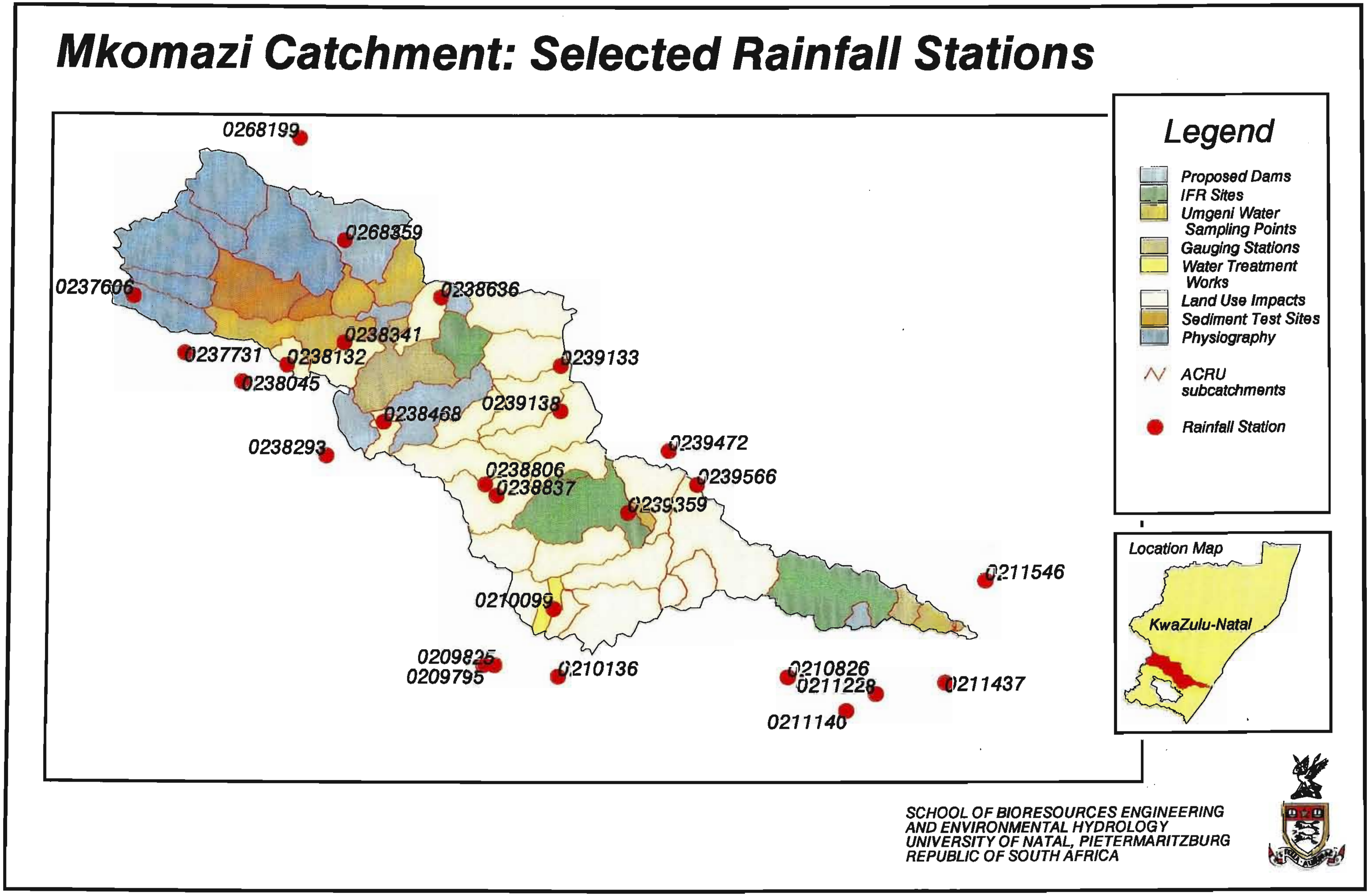

Figure 4.12 Mkomazi Catchment: Selected rainfall stations

monthly adjustment factors associated with the rainfall stations for each of the 52 subcatchments is indicated in Appendix A, Table A3.

4.9.2 Potential evaporation and temperature

Month-by-month A-pan equivalent reference potential evaporation totals (E_r) were derived on a regional basis by multiple regression analysis from factors such as maximum temperature, day length, distance from sea and altitude (Schulze, 1997). These were plotted on a 1' x 1' latitude / longitude grid (Schulze, 1997) and the values were area-weighted per subcatchment and then converted, internally within *ACRU* to daily values by a Fourier Analysis. The derived daily values of E_r are then adjusted down on a rainday or up on a rainless day within the *ACRU* model on a day-by-day basis, according to whether or not a threshold 5mm rainfall was exceeded on that day. The monthly means of daily maximum and minimum temperatures were obtained from the BEEH 1' x 1' latitude / longitude grid (Schulze, 1997).

The variability of these climatic features is indicated in Figures 4.13 to 4.15. The variation in potential evaporation for the Mkomazi Catchment between the months of January and July is show in Figure 4.13, whereas the maximum temperatures for January and the minimum temperatures for July are shown in Figures 4.14 and 4.15 respectively.

4.9.3 Soils

Soils play a crucial role in catchments' hydrological responses by:

(a) facilitating the infiltration of precipitation, and thereby largely controlling stormflow generation,

(b) acting as a store of water which makes soil water available to plants,

(c) redistributing water, both within the soil profile and out of it and

(d) controlling soil water evaporation and plant transpiration processes, within the root zone as well as drainage rates below the root zone where the drained water eventually contributes into the groundwater zone which feeds baseflow.

Umgeni Water made a detailed coverage of soils Land Types for the Mkomazi Catchment, compiled by the Institute for Soil, Climate and Water (ISCW), available for the Mkomazi

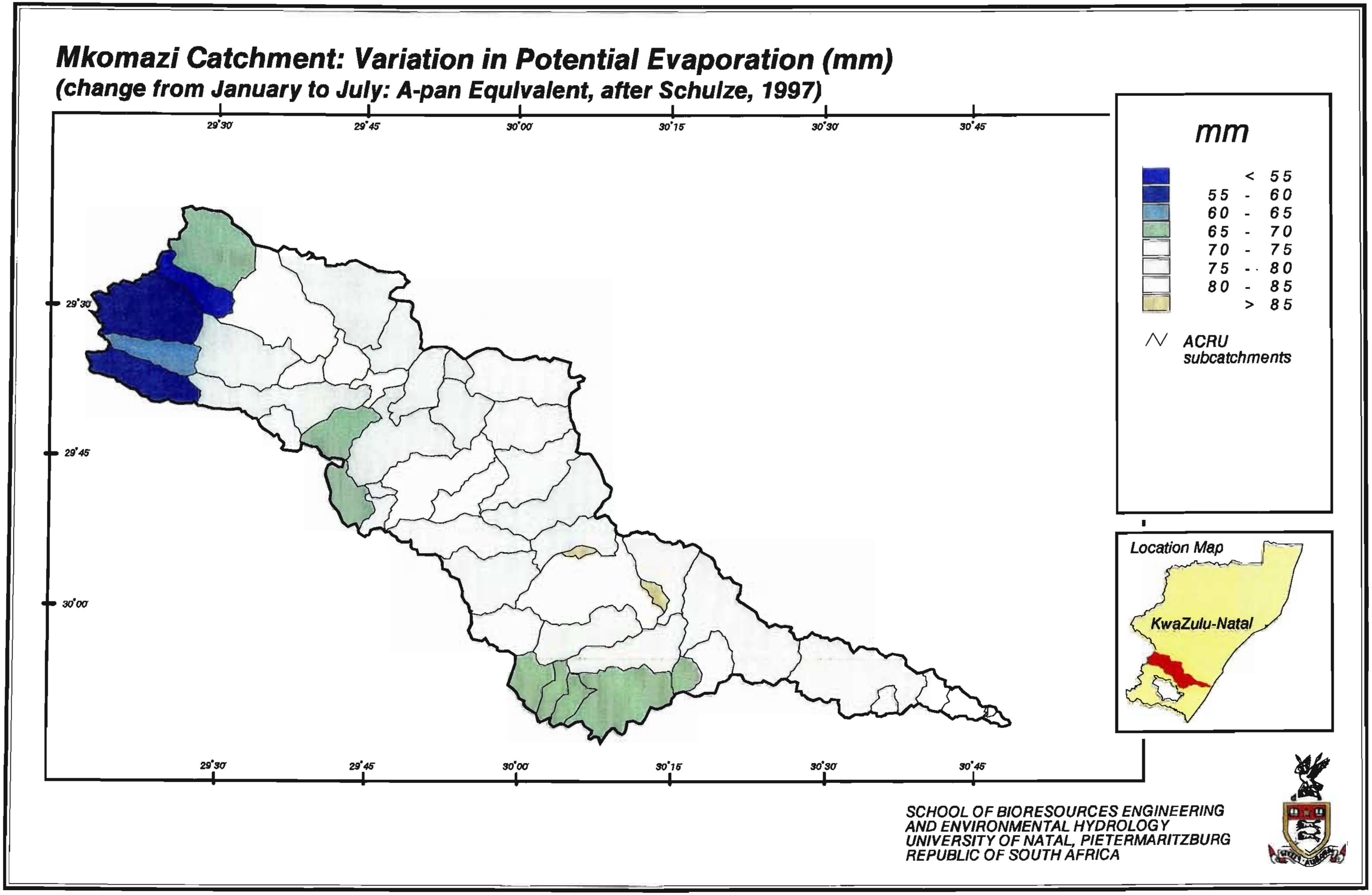

Figure 4.13 Mkomazi Catchment: Variation in potential evaporation (after Schulze, 1997)

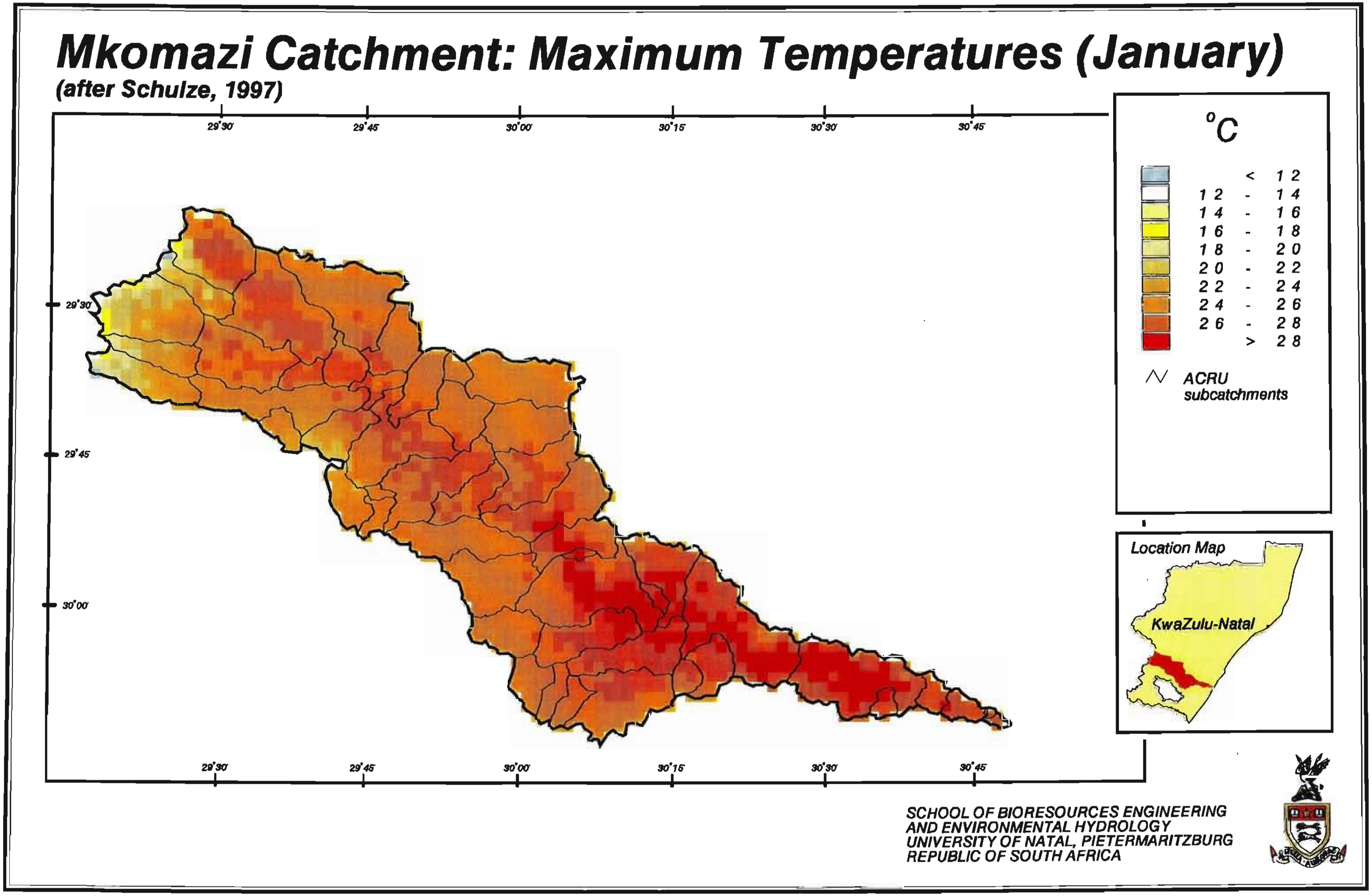

Figure 4.14 Mkomazi Catchment: Maximum temperatures, January (after Schulze, 1997)

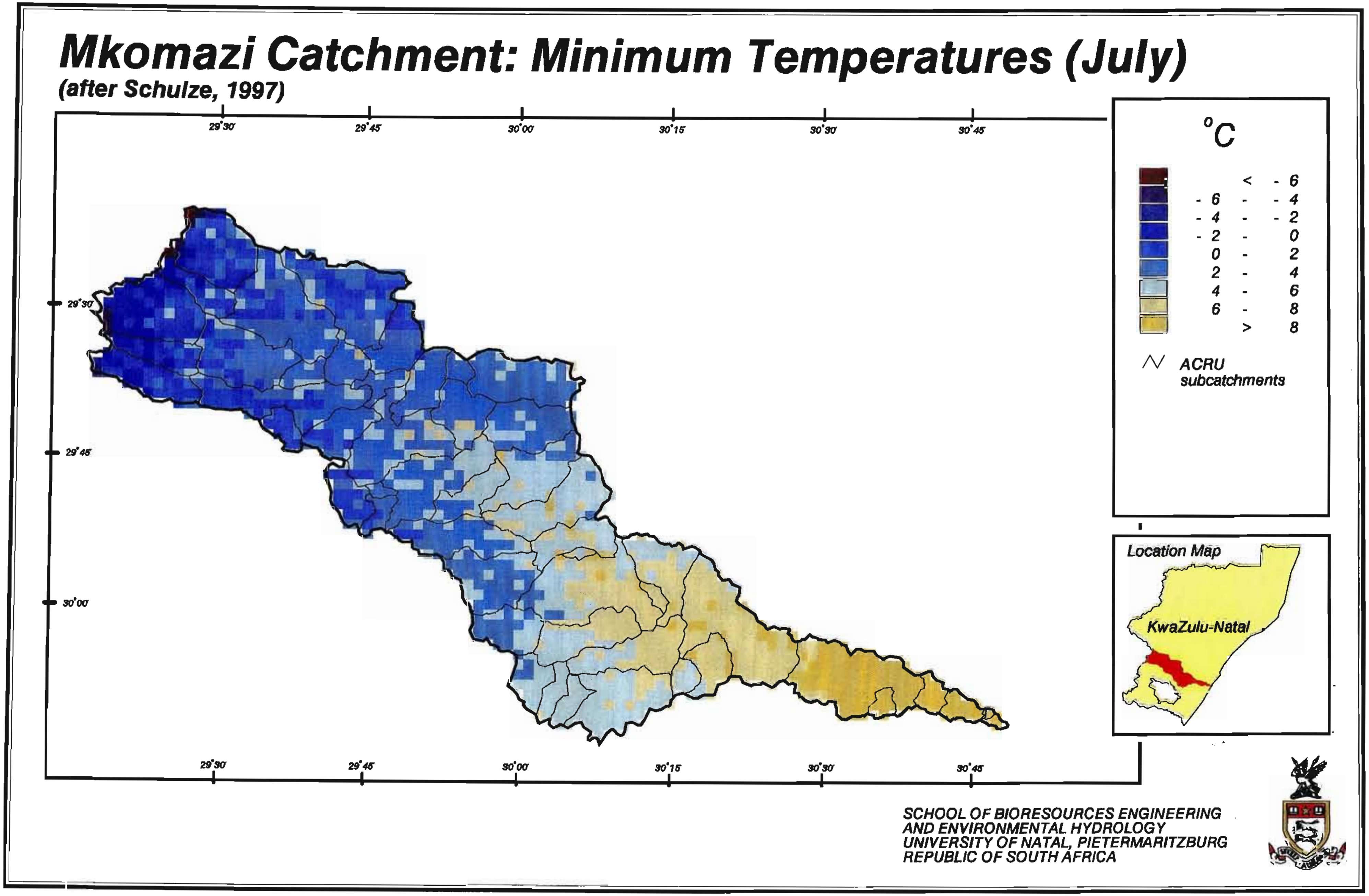

Figure 4.15 Mkomazi Catchment: Minimum temperatures, July (after Schulze, 1997)

Catchment. For each of the 177 soils Land Types (as shown in Appendix A, Table A4), a vast amount of information on percentages of soil series per terrain unit, soils depths, texture properties and drainage limiting properties was provided by the ISCW. This Land Type information was "translated" to those hydrological soil characteristics for a two-horizon soil profile as required by *ACRU* using the AUTOSOILS program, developed by Pike and Schulze (1995) from information contained in Schulze (1995a).

AUTOSOILS output includes the thicknesses of the topsoil and subsoil horizons, values of the soil water content at permanent wilting point, drained upper limit (*i.e.* field capacity) and saturation (porosity) for both soil layers and saturated drainage redistribution rates from top-to subsoil and out of the subsoil. Values of the above variables were determined for each soil series making up a Land Type and then area-weighted according to the proportions of soil series in a Land Type and then the various Land Types found within a subcatchment. *ACRU* also requires a soil texture class for calculations of soil water evaporation and sediment yield estimations, and from available information an average dominant texture class of sandy clay loam was input for all subcatchments. The final subcatchment values of the variables used in simulations identified in Section 4.3 of this study are summarised in Appendix A, Table A5. The table also contains runoff related values, derived from Land Type information, of two further variables, *viz* fractions of:

(a) adjunct impervious areas within a subcatchment, constituting the areas around channel zones assumed to be permanently wet and from which direct overland flow is hypothesised to occur after a rain, and

(b) disjunct impervious areas such as rock outcrops, from which rainfall running off, infiltrates into surrounding areas and influences their water budgets.

In accordance with recommendations made by Summerton (1996), the thickness of the subsoil horizons in those subcatchment areas where the land use classification is represented by the forest, plantation and riparian categories (*cf.* Figure 4.8) is increased by a 0.25m, to account for the trees' deeper rooting patterns.

4.10 Water Allocations and Abstractions

To effectively assess the impacts of any water resource development on the generation of streamflows, it is necessary to address the conditions which satisfy the Reserve (NWA,

1998) in addition to any direct anthropogenic streamflow abstractions for irrigation performed within the Catchment. For the purpose of this study these were viewed as comprising two basic water allocations, *viz*:

(a) environmental flow requirements and

(b) irrigation abstractions.

4.10.1 Environmental requirements: instream flow requirements

The determination, and fulfilment, of the environmental reserve for the Mkomazi Catchment is a major issue of concern. Much preparatory work by the Institute for Water Research, University of Rhodes, Grahamstown (IWR, Environmental) has already been conducted to determine the Instream Flow Requirements (IFRs) for the Mkomazi River (DWAF, 1998b). The output of this work is a set of Building Block Methodology tables (*cf.* Section 3.7) in which flow values for each month of the year are specified at certain points of interest known as "IFR Sites".

At the time of the model simulations applied in this study (1998 – 2000), the necessary daily design abstractions and operating rules for dam releases to meet the instream flow requirements as specified in the Mkomazi IFR Tables were unavailable. Consequently, the instream flow requirements were not *simulated* as an allocation as such. Notwithstanding this factor, recognition of the necessity for legal flow releases for downstream use, as defined in terms of previous water legislation, was addressed by simulating "normal flow" releases which are described in Section 4.10.3.

Nonetheless, assessment of the Mkomazi's environmental demand in accordance with the flows specified in the Mkomazi's IFR Tables is addressed in Chapter 8 as a water allocation from available streamflows. Furthermore, assessment of the Mkomazi's environmental flow requirements is addressed in Chapters 9, 10 and 11 of this dissertation.

4.10.2 Irrigation Abstractions

There is a paucity of information available to accurately perform the necessary *ACRU* irrigation modules for the Mkomazi Catchment. For this reason, certain field observed and experience-based assumptions were made to simulate effective irrigation abstraction *viz*:

(a) With the exception of those irrigated areas identified by the LANDSAT TM image as improved grassland, irrigated areas in upper subcatchments, SC Numbers 1-27, were, following fieldwork, input as winter wheat and spring cabbages, with typical maximum rooting depths of 0.3m, whereas irrigated areas in lower subcatchments, SC Numbers 28-52, were assumed to be under citrus, with typical maximum rooting depths of 1.00m.

(b) Soil water extraction by winter wheat and spring cabbages was concentrated in the top 0.2m, whereas for citrus it was in the top 0.6m.

(c) The crop coefficient of the irrigated crop at which ground cover / shading was at a maximum was 80% of the maximum monthly water use coefficient as shown in Appendix A, Table A2, and recommended as such from previous *ACRU* verification studies.

(d) The crop coefficient of the irrigated crop when rooting depth reached a maximum was also 80% of the maximum monthly water use coefficient.

(e) The irrigation scheduling was for a 15mm net application in a 5-day cycle.

(f) The irrigation cycle was halted once a threshold daily rainfall of 15 mm was exceeded.

(g) Irrigated soils were assigned the same soil water retention values as their respective subcatchments' soils.

(h) Conveyance losses as well as wind drift and spray evaporation losses were input as 10% each although it is acknowledged that the latter may be as high as 40%.

(i) Where water bodies had been identified by the LANDSAT TM image these were confirmed as being farm dams from examination of Aerial Photographs (1:30 000) of the Mkomazi Catchment. Where farm dams existed, irrigation abstractions were drawn from this source, within each subcatchment. In those subcatchments where there was an absence of farm dams, irrigation abstractions were drawn from river sources. In all instances irrigation return flows were returned to their own subcatchments.

4.10.3 Systems Operation and Dam Operating Rules

The level of dam operating rules required for the operation of the *ACRU* model was, at the time of writing (January 2001), unavailable for the proposed Smithfield Dam. However, certain assumptions based on previous *ACRU* modelling experience (Schulze *et al.*, 1996; Taylor, 1997) were incorporated to the model simulations *viz*:

(a) For computational purposes, all dams within a given subcatchment were combined into one single dam, located at the respective subcatchment outlet, for surface evaporation and irrigation abstraction purposes.

(b) All reservoirs (including the proposed Smithfield Dam) were assumed to be fully operational, accounting for daily gains from streamflows and rainfall on the water surfaces, and losses through surface water evaporation, irrigation abstractions and other operations, overflow, normal flow releases and seepage.

(c) The LANDSAT TM, image used to determine land cover in the Mkomazi catchment identified the surface area of the water bodies during April 1996. As well as being unrepresentative of the full supply capacity criteria required for reservoir modelling in *ACRU*, no other technical information regarding dam capacity or length of dam wall was available. In such instances of inadequacy of available information, the surface area available is applied in the following relationship to obtain the volume of the reservoir:

$$A = 7.2\,(S_v)^{0.77}$$

where A = the surface area of the reservoir (m^2) and

S_v = the volume of the reservoir (m^3) (Schulze, Smithers, Lecler, Tarboton and Schmidt, 1995).

(d) Area:volume relationships were also unavailable for the Mkomazi reservoirs, therefore, the default area:volume relationship was applied. This negated the necessity for the knowledge of the length of the reservoir wall.

(e) It was assumed in the case of farm dams, that no "legal flows" (*cf.* 4.10.3, g) would be released in practice. However, because of their earth wall construction, seepage volumes were calculated as being equivalent to 0.0006 x the storage capacity (Schulze, Smithers, Lecler, Tarboton and Schmidt, 1995). This approximates the reservoirs' emptying about once in every five years.

(f) No seepage was assumed from the proposed Smithfield Dam, because it is considered that seepage from dams with impermeable lining and concrete walls is negligible.

(g) Legal flow releases are anticipated from the proposed Impendle and Smithfield Dams. However, in the absence of the necessary daily design abstractions and operating rules for dam releases to meet those flow requirements in terms of the Reserve, these were preliminarily estimated in the same manner as seepage volumes, *i.e.* at 0.0006 x the full supply capacity per day, on two conditions incorporated in the *ACRU* model:

- If the total streamflow into the reservoir on a given day was less than the legal flow releases (hereafter termed "normal flow" or "compensation flow") the releases were reduced to equal those of the total inflows.
- If the storage volumes were below dead storage level, no normal flow releases were made.

(h) The dead storage level of the reservoir, *i.e.* the level below which no further abstractions can take place, nor would normal flows be released, was input as 10% of full supply capacity, as suggested by Schulze, Smithers, Lecler, Tarboton and Schmidt (1995).

(i) All the reservoirs where set to full capacity at the beginning of the simulation period.

Several of the values derived from these assumptions are provided in Appendix A, Table A6.

4.11 Land Use Change, Water Resources Development and Potential Scenarios

4.11.1 Baseline land cover

It is necessary to have a baseline land cover against which to compare the hydrological responses of different land uses. This is especially pertinent to the assessment of the impacts of potential land use change and scenarios on water resources. There are several options available for a baseline cover (Schulze *et al.*, 1999) using, for example,

(a) veld in a specified hydrological condition, *e.g.* in good, fair or poor condition, as defined in Schulze and Hohls, (1993)
  - however, not all land uses were converted from veld in a specified, say fair, hydrological condition
  - veld in fair hydrological condition has different hydrological response attributes at different altitudes; or

(b) actual land cover or land use in a specified baseline year, *e.g.* 1972, when the afforestation permit system was introduced

- however, land cover in a specified year could be associated with regional development levels at a particular point in time and as such may be anomalous for historical, political, social or economic reasons; or

(c) a land cover representing "natural" vegetation, or a land cover in pristine or near pristine condition

- however, there is no natural vegetation or land cover classification which is wholly appropriate from a hydrological perspective (Schulze, *et al.*, 1999).

Nonetheless, option (c) was considered the best, and in this study, the land use classification used to represent natural land cover conditions for the entire Mkomazi Catchment was Acocks' Veld Types (Acocks, 1988), in accordance with recent research by Schulze (2000). The distribution of Acocks' Veld Types within the Mkomazi Catchment was shown in Figure 4.11. The Mkomazi Veld Types, by subcatchment, and the relevant areal extents applied in the baseline land cover simulations are provided in Appendix A, Table A7. The water use coefficients applied were taken from Schulze *et al.* (1999) and Schulze (2000) and are provided in Appendix A, Table A2. Table 4.4 gives the baseline land cover and water use coefficients pertaining to two subcatchments in the Mkomazi, one the upper and the other in the lower catchment.

Table 4.4 Baseline land cover and water use coefficients pertaining to two Mkomazi subcatchments

SC	**Baseline Land Cover**	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	Highland Sourveld and Döhne Sourveld	Water use coefficient	0.60	0.60	0.60	0.45	0.20	0.20	0.20	0.20	0.30	0.50	0.60	0.60
		Interception loss	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Roots in topsoil	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.90
		Coefficient of I_a	0.15	0.15	0.15	0.20	0.25	0.25	0.25	0.25	0.25	0.20	0.20	0.15
52	Coastal Forest and Thornveld	Water use coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
		Interception loss	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
		Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		Coefficient of I_a	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

4.11.2 Inter-basin transfers

The first phase of the MMTS will involve the construction of the proposed Smithfield Dam on the Mkomazi River. DWAF plan that initially 5.6 $m^3.s^{-1}$ will be a transferred (with a peak transfer capacity of 7.0 $m^3.s^{-1}$) from the proposed Smithfield Dam to the Mgeni Catchment via a pumpstation-shaft-tunnel to an existing dam near Baynesfield (*cf.* Figure 4.1). The operation of this initial inter-basin transfer, the Smithfield Scheme Phase1 of the MMTS, was input to the *ACRU* reservoir routine in accordance with the considerations outlined in Section 4.10.3 and the input values given in Appendix A, Table A6. The input values of the dam storage capacity at full supply level (FSL), *viz.* 137 x 10^6 m^3, and its surface area at FSL of 583 ha, are those given in the DWAF MMTS Pre-Feasibility Study (DWAF, 1998a). The transfer capacity rate was input to an *ACRU* MMTS Phase 1 menu as a daily draft of 604.8 x $10^3 m^3$ (*i.e.* 7.0 $m^3.s^{-1}$) out of the configured Mkomazi system. The normal flow releases from the dam were input as 91.33 x $10^3 m^3$ (*i.e.* 0.0006 x the full supply capacity) each day.

4.11.3 Potential climate change

Predictions of the impacts of changes in atmospheric concentrations of carbon dioxide, CO_2, are generally made using the output from global scale General Circulation Models (GCMs) run for an effective doubling of CO_2 from 280 to 560 ppmv. For the 2 x CO_2 climate scenario the GCM output of temperature and precipitation, which is generally available as mean monthly changes from the present, is transposed for application as monthly adjustments to daily or monthly baseline climate conditions, assuming no changes in climatic variability or in daily persistences of wet and dry and sequences between the baseline and future climates (Schulze and Perks, 2000).

The HadCM2 transient GCM (Murphy and Mitchell, 1995), which includes a coupled ocean model and runs at a spatial resolution of 2.50° latitude and 3.75° longitude, was developed by the UK Meteorological Office and the Hadley Centre. In this study, scenarios of potential climate change were carried out by applying conversions of the HadCM2 simulations. Furthermore, the simulation output applied includes greenhouse gas forcing (excluding sulphates) through a 1% per year increase in atmospheric CO_2 concentrations, with the future 2 x CO_2 scenarios being estimated to represent the period

2030 – 2059 based on a baseline climate representing the period 1961 - 1990. GCM grid point output for monthly values of precipitation, maximum and minimum temperature was provided to the BEEH by the University of Cape Town, South Africa. These values were downscaled for South Africa to a 1/4° x 1/4° latitude / longitude resolution grid using interpolative procedures described in Perks *et al.* (2000). The relevant values for each of the 52 Mkomazi subcatchments were extracted from this 1/4° surface for this climatic change impact assessment.

For climate change scenarios the following changes were made to each subcatchment of the Mkomazi present climate conditions:

(a) the monthly A-pan equivalent reference potential evaporation values were increased to account for the change in atmospheric demand, this being assessed at a 3% increase per °C increase of maximum temperature (Schulze and Kunz, 1993)

(b) the option in *ACRU* for soil water evaporation and plant transpiration to be computed separately was invoked, to call the *ACRU* routine which can simultaneously account for enhanced soil water evaporation rates as well as transpiration loss feedbacks under a 2 x CO_2 scenario

(c) daily rainfall values, were adjusted for each month according to the GCM generated changes in precipitation, as downscaled to the individual subcatchments of the Mkomazi Catchment and

(d) the enhanced CO_2 -induced stomatal conductance routine in *ACRU* which enables the CO_2 feedback on transpiration to be achieved, was invoked for both C3 and C4 plants, depending on whether the dominant land use in a given subcatchment was C3 or C4.

The values extracted from the 1/4° x 1/4° resolution grid which were derived from the HadCM2 simulations, indicate increases in the monthly means of daily maximum and daily minimum temperatures for the entire Mkomazi Catchment as a result of potential climate change. Slightly greater increases are simulated by the HadCM2 at the higher altitude, western subcatchments than at the lower altitude, eastern subcatchments. Table 4.5 gives the daily A-pan adjustment factors for two subcatchments in the Mkomazi, one the upper and the other in the lower catchment.

Table 4.5 Month-by-month multiplicative factors used for adjustment of present climate A-pan equivalent values to represent a 2 x CO_2 climate derived from HadCM2 simulations, for two subcatchments in the Mkomazi Catchment

SC	**A-Pan Equivalent Adjustment Factors**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
52	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04

The extent of change in monthly rainfall as a result of the impacts of climate change indicates that, in general, decreases in rainfall would be experienced from December through May (which includes most of the main rain season), yet increases in rainfall would be experienced from June to November (which includes the period of spring rains). Table 4.6 gives the month-by-month adjustment of daily precipitation values used for the *ACRU* menus for present climate conditions and for the climate change impact assessment, for subcatchments 1 and 52.

Table 4.6 Month-by month multiplicative factors used for adjustment of present climate daily precipitation values to represent a 2 x CO_2 climate derived from HadCM2 simulations, for two subcatchments in the Mkomazi Catchment

SC	**Climate**	**Daily Precipitation Adjustment Factors**											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Present	1.01	0.90	1.11	1.19	1.10	0.79	0.70	0.78	0.84	0.99	0.91	0.91
1	Change	0.81	0.81	1.00	0.96	0.78	0.95	0.72	1.02	0.94	1.19	0.93	0.75
52	Present	1.03	1.01	1.04	0.98	0.90	0.89	0.89	0.94	0.95	1.01	0.99	1.06
52	Change	0.82	0.92	0.87	0.77	0.70	1.07	0.93	1.30	1.00	1.10	1.05	0.70

The values used for the adjustment of monthly A-pan values and for the month-to-month adjustment of daily precipitation values in the *ACRU* menus for the climate change impact assessment for the entire Mkomazi Study area are provided in Appendix A, Tables A8 and A9 respectively.

The Mkomazi land use applied to the *ACRU* climate change menu was the same as that applied to the *ACRU* present land use menu. Furthermore, a present land use simulation was run with soil water evaporation and plant transpiration computed separately in order to have a baseline by which to compare any hydrological impacts of climate change.

4.12 Conclusions Regarding Modelling Needs for Water Resources Management

There are a considerable number of databases that are critical to the menu configuration required by a daily simulation model such as *ACRU*. However, access to these databases through the facilities provided by the Computing Centre for Water Research (CCWR) is relatively straightforward. Additionally, this study of the modelling needs of water resources management also provided the opportunity to develop some new technical assistance (*i.e.* the BEEH CAL_PPTCOR program). However, the amount of information required to configure a menu representing a catchment discretisation of as many as 468 inter-linked cells was a challenging, time consuming and arduous task.

The subcatchment discretisation of the 52 inter-linked subcatchments from the original DWAF 12 QCs was essential to represent the management plans of Umgeni Water. The benefits of the additional discretisation of the 9 individual *ACRU* land use categories to the installed modelling system for the Mkomazi Catchment will be highlighted in Chapter 8 in which the water use and requirements of the dominant water use sectors are investigated. Moreover, it is anticipated that water resources managers of the Mgeni-Mkomazi system will attempt to regulate land use impacts in the Mkomazi to augment the water supply to the Mgeni. Implementation of catchment management at that stage will require the assessment of the impacts of streamflow reduction activities (principally commercial afforestation, alien riparian vegetation and subsistence farming) and irrigative agriculture on the hydrological regime of the Mkomazi Catchment. The Mkomazi Catchment discretisation and configuration described in this chapter is, therefore, considered to be appropriate for application to such scenarios.

* * * * *

The following Chapters 5, 6 and 7 present the results of the study of the impacts of land use, climate and catchment development on the hydrological responses of the Mkomazi Catchment. Chapter 8 then addresses the issues of water resource management and allocation required for sustainable development of the Mkomazi Catchment.

5 ESTABLISHING CONFIDENCE OF SIMULATIONS: MKOMAZI VERIFICATION STUDIES

5.1 Introduction

As a physical-conceptual model, physically realistic and observationally derived variables on climate, soils, vegetation, catchment characteristics, irrigation and dams are input in *ACRU*. Structurally and conceptually *ACRU* has, therefore, been designed specifically to simulate predictive scenarios based, *inter alia*, on land use change. *ACRU* is not a parameter-fitting model, which is calibrated until simulated values mimic observed values. It is a deterministic model structured to give realistic answers for the right hydrological reasons.

It is, however, essential to have the assurance that the modelled streamflow values reflect observed values. It is particularly pertinent that simulated streamflows satisfactorily mimic the high flows and low flows of the actual streamflow regime since these components determine the extent of hydrological variation required to sustain the integrity of aquatic ecosystems. For this reason verification studies were performed to compare the *ACRU* simulated streamflows with the observed streamflow records at the subcatchments representing the DWAF gauging stations U1H005 (Camden), U1H006 (Delos Estate) and U1H003 (Umkomazi Drift), all on the Mkomazi River (see Figure 4.2). However, the observed records for U1H003 are relatively short, commencing in 1957 and terminating in 1969, and the verification of these streamflows will not be discussed.

The *ACRU* model was run with an initial menu comprising the present land use of the Mkomazi Catchment using the land use identified from the 1996 LANDSAT TM image and those input factors identified in Chapter 4. While this initial run cascaded the daily streamflows downstream as indicated in Figures 4.8 and 4.9, explicit flow routing in the sense of lagging and attenuating flows through channels and reservoirs was not performed. The difference in Median Annual Runoff (MED) at the Mkomazi estuary mouth, applying the present land use menu with *ACRU* (1040 million m^3) and the Mean Annual Runoff (MAR) assessed by BKS PTY LTD (959 million m^3) using calibrated monthly time step Pitman model simulation and with some present day water use (DWAF, 1998b) is only 8%.

This comparison is only partially valid, however, in that different scales apply in terms of both the modelling time step (daily *vs.* monthly) as well as the duration for which the streamflows were assessed (*ACRU*: 1945 to 1996; Pitman: 1925 to 1995). Moreover, the comparison is made between values of MED and MAR. However, it does confirm that the uncalibrated *ACRU* simulated streamflows for the ***entire catchment*** are similar to previous studies.

Statistical verification results for the Mkomazi with the present land use menu for the streamflows simulated at two DWAF gauging stations are given in Table 5.1. The verification results are shown graphically for U1H005 and U1H006 in Figures 5.1 (p 96) and 5.3 (p 102) respectively.

Table 5.1 Verification of the Mkomazi streamflows using the present land use *ACRU* input menu for the streamflows generated from 1945 to 1996 at two DWAF gauging stations

DWAF Gauge Number	**SC No**	**Upstream Area (km^2)**	***ACRU* Streamflows (10^6m^3)**	**Observed Streamflows (10^6m^3)**	**Difference %**
U1H005	18	1741.74	630.86	594.11	6.19
U1H006	48	4347.27	1035.08	747.29	38.51

5.2 Verification of Streamflows Generated under Relatively Undeveloped Catchment Conditions: U1H005 (Camden)

The difference between the median annual *ACRU* simulated streamflows (631 million m^3) and the observed streamflows (594 million m^3) at Camden (U1H005) when using the present land use *ACRU* menu is only 6% (*cf.* Table 5.1). This result is encouraging for the simulation of the upper Mkomazi Catchment streamflows. However, it is necessary to analyse the streamflows at a finer resolution to be confident of the model results. The automation of gauging records at U1H005 only commenced in 1960 and it was therefore considered appropriate to restrict the analysis of the verification of *ACRU* simulated streamflows to the period from 1960 to 1996.

Verification of *ACRU* simulated streamflows at Camden

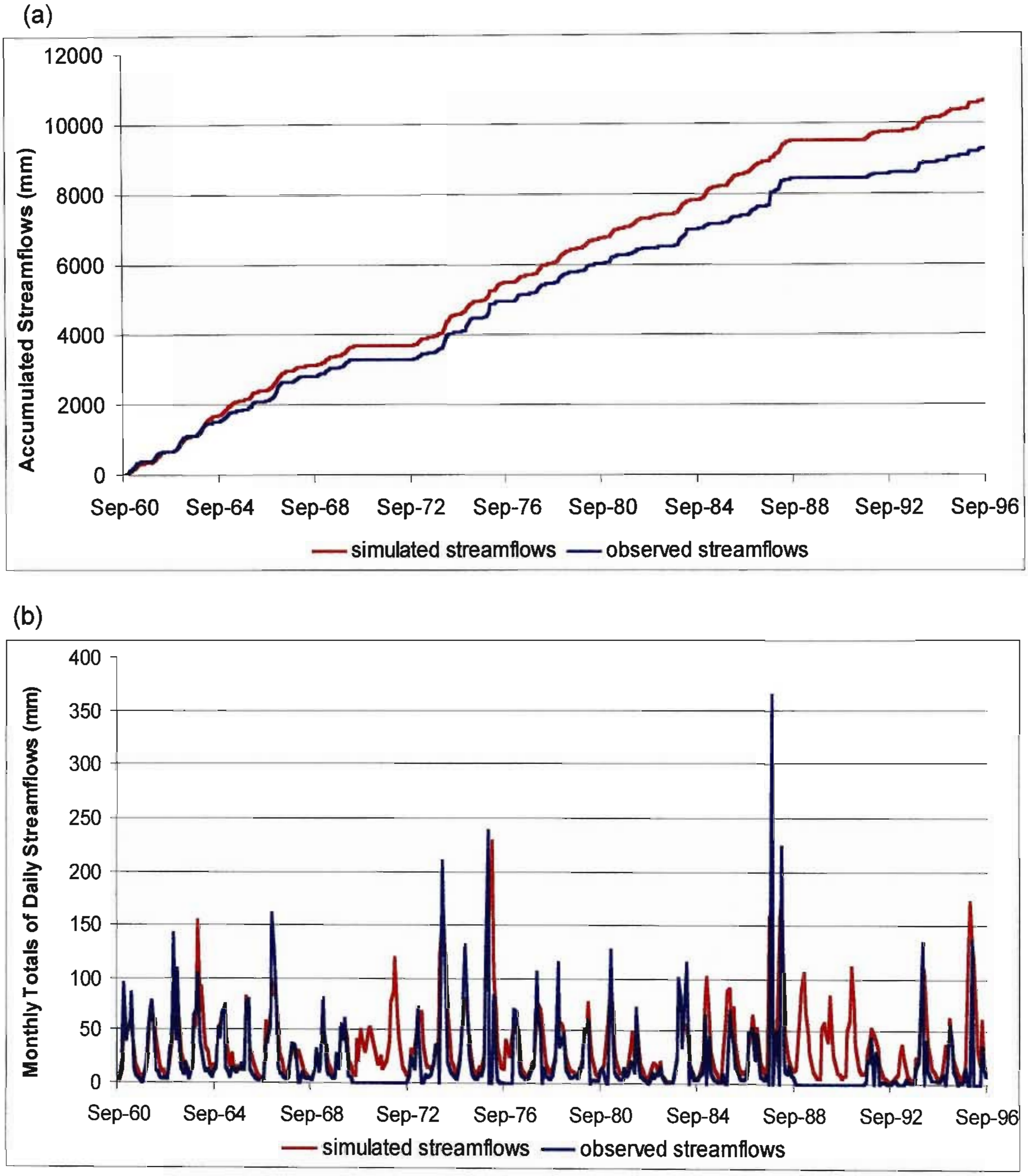

Figure 5.1 Comparisons of (a) accumulated streamflows and (b) monthly totals of daily streamflows at (UH1005 (Camden)

5.2.1 Accumulated streamflows

The accumulated monthly streamflows, over the 37-year period from 1960 to 1996 are shown in Figure 5.1 (a). Comparing the accumulated simulated values with the observed values indicates that for the given time period *ACRU* is over-simulating the Mkomazi streamflows with the present land use input values. Over the time period there is a 13.5% difference in ***accumulated streamflows***. As stated previously, these are the results from an uncalibrated simulation. It is, nevertheless necessary to identify the reason(s) for the discrepancy. However, the most likely explanation for the divergence could be attributable to changes in land use over the time period. Substantial tracts of land in SCs 3, 4, 7, 8, 16 and 18 (*cf.* Figure 4.7 for numbering) are degraded unimproved grassland according to the classification of the LANDSAT TM imagery (*cf.* Figure 4.10). Of the land use identified by the imagery, degraded unimproved grassland comprises 6.25% of the total area upstream from U1H005 (Camden) and it is postulated that runoff from these areas has increased over the time period. Additionally, there is a poor distribution of adequate raingauges in the upper Drakensberg (*cf.* Figure 4.12) and this factor may have led to unrepresentative daily rainfall being applied to the upper subcatchments in the *ACRU* menu input.

5.2.2 Monthly totals of daily streamflows

The differences in streamflows described in Section 5.2.1 can be investigated by comparing the individual monthly totals of daily simulated streamflows with the observed streamflows for the same time period, as shown in Figure 5.1 (b). In this study, zero values were input where there were periods of missing observed data. While it is necessary to bear this in mind, it does appear that with the present land use menu, *ACRU* is over-simulating low flows, most notably during the years 1964, 1973, 1982, 1986, 1988, 1992 and 1994. However, these were drought years in which the El Niño-Southern Oscillation signal was very strong and a possible explanation for the differences could be attributed to dam or river abstractions not accounted for in the initial menu preparation.

Figure 5.1 (b) indicates a marked divergence between the simulated and observed values for October 1987 when the observed monthly value substantially exceeds the *ACRU* simulated monthly value. In a daily model an extreme and continuous multi-day rainfall event such as that of late September 1987 is recorded as discrete daily events over the period of the event (in this case 26, 27, 28 and 29 September 1987). In reality such a continuous single event results in model undersimulating.

The time series of simulated streamflows is reproduced for shorter time spans in Figure 5.2 (a), (b), (c) and (d) for enhanced illustration of the features that require further consideration. Overall, the simulated streamflows follow the observed streamflows very well. Nonetheless, the present land use *ACRU* menu is under-simulating high flows as well as over-simulating low flows. This can be seen for 1961, 1967, 1978, 1979, 1984, and 1988. However, these were La Niña (*i.e.* wet) years and it is hypothesised that a daily soil water accounting system does not generate realistic antecedent soil moisture conditions for continuous rain events.

It does appear that over the 37 years there is an increasing divergence in the association between the simulated and the observed streamflow of the upper Mkomazi Catchment. This could be attributable to a change in land use over the time period or to problems with the recording equipment. The upper Mkomazi is relatively unimpacted by anthropogenic use and change, and it is postulated that the apparent oversimulation shown in Figure 5.2 (d) is as a result of gauging problems. However, Figure 5.2 (a), (b) and (c) show that overall seasonal magnitudes and trends are simulated well and the simulations for the period 1960 to 1969, *cf.* Figure 5.2 (a), are particularly good, reflecting a close correlation to the observed streamflows.

It is clear that there have been gauging problems at certain times in the history of the DWAF records. There are several lengthy periods of no recorded data in the record. Furthermore, when the gauging mechanism was overtopped by flood events, *e.g.* January / February 1976 and September 1987, and no data were recorded, subsequent recordings appear to be anomalous, indicating that gauging structures required immediate cleaning and stage-height: flow relationships re-calibration after high flood events.

Verification of *ACRU* simulated streamflows at Camden

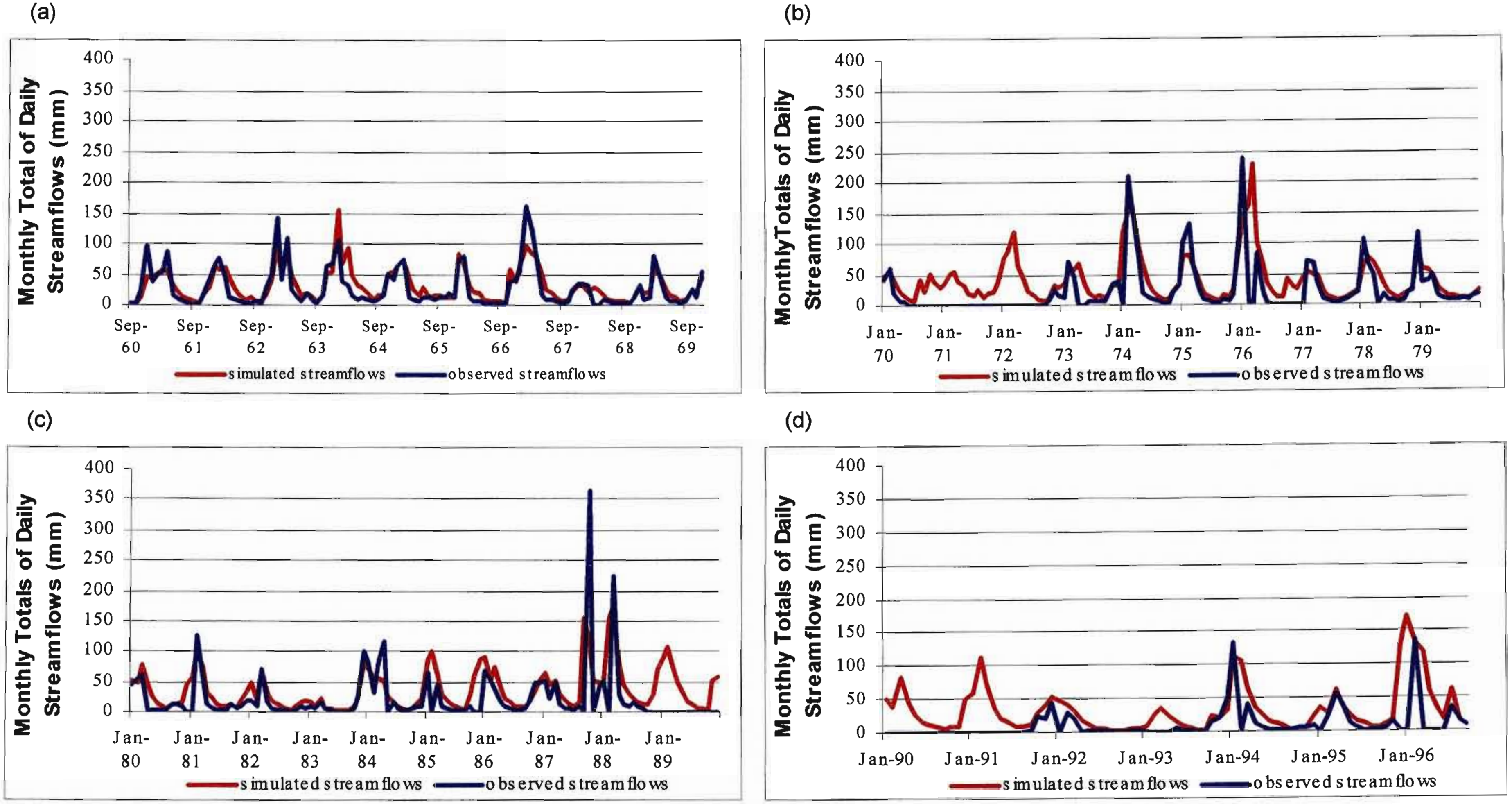

Figure 5. 2 Comparisons of monthly streamflows at U1H005 (Camden) for the periods (a) September 1960 - December 1969, (b) January 1970 - December 1979, (c) January1980 - December 1989 and (d) January 1990 - September 1996

5.2.3 Statistical analyses of monthly totals of daily streamflows

A statistical analysis was performed for individual month-by-month simulated *vs* observed values for median flows. Table 5.2 shows some of the statistical results for monthly totals of daily values.

Table 5.2 Verification statistics of streamflows at Camden (U1H005)

Statistical comparison	**Value**
Difference between means of observed and simulated flows	14.6%
Difference between coefficients of variation of observed and simulated flows	27.8%
Difference between the skewness coefficients of observed and simulated flows	20.6%
Correlation coefficient	0.89
Coefficient of agreement, observed *vs* simulated flows	0.94
Slope of scatter plot of observed *vs* estimated flows	0.74

The verification study of streamflows at Camden instilled confidence that the configuration of the *ACRU* menu for present land use menu for the upper 1742 km^2 of the Mkomazi system could be expected to give realistic results for scenarios which assess the impacts of potential catchment development.

5.3 Verification of Streamflows Generated under Anthropogenically Perturbed Conditions: U1H006 (Goodenough)

At Goodenough (U1H006), the difference between the median annual *ACRU* simulated streamflows (1035 million m^3) and the observed streamflows (747 million m^3) when using the present land use *ACRU* menu is 39% (*cf.* Table 5.1). However, the DWAF recording gauge at this site has a low discharge table limit and therefore produces unreliable high flow measurements (DWAF, 1998b). Furthermore, other sources (DWAF, 1998b) estimate the present MAR at U1H006 to be 956 million m^3 (BKS) and 973 million m^3 (Water Resources 90 (WR90), (Midgely *et al.*, 1994; cited in DWAF, 1998b) for the period 1920 to 1995. Again, this confirms that the *ACRU* simulated streamflows at Goodenough are within the predicted magnitude, deviating by only 8% and 6% respectively from the calibrated simulations. Notwithstanding the anomalies of the recording gauge at U1H006, it was considered appropriate to analyse the streamflows in a procedure similar to that performed for the streamflows at U1H005. The automation of gauging records at U1H006 commenced in 1962 and it was therefore considered pertinent to restrict the analysis of the verification of *ACRU* simulated streamflows to the period from 1962 to 1996.

5.3.1 Accumulated streamflows

The accumulated monthly streamflows, over the 35-year period from 1962 to 1996 are shown in Figure 5.3 (a). As expected, the accumulated *ACRU* values for the downstream Mkomazi streamflows resulting from the present land use menu are greatly oversimulated when compared with the observed values. Over the time period there is a 47 % difference in ***accumulated streamflows***. The land use in the downstream Mkomazi Catchment has experienced more anthropogenic changes than the upper catchment. However, in light of the knowledge that the gauging station is unreliable, this component of the verification study is somewhat superficial, but is included for the sake of completeness.

5.3.2 Monthly totals of daily streamflows

Figure 5.3 (b) shows the differences in the individual monthly totals of daily, simulated streamflows with the observed streamflows for the same time period. The principal of applying zero values where there were periods of missing observed data, described above, was repeated. In spite of the gauging problems at U1H006, *ACRU* simulated streamflows do follow the same trends of magnitude and seasonality as the observed streamflows. However, it is apparent that even when ignoring the affects of the low discharge table, the present land use *ACRU* menu results in some over-simulation of low flows.

Comparing Figure 5.1 (b) with Figure 5.3 (b) shows that there are similarities in the hydrological regimes of the two sites. This concurs with the study performed by Smakhtin and Hughes for the DWAF Mkomazi IFR Study in 1998 (DWAF, 1998b) in which it was also noted that gauge U1H006 shows a slight increase in low flows, particularly in dry months of the year, relative to U1H005. Smakhtin and Hughes suggest that this might be as a result of a slightly more baseflow-driven regime in the lower reaches of the Mkomazi river (DWAF, 1998b). The relative increase in low flows can be seen in Figure 5.3 (b), but

Verification of streamflows at Goodenough with the *ACRU* model

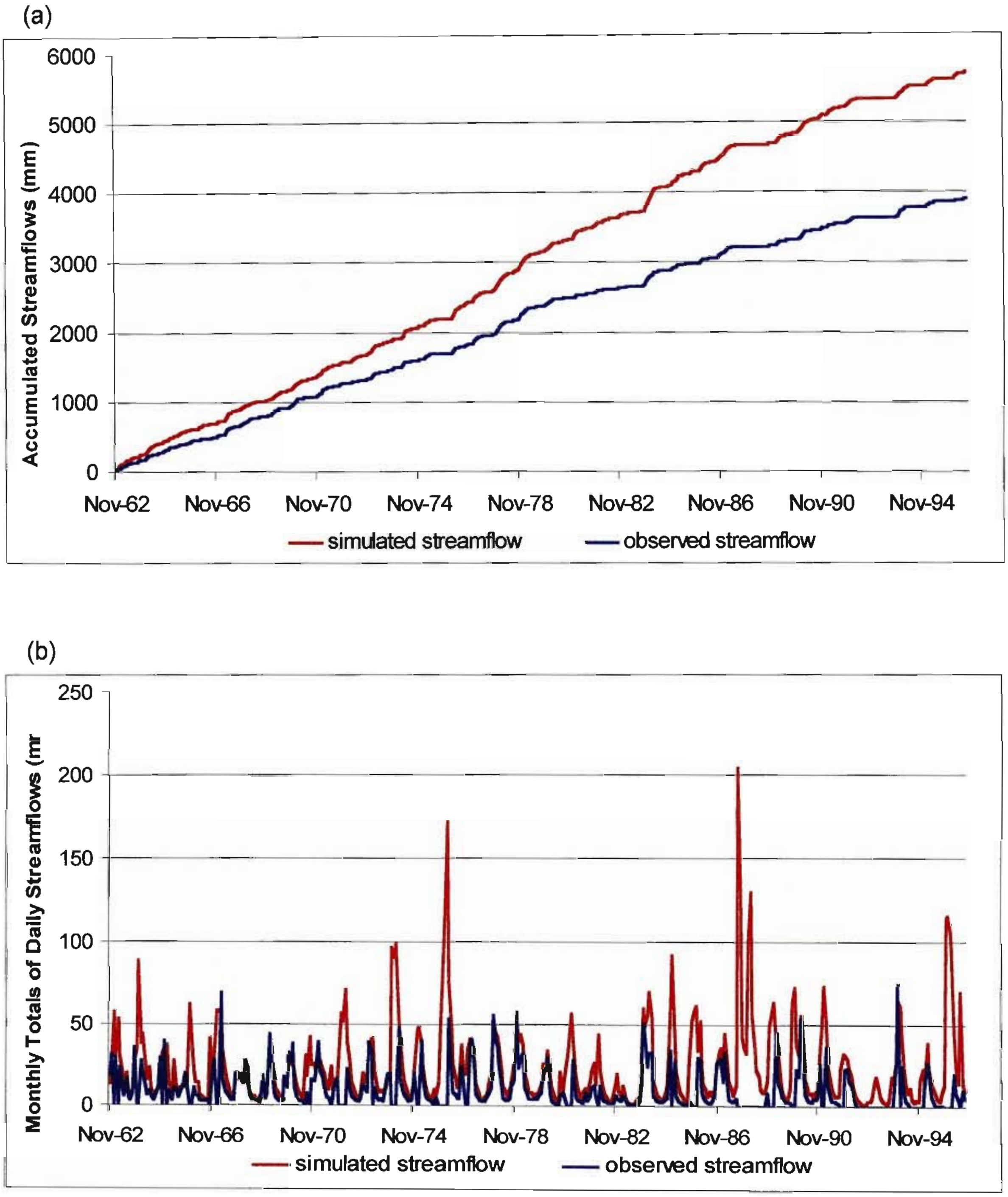

Figure 5.3 Comparisons of (a) accumulated streamflows and (b) monthly totals of daily streamflows at U1H006 (Goodenough)

is further investigated in Figure 5.4, which shows the time series of simulated streamflows reproduced in shorter time spans.

The most notable instances of over-simulation of low flows in the lower Mkomazi catchment are during the years 1964, 1965, 1972, 1973, 1974, 1976, 1981, 1982 1985, 1986, 1991 and 1994. The occurrence of this feature increases with time, so it may well be that the present land use of the lower Mkomazi has changed more substantially than in the upper part of the catchment. This suggests that the influence of dam and / or river abstractions in the most downstream reaches of the Mkomazi may be much larger than captured by the present land use *ACRU* menu.

In contrast to the verification study of streamflows at Camden, the *ACRU* menu for present land use appears to be over-simulating high flows, *e.g.* in 1979, 1984, 1987 and 1992. This feature was investigated by examination of the *ACRU* daily output file of streamflows at Goodenough. It transpires that during and subsequent to extreme rainfall events, the gauging weir experiences over-topping, with observed daily streamflows, when recorded, consistently being measured as between 4.00 and 4.50mm.

There is however, very good correlation of streamflows for the periods 1968 to 1970, (*cf.* Figure 5.4 (a) and (b)), 1977 to 1980, (*cf.* Figure 5.4 (b) and (c)) and 1989 to 1990 (*cf.* Figure 5.4 (c) and (d), years in which the problem of overtopping does not arise.

5.3.3 Statistical analyses of monthly totals of daily streamflows

A statistical analysis was performed for individual month-by-month simulated *vs* observed values for median flows. Table 5.3 shows some of the statistical results for monthly totals of daily values.

Clearly the gauging problems at U1H006 have resulted in unreliable recorded data of high flows in the lower reaches of the Mkomazi. However, it is considered that the present land use *ACRU* menu is quite acceptable for the application of scenarios studies to assess the impacts of potential Mkomazi Catchment development.

Verification of *ACRU* simulated streamflows at Goodenough

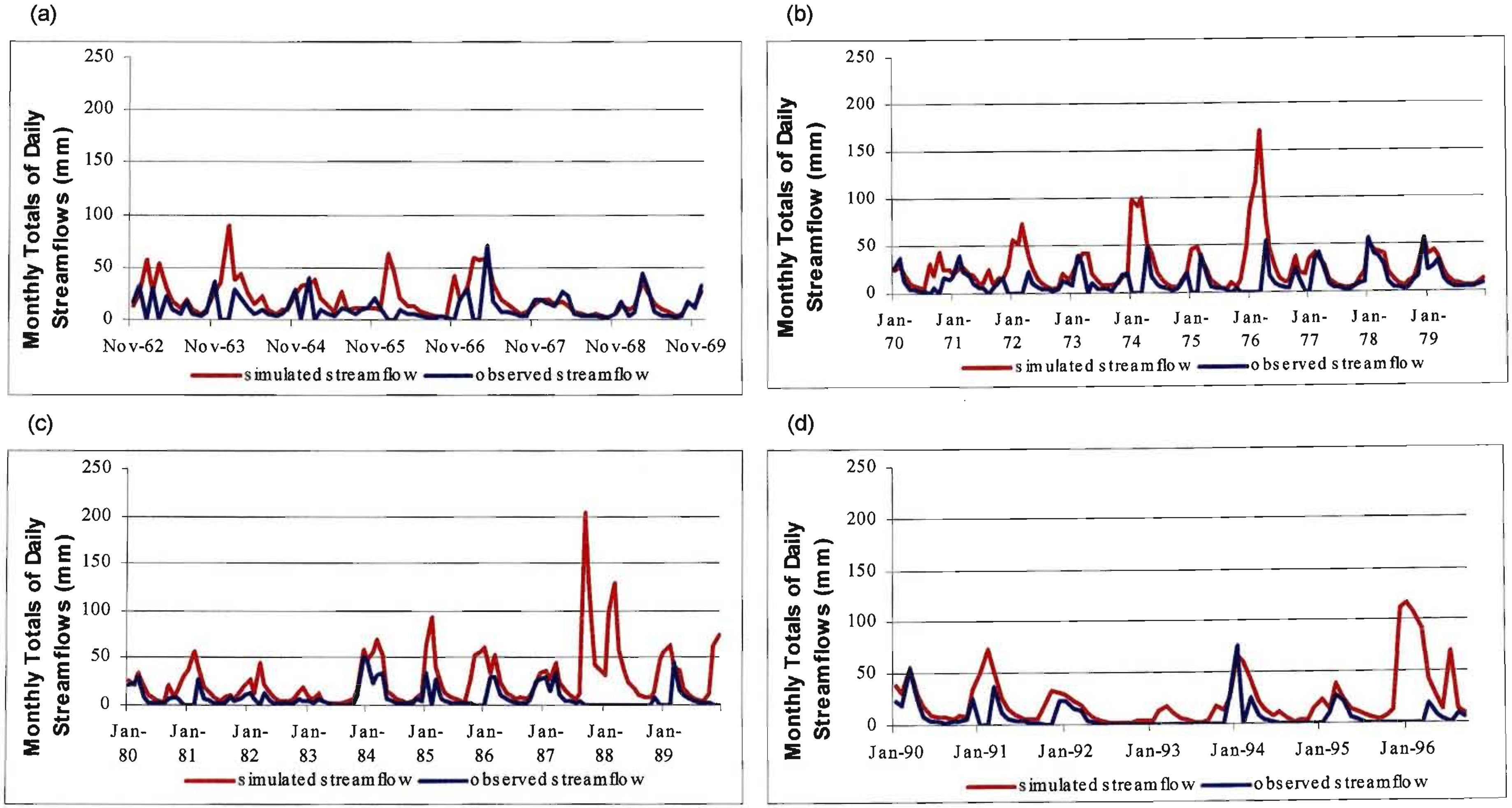

Figure 5.4 Comparisons of monthly streamflows at U1H006 (Goodenough) for the periods (a) November 1962 - December 1969, (b) January 1970 - December 1979, (c) January1980 - December 1989 and (d) January 1990 - September 1996

Table 5.3 Verification statistics of streamflows at Goodenough (U1H006)

Statistical comparison	**Value**
Difference between means of observed and simulated flows	45.7%
Difference between coefficients of variation of observed and simulated flows	23.6%
Difference between the skewness coefficients of observed and simulated flows	22.62%
Correlation coefficient	0.88
Coefficient of agreement, observed *vs* simulated flows	0.93
Slope of scatter plot of observed *vs* estimated flows	0.98

5.4 Conclusions: Statement of Level of Confidence

ACRU simulates streamflow volumes similar to those of the DWAF studies (DWAF, 1998a) and the verification studies of the *ACRU* menu for present land use give encouraging results. The Mkomazi Catchment is, relatively, unimpacted anthropogenically and this is reflected in the results for the upper catchment. The menu for present land use could have benefited from more comprehensive information with regard to the farm dam and river abstractions as well as present irrigation scheduling. Insufficient information for these land use practices is perhaps the greatest limitation of applying the LANDSAT TM imagery, which indicates only the *presence* of dams and irrigated crops. However, irrigation is not a major land use even in the lower Mkomazi Catchment. In view of these considerations, a level of high confidence is expressed in the results of the generation of realistic streamflows at the points of interest specified by the potential end-user, Umgeni Water.

* * * * *

The following Chapters 6, 7, 8, 9, 10, 11 and 12 describe the application of the *ACRU* model configuration to the assessment of the water resources management required for the Mkomazi Catchment.

6 IMPACTS OF PROPOSED DEVELOPMENT ON THE WATER RESOURCES OF THE MKOMAZI CATCHMENT

6.1 Introduction

The Mkomazi Catchment offers the regional water board, Umgeni Water, the opportunity to augment the water resources of the neighbouring Mgeni Catchment and to apply long-term regional management and planning strategies for water resources development. Chapter 4 described the procedures adopted to model the hydrological dynamics of the Mkomazi Catchment using the *ACRU* agrohydrological model. Confidence in the efficacy of the catchment configuration for the assessment of land use impacts, climate and catchment development on streamflows was established in Chapter 5. This chapter describes some of the impacts of land use, climate and proposed development on the generation of streamflows in the Mkomazi Catchment.

In this chapter and in Chapters 7 and 8 the term "accumulated" streamflows is used to describe the streamflows simulated upstream of a subcatchment outlet (*i.e.* total streamflows from a subcatchment, including upstream contributions). The term "individual" subcatchment streamflows is used to describe simulated streamflows from a given subcatchment only (*i.e.* excluding upstream contributions). The Mkomazi town and district / region names and sites of specific interest referred to in this and the succeeding chapters are shown in Figure 4.1, whereas the subcatchment (SC) numbering is shown in Figure 4.7.

6.2 Impacts of Present Land Use Conditions on Streamflows

The principles applied to the assessment of the impacts of present land use, using Acocks' Veld Types as a comparison baseline land cover, were discussed in Section 4.11.1. The procedure for the assessment required two *ACRU* runs, the first with Acocks' Veld Types as the baseline land cover and the second with the present land use and cover according to the CSIR land use classification of the LANDSAT TM coverage described in Section 4.8.1.

6.2.1 Impacts of change on streamflows from baseline land cover

In order to ascertain the *relative* impacts of present land use on the streamflows of the Mkomazi in a year of median flows (MED), the accumulated volumes of MED simulated under present land use for each of the 52 SCs was expressed as a percentage of the corresponding accumulated volume of MED simulated under the baseline land cover. The percentages of change in accumulated MED are shown in Figure 6.1.

It may be seen from Figure 6.1 that the most impacted areas are those which have experienced greatest anthropogenic changes. The afforested areas around Goodhope (SC 25), Boston (SC 26), Bulwer (SC 22), Donnybrook (SC 29 and 30), Ixopo (SC 33, 40, 43 and 44) are among the most severely impacted SCs, with percentage reductions of streamflows exceeding 30% and reaching up to 80% (Ixopo, SC 40). A number of these SCs also feature irrigation as a land use and it transpires that the most severely impacted SCs are those in which irrigation is the major land use. The agricultural region around Ixopo is clearly the most impacted region in the Mkomazi Catchment with SCs 41 and 42 experiencing streamflow reductions from baseline conditions of 96% and 97% respectively. Subcatchments where the areal extent of afforestation exceeds the areal extent of irrigation (*e.g.* SCs 22, 25, 26, 29, 30, 33 and 40, 43 and 44) have a less deleterious impact on streamflows than those where irrigated land use exceeds afforestation (SCs 41 and 42). This concurs with Taylor's (1997) findings in the Pongola Catchment.

The generation of streamflows from present land use in the upper Mkomazi Catchment shows very little change from that of baseline conditions. This is not surprising, since the major present land cover of this area was identified from the 1996 LANDSAT TM image as unimproved grassland (Figure 4.10). Also, this area is sparsely populated and consequently there are few anthropogenic effects on streamflow generation. There are, however, some exceptions that require explanation.

First the agricultural areas around Bulwer (SC 12, 13 and 17), where irrigation and afforestation are practiced, indicate moderate streamflows reductions (16%, 7% and 9% respectively) from baseline conditions. Secondly, as mentioned above, where there is substantial afforestation such as around Bulwer (SCs 20, 21 and 22, *cf.* Figure 4.10), the

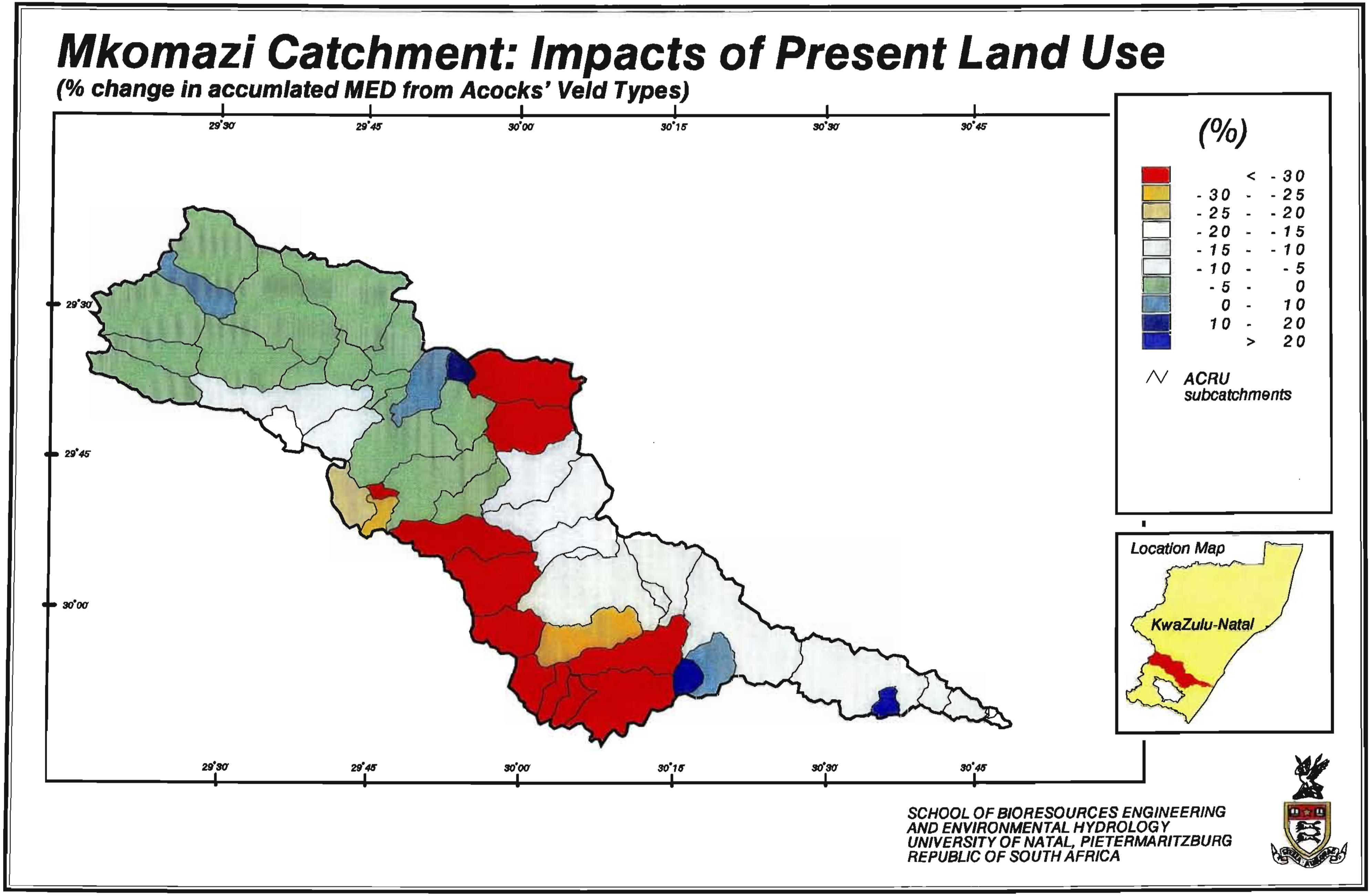

Figure 6.1 Mkomazi Catchment: Impacts of present land use

streamflows are reduced to a greater extent (20%, 27% and 36% respectively). Thirdly, there is greater population density around Impendle (SCs 15 and 16) and the major land use is semi-commercial / subsistence dryland agriculture (SC 15), with indication of degraded unimproved grassland (SC 16). In this instance, the streamflows generated are higher than those under baseline conditions by 11% (SC 15) and 0.75% (SC 16) respectively.

Other areas indicate an increase in streamflow generation under present land use. Subcatchments 38 and 39 were specifically delineated to represent the impacts of subsistence agriculture (SC 38) and degraded land (SC 39). The streamflows generated from SC 38 are substantially higher (25%) than under baseline conditions, whereas the increase in streamflows from SC 39 is 5%. The increase (22%) in SC 46 is the result of the replacement by thicket and bushland (Figure 4.10) of an area which under baseline conditions was coastal forest and thornveld.

The main Mkomazi River is relatively unimpacted. However, the impacts of reduced flows from the Donnybrook / Ixopo area as a result of commercial land uses can be observed as a reduction in the Mkomazi River flows downstream from IFR Site 2 (*cf.* Figure 4.2).

6.2.2 Accumulated streamflows in the Mkomazi

The *absolute* volumes of accumulated streamflows simulated under present land use for a year of median flows are indicated in Figure 6.2. The generation of streamflows in the head-waters of the Drakensberg Mountains is substantial. Figure 6.2 shows that the quantity of water available in the upper Mkomazi increases significantly at the confluence of the main tributaries of the Nzinga and the Mkomazi at the site of the proposed Impendle Dam (SC 14).

Further down the Mkomazi Catchment the influence of tributaries becomes less pronounced with little contribution from the Ixopo area. The areas where there is greatest anthropogenic influence result in the lowest water producing areas. However, the dominance of the Mkomazi River valley can be clearly seen in Figure 6.2 as the streamflows accumulate downstream.

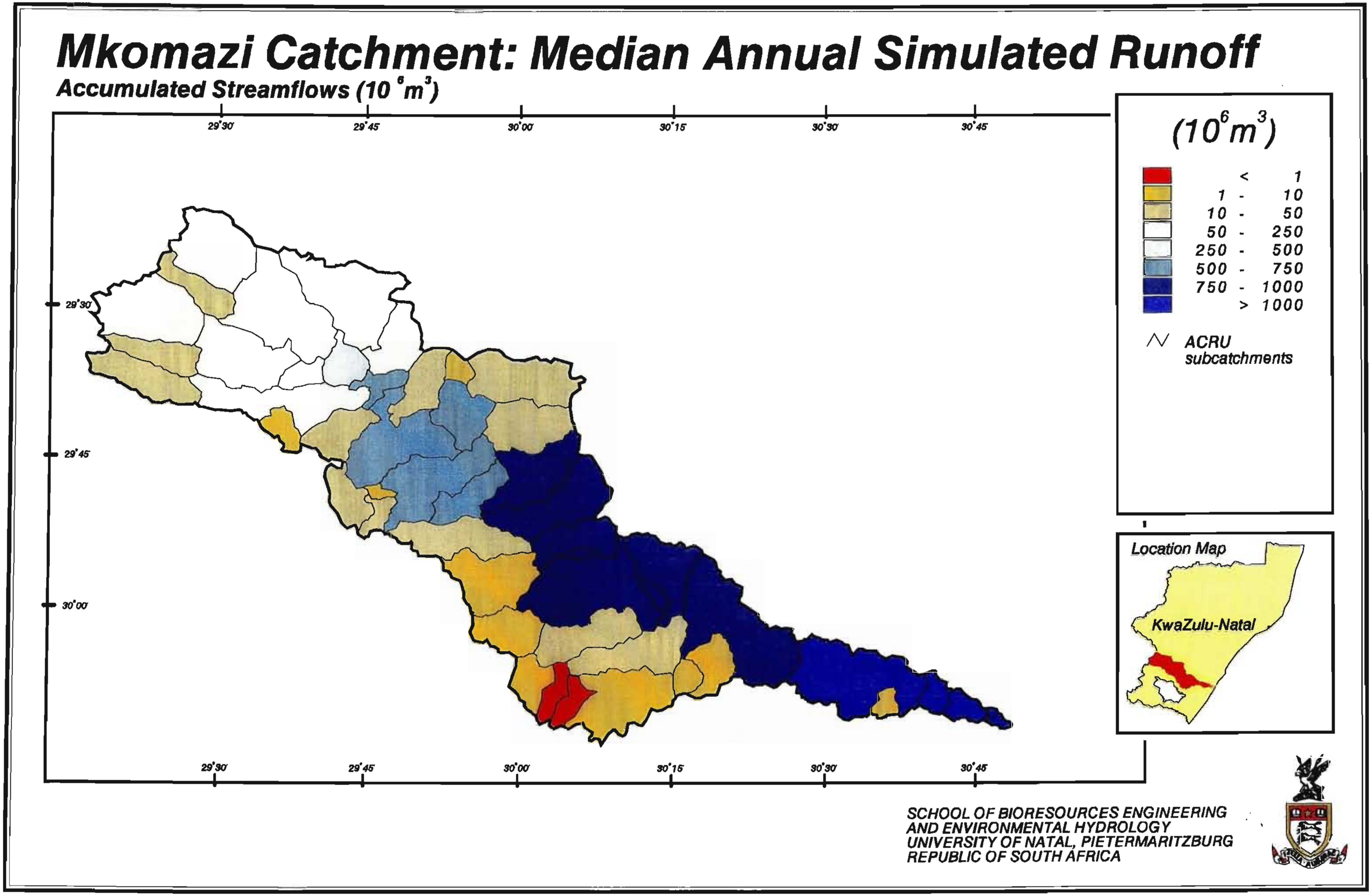

Figure 6.2 Mkomazi Catchment: Accumulated subcatchment median annual simulated runoff

6.2.3 Individual subcatchment contribution

The *absolute individual* subcatchment contributions for a year of median flows are shown in Figure 6.3. The visual impact of a pattern of generated streamflows is less striking in this instance than in the case of *absolute accumulated* streamflows. However, examination of the catchment configuration supports the findings in Section 6.2.2. The most significant volumes of streamflows are generated in the upper catchment, whilst the streamflows around the Ixopo area are so heavily impacted that they have all but ceased.

6.3 Impacts of the Proposed Smithfield Dam on Streamflows

As described above, there is substantial available water in the upper Mkomazi Catchment for allocation to other land uses or to inter-basin transfers. This section focuses on the impacts of Phase 1 of the proposed MMTS in which water from the proposed Smithfield Dam would be transferred out of the Mkomazi and into the Mgeni system, as discussed in Chapter 4.11.2.

In order to ascertain the *relative* impacts of Phase 1 of the proposed MMTS in a year of median flows, the accumulated volumes of MED simulated under the transfer conditions for each of the 52 SCs was expressed as a percentage of the corresponding accumulated volume of MED simulated under present land use conditions. The percentages of change in accumulated MED are shown in Figure 6.4. Therefore, Figure 6.4 illustrates the impacts of transferring 7 $m^3.s^{-1}$ out of the Mkomazi Catchment from the proposed Smithfield Dam in a year of median flows, assuming that with exception of this development, all other land use and cover remains the same as under present land use conditions.

Clearly the greatest impact on accumulated streamflows is at the site of the proposed transfer, where there is expected to be a 32.40% reduction in MED streamflows compared with those from present land use. The impact of the proposed transfer diminishes downstream. However, the Mkomazi River does not recover and median annual streamflows at the estuary are still reduced by 22%. Whilst the main water consumers under present land conditions, *i.e.* irrigated agriculture and afforestation, are not directly affected by the proposed Smithfield Dam, there are streamflow reductions in accumulated flows where tributaries from the Donnybrook area, *viz.* SCs 29 and 30, join the mainstream

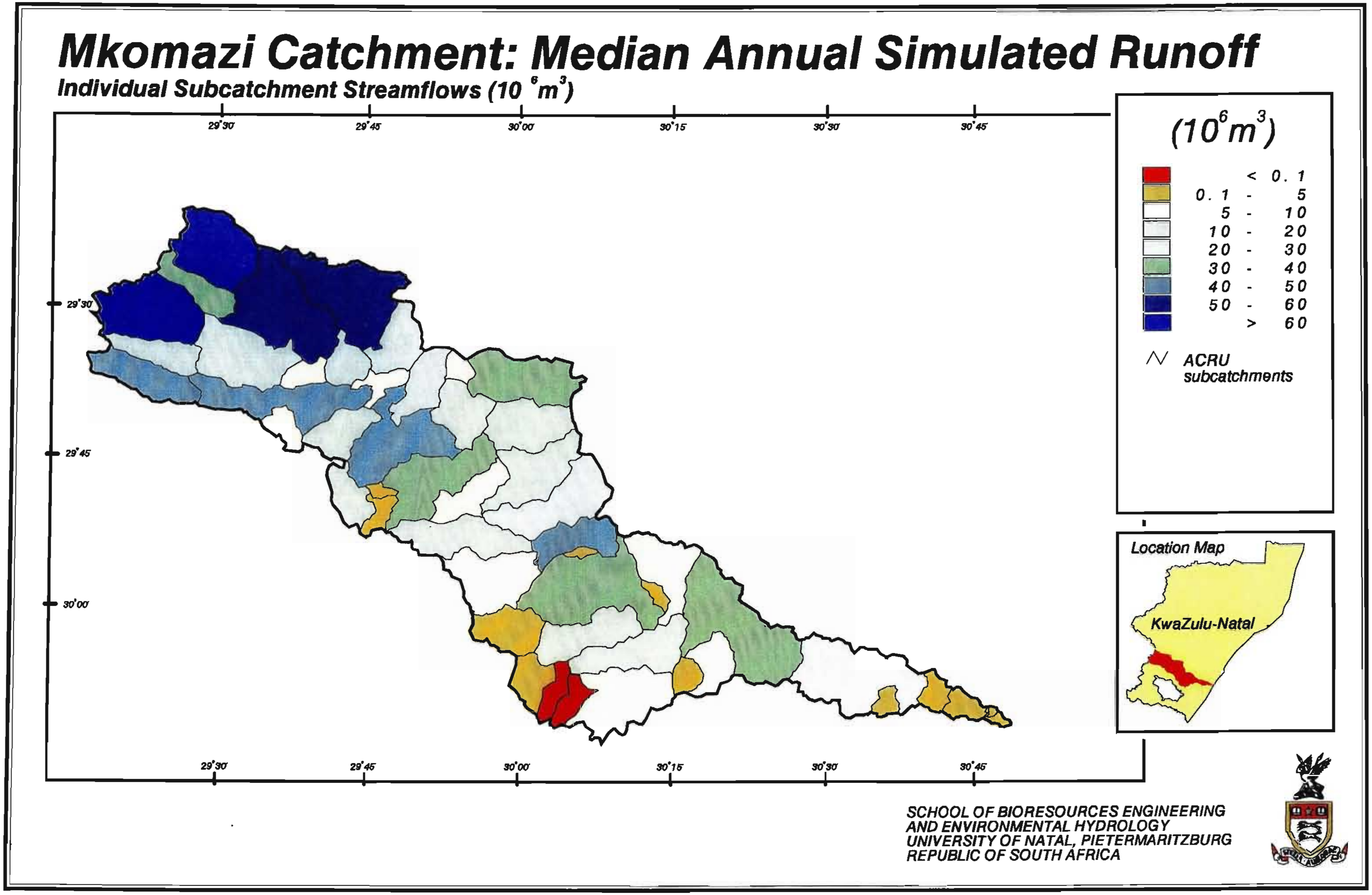

Figure 6.3 Mkomazi Catchment: Individual subcatchment median annual simulated runoff

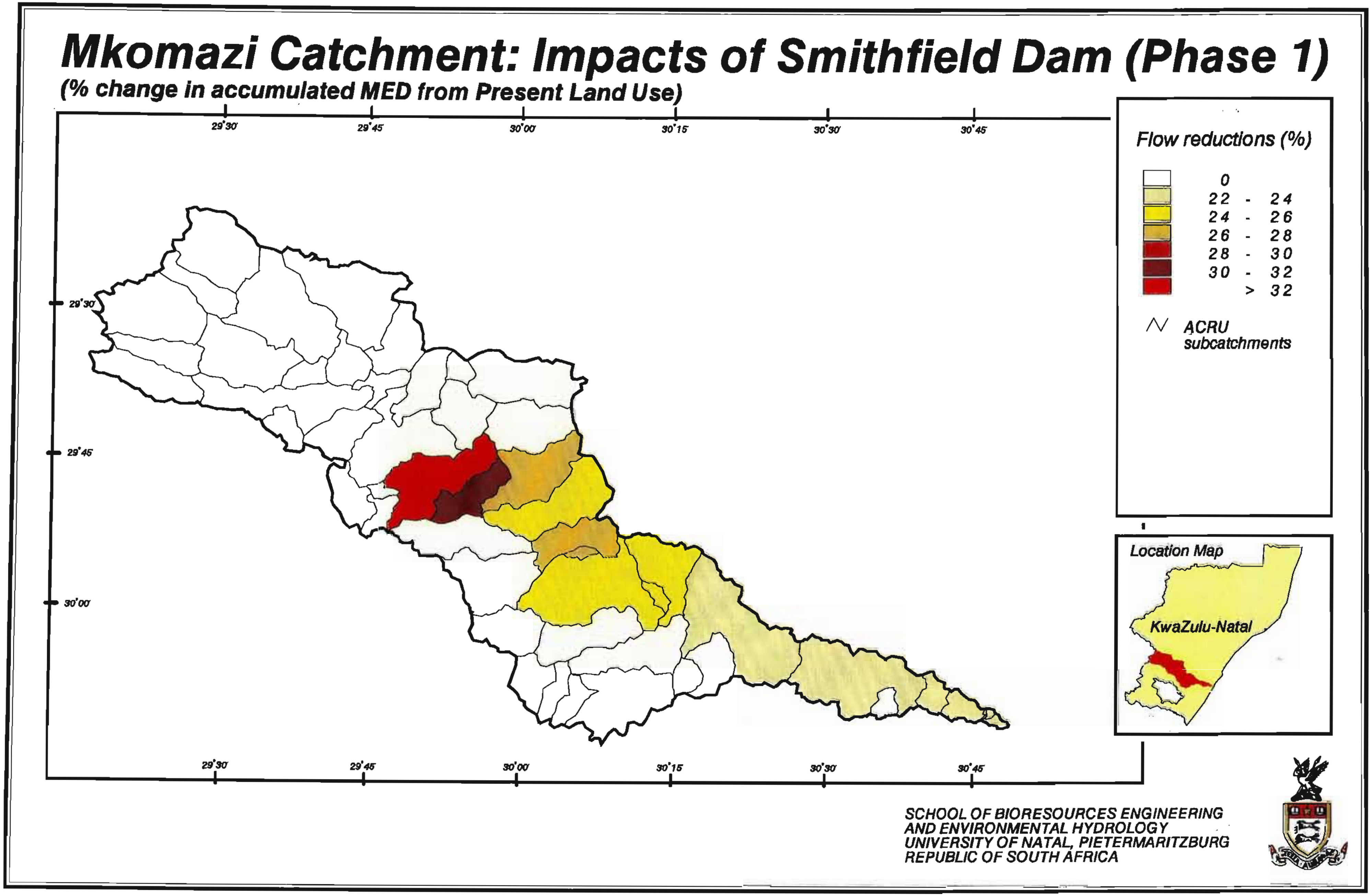

Figure 6.4 Mkomazi Catchment: Impacts of Smithfield Dam (Phase 1)

Mkomazi. The impacts of afforestation and irrigated land use on streamflows from the Ixopo area do not appear to exacerbate the reduction in mainstream Mkomazi river flows. Nonetheless, their operation, in conjunction with the releases from Smithfield Dam, may need regulation in order to satisfy the requirements of the environmental Reserve.

6.4 Impacts of Potential Climate Change on Streamflows Assuming Present Land Use Practices

The principles adopted to assess the impacts of potential climate change on the generation of streamflows in the Mkomazi Catchment were described in Chapter 4.11.3. The procedure for the assessment of the impacts of change, assuming present land use practices, required two *ACRU* runs, *viz.*

(a) the first with present land use, adapted to compute the soil water evaporation separately from plant transpiration to represent a climate change baseline condition and

(b) the second with the potential climate change to precipitation, temperature and evaporation, as described in Chapter 4.11.3 for a 2 x CO_2 scenario.

In order to ascertain the *relative* impacts of potential climate change on the streamflows of the Mkomazi in a year of median streamflows, the accumulated volumes of MED simulated under potential climate change for each of the 52 SCs were expressed as a percentage of the corresponding accumulated volume of MED simulated under the climate change baseline condition.

Figure 6.5 indicates that virtually the entire the Mkomazi is likely to be heavily impacted in a year of median flows by potential climate change and that the SCs most likely to be affected are those in which there is presently excess water which can be utilised by plants in transpiration. Streamflow reductions in the upper Drakensberg are shown as being as significant as reductions in the lower Mkomazi. Areas supporting commercial afforestation as well as irrigation are amongst those most severely affected by potential climate change (SCs 25 and 40).

However, Figure 6.5 highlights an apparent anomaly, in that where there is a greater areal extent of irrigated land compared with afforestation, the percentage reduction from present

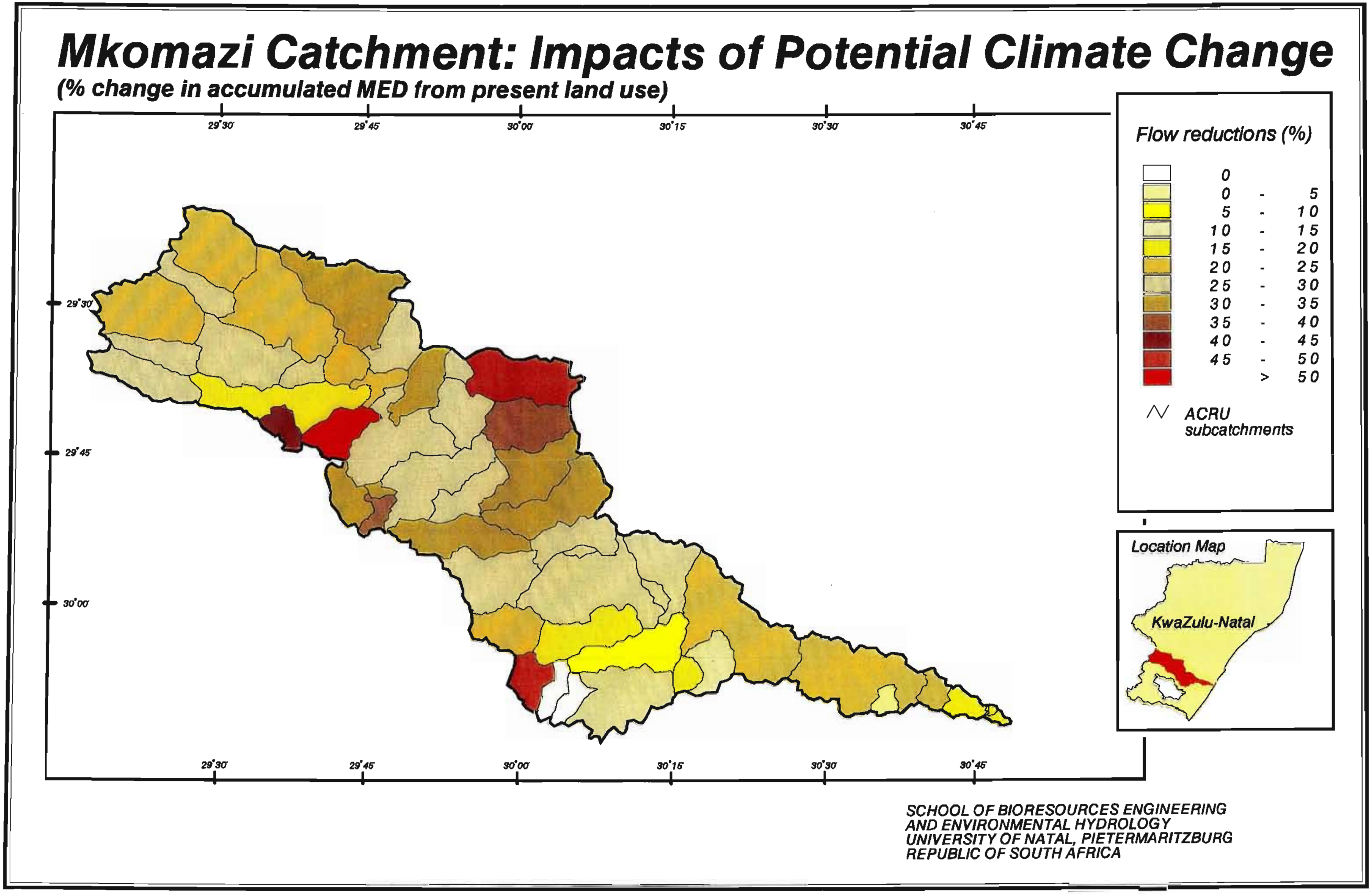

Figure 6.5 Mkomazi Catchment: Impacts of potential climate change under present land use conditions

land use is negligible (SCs 41 and 42). This can be attributed to there being no available water in those SCs for *further* use and concurs with the findings in Sections 6.2.2 and 6.2.3.

SC 17 in the upper catchment is also anomalous in that this SC experiences the greatest *relative* streamflow reductions under potential climate change. With the exception of some afforestation (*cf.* Figure 4.10), this SC has not experienced any major anthropogenic change, it is hypothesised that the streamflow reductions are attributable to increased soil water evaporation under conditions of low basal cover of the grassland. Moreover, the streamflows generated within this SC under both the baseline condition and the climate change scenario are both relatively small (5.85 x 10^6m^3 for the former and 4.69 x 10^6m^3 for the latter). Hence comparison of the two values in this way would incur a high relative percentage and the finding may not be as anomalous as initially perceived.

The percentage change in accumulated MED at the estuary as a result of potential climate change (19.84%) is almost as high that experienced by the Smithfield Phase 1 inter-basin transfer (22.08%).

6.5 Impacts of proposed Smithfield Dam with climate change

The *relative* impacts of Phase 1 of the Smithfield Dam transfer under potential climate change on the streamflows of the Mkomazi, were assessed by comparing the accumulated volumes of MED simulated for each of the 52 SCs with the dam in place, with the corresponding accumulated volume of MED simulated without the dam in place.

Figure 6.6 indicates the impacts of transferring 7 m^3.s^{-1} out of the Mkomazi Catchment from the proposed Smithfield Dam under the scenario of climate change, assuming that with the exception of this development, all other land use and land cover remains the same as under present land use conditions.

As expected, the greatest impact on accumulated streamflows is at the site of the proposed transfer. However, under conditions of potential climate change there is expected to be a 79% reduction in accumulated MED at the site of Smithfield Dam, compared to the 32% reduction without climate change.

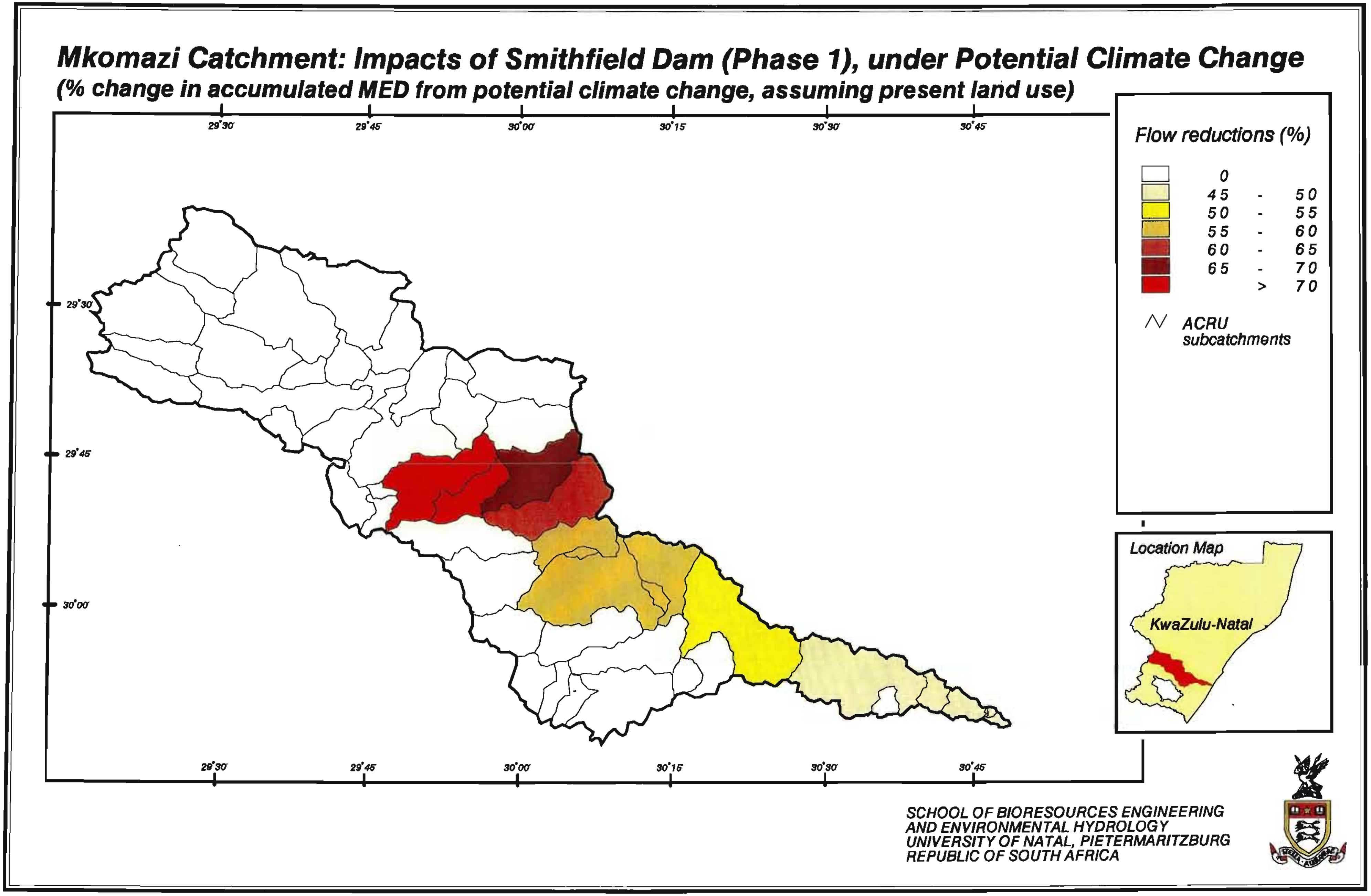

Figure 6.6 Mkomazi Catchment: Impacts of Smithfield Dam (Phase 1) under potential climate change

The impact of the proposed transfer diminishes downstream, with the Mkomazi's streamflows at its estuary being reduced by 46% (compared with 22% without climate change). The impacts of commercial forestry and irrigated land do not appear to compound streamflow reductions under potential climate change, presumably because, as stated in Section 6.3, the tributaries from those catchments do not experience *further* streamflow reductions.

6.6 Conclusions: Implications of Catchment Development for Water Resource Management

Several conclusions can be drawn from the above studies regarding implications for water resource management. The assessment of streamflows in a year of median flows under present land use conditions revealed that there are areas in the Mkomazi where present streamflow generation is greater than under natural conditions. This was highlighted in SCs where there is evidence of urban / built up land, subsistence agriculture and degraded grassland. Furthermore, it appears that the impacts of subsistence agriculture are greater than those of degraded land. This is of significance in the Mkomazi Catchment since these activities and their impacts on streamflows are expected to increase. The perpetuation of these activities is likely to lead to increased soil erosion, ultimately posing problems of sedimentation of rivers, farm dams and proposed major impoundements as well as to environmental change in aquatic ecosystems.

While the impacts of irrigation are greater than those of afforestation on a unit area, the impacts of both these commercial practices on the generation of Mkomazi streamflows are relatively high when compared to natural conditions. Impacts of irrigation on streamflows around the Ixopo area are such that there is no discernible streamflow downstream of irrigation abstractions, even in a year of median flows. However, this does not indicate that there is no water within the SCs, only that the streamflows have been dammed. Notwithstanding this factor, such reductions would be further exacerbated during low flow years as well as under conditions resulting from climatic change, with severe implications for ecosystem functioning.

Phase 1 of the Smithfield Dam inter-basin transfer reduces the Mkomazi Catchment accumulated MED by just over 22% at the estuary. However, investigation of the simulated daily streamflows is necessary to ascertain whether the instream flow requirements defined as the environmental reserve by the NWA can be satisfied. This necessitates that the baseline land cover simulated streamflows be used to generate a daily time series of flows which occurs within the natural flow range (*cf.* Chapters 9, 10 and 11). Such a time series is critical for the effective operation of dam release rules designed to meet the needs of all catchment stakeholders.

Potential climate change could have further implications for the impoundment of the Mkomazi River, since it was shown in Section 6.4 that even in the absence of the dam the Mkomazi catchment yield under potential climate change would be reduced by 20% at the estuary.

* * * * *

The issues regarding Mkomazi streamflows to meet the environmental reserve of the river will be discussed in Chapters 9 10 and 11. First, Chapter 7 investigates the impacts of catchment development on the water resources of the Mkomazi under more extreme climatic conditions than those which produce a year of average flows, as well the impacts on seasonal low flows.

7 RISK ANALYSES OF THE IMPACTS OF DEVELOPMENT ON MKOMAZI CATCHMENT WATER RESOURCES

7.1 Introduction

The assessment of the impacts of proposed development on Mkomazi water resources described in Chapter 6 was carried out on the simulated median annual streamflows from each of the 52 subcatchments. However, water resource managers frequently need to make decisions regarding the impacts of land use change under different climatic conditions, particularly in instances where flows are already impacted by present land use. This chapter therefore addresses the more extreme streamflow scenarios and sequences that are likely to be of interest to water resource managers. First, an assessment is made to ascertain which subcatchments are more susceptible than others in dry (low flow) years and in wet (high flow) years under present land use. This is followed by assessment of the impacts on the seasonal low flows under (a) present land use and (b) conditions as a result of the proposed Smithfield Dam Phase1.

In this chapter hydrological years in which the total flows for the year, at a specified level of risk, are considerably lower than the mean or median flows are referred to as "low flow years". Hydrological years in which total flows are considerably higher than the mean or median flow, again at a specified level of risk, are referred to as "high flow years". The *period* of low flow within a year representing the six consecutive months of lowest combined flow is defined as "the low flow season" whereas the *flows* themselves are referred to as "the seasonal low flows".

7.2 Flow Reductions under Present Land Use in Low Flow Years

The impacts of low flow years on the generation of Mkomazi streamflows under present land use were assessed by the evaluation of the 20th percentile of exceedence. This represents the statistically lowest annual flow in five years, *i.e.* a flow the annual streamflow depth of which is exceeded in four years out of five. The percentage change in accumulated streamflows from those in a year with median flows, under conditions of present land use in the year of lowest flows in five, are shown in Figure 7.1.

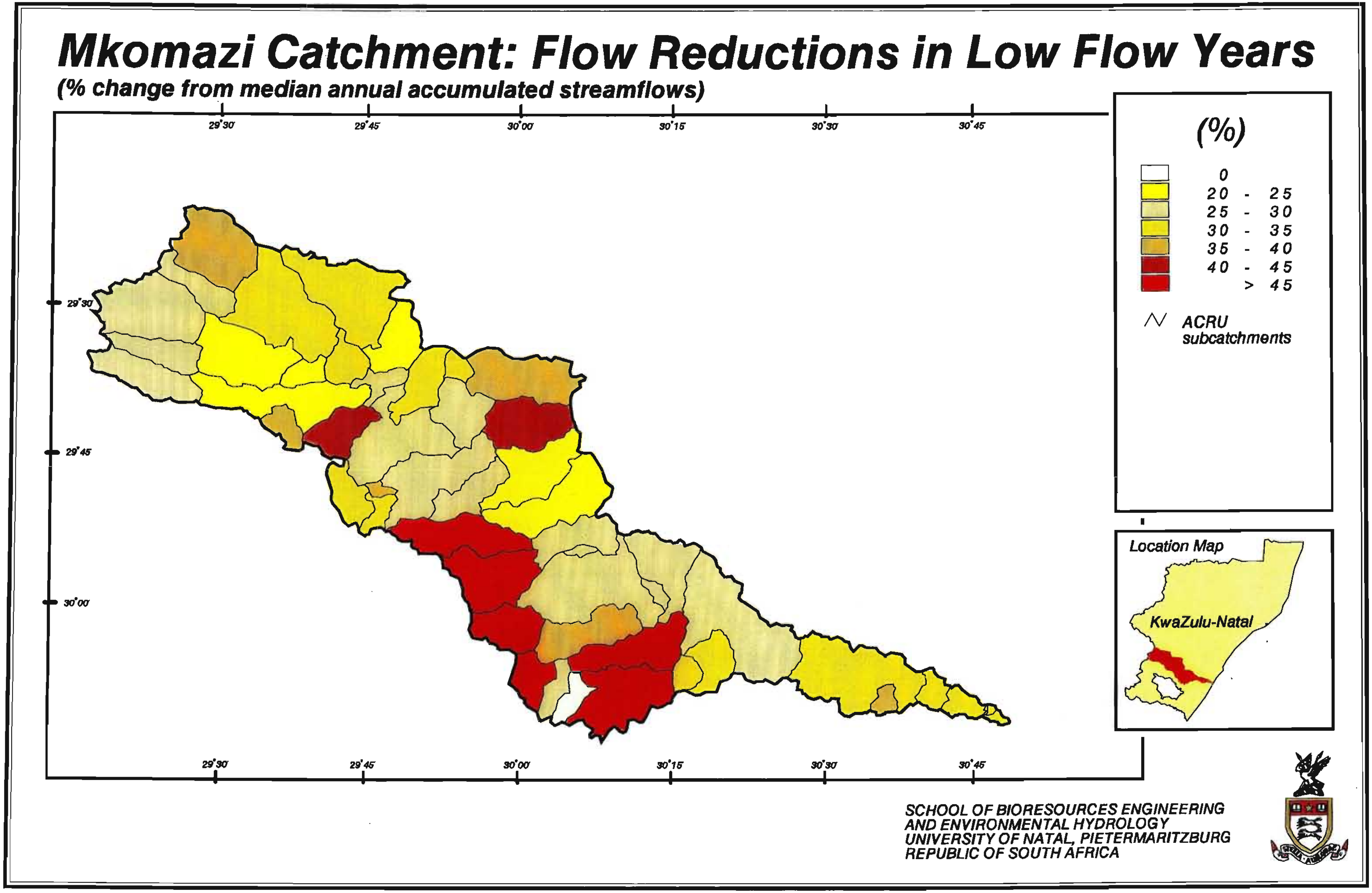

Figure 7.1 Mkomazi Catchment: Flow reductions in low flow years

Figure 7.1 shows that in low flow years subcatchments generally experience at least a 20% reduction in streamflows from a year with median flows. The upper Mkomazi, mid Mkomazi valley and lower Mkomazi experience reductions in the range of 20% - 40%, with areas of the upper catchment being as impacted as those in the lower catchment. However, those subcatchments that were identified as being the most impacted in years with median flows (Chapter 6), are also the most impacted in low flow years. Figure 7.1 shows that the SCs where commercial afforestation and irrigation are practiced are likely to have reductions in streamflows exceeding 45%, from those in a year of median flows. The reductions for the areas around Donnybrook and Ixopo (SCs 29, 30, 33, 40, 43, and 44) are 45%, 46%, 48%, 83%, 67% and 57% respectively. SCs 41 and 42, where irrigated land cover exceeds that apportioned to afforestation, should also be expected to have high percentage reductions. However, investigation of the streamflows reveals that these SCs were already heavily stressed under in a year with median flows. There is thus little change in simulated streamflows in low flow years, because even in the year of median streamflows they are already nearly fully utilised.

7.3 Flow Increases under Present Land Use in High Flow Years

The impacts of high flow years on the generation of Mkomazi streamflows under present land use were assessed by the evaluation of the 80th percentile of exceedence. This represents the statistically highest annual flow in five years, *i.e.* flow the annual streamflow depth of which is exceeded only in one year out of five. The percentage change in accumulated streamflows from the year of median flows, under conditions of present land use in the year of highest flows in five, are shown in Figure 7.2.

Figure 7.2 indicates that in high flow years most subcatchments experience between 30% and 60% increase in streamflows from those of a year with median flows. This change is fairly uniform throughout the catchment. The exceptions to this are, again, those areas where there is most anthropogenic change as a result of afforestation and irrigation and SCs 29, 30, 33, 40, 41, 42, 43 and 44 experience increases in streamflows, over those in the median year, in excess of 80%. The extent of the percentage increase in streamflows over the year with median flows from these subcatchments is another indication that these are, generally, hydrologically severely impacted areas in years of median flows.

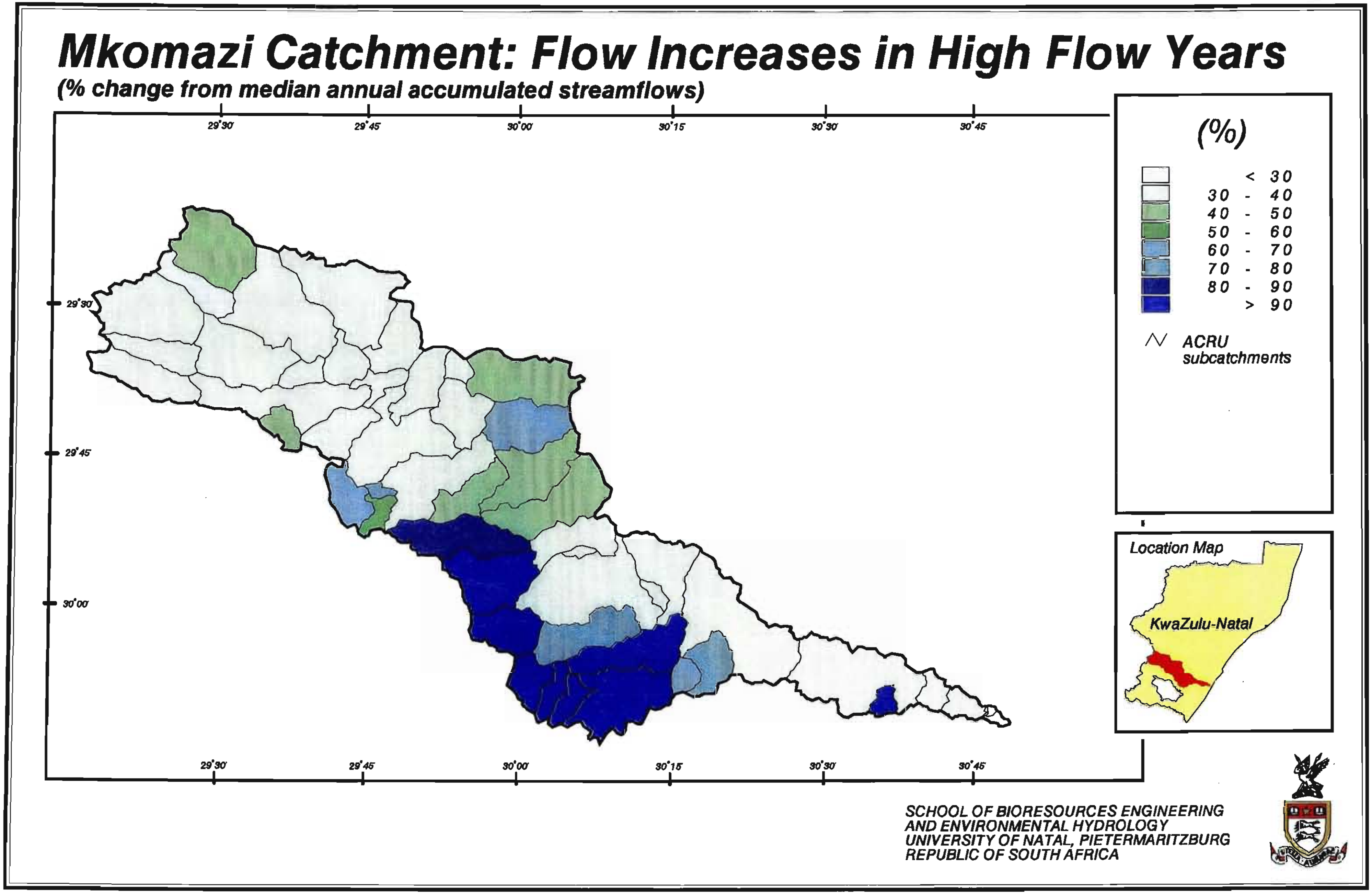

Figure 7.2 Mkomazi Catchment: Flow Increases in high flow years

7.4 Impacts of Development on Seasonal Low Flows

Water resources managers and consumers repeatedly identify the season of low flows as being the most critical period of the streamflow regime. Frequently conflict arises over water usage at this time and instances of moratoria for new afforestation permits have been enacted on the strength of perceived reductions in seasonal low flows attributable to commercial forests (Schulze *et. al.*, 1996). Whilst this chapter does not set out to assess the water usage of any individual land use (*cf.* Chapter 8), it is considered pertinent that an evaluation of the impacts of present land use is carried out on the seasonal low flows of the Mkomazi. It is anticipated that this evaluation will prove beneficial to water resources managers in any decision making.

The monthly low flows of the Mkomazi were examined to ascertain which consecutive six months experienced the lowest flows. These were identified as June through November (the low flow season). In order to evaluate the impacts of land use scenarios on seasonal low flows, the flows for June through November in the year of median flows were added together for each scenario investigated. Whilst in *ACRU*'s frequency analysis each month is treated as an entity and not as part of a sequence of flows at a specified percentile, this comparison, while statistically not ideal, is nevertheless appropriate. Furthermore, the scenarios investigated were assessed on "accumulated" streamflows as defined in Chapter 6 (*i.e.* total streamflows from a subcatchment, including upstream contributions).

7.4.1 Impacts of present land use on seasonal low flows

The impacts of present land use on the seasonal low flows of the Mkomazi were assessed by the change in seasonal low flows simulated under present land use conditions from the seasonal low flows simulated under the baseline land cover of Acocks' Veld Types (Acocks, 1988) described in Section 4.11.1. This was achieved by expressing the seasonal low flows simulated under present land use conditions as a percentage of the seasonal low flows simulated under the baseline land cover.

The impacts of present land use on the seasonal low flows of the Mkomazi, in a year of median flows are shown in Figure 7.3. The change in streamflows from the baseline cover indicates that, generally, the catchment experiences up to 20% reduction in streamflows

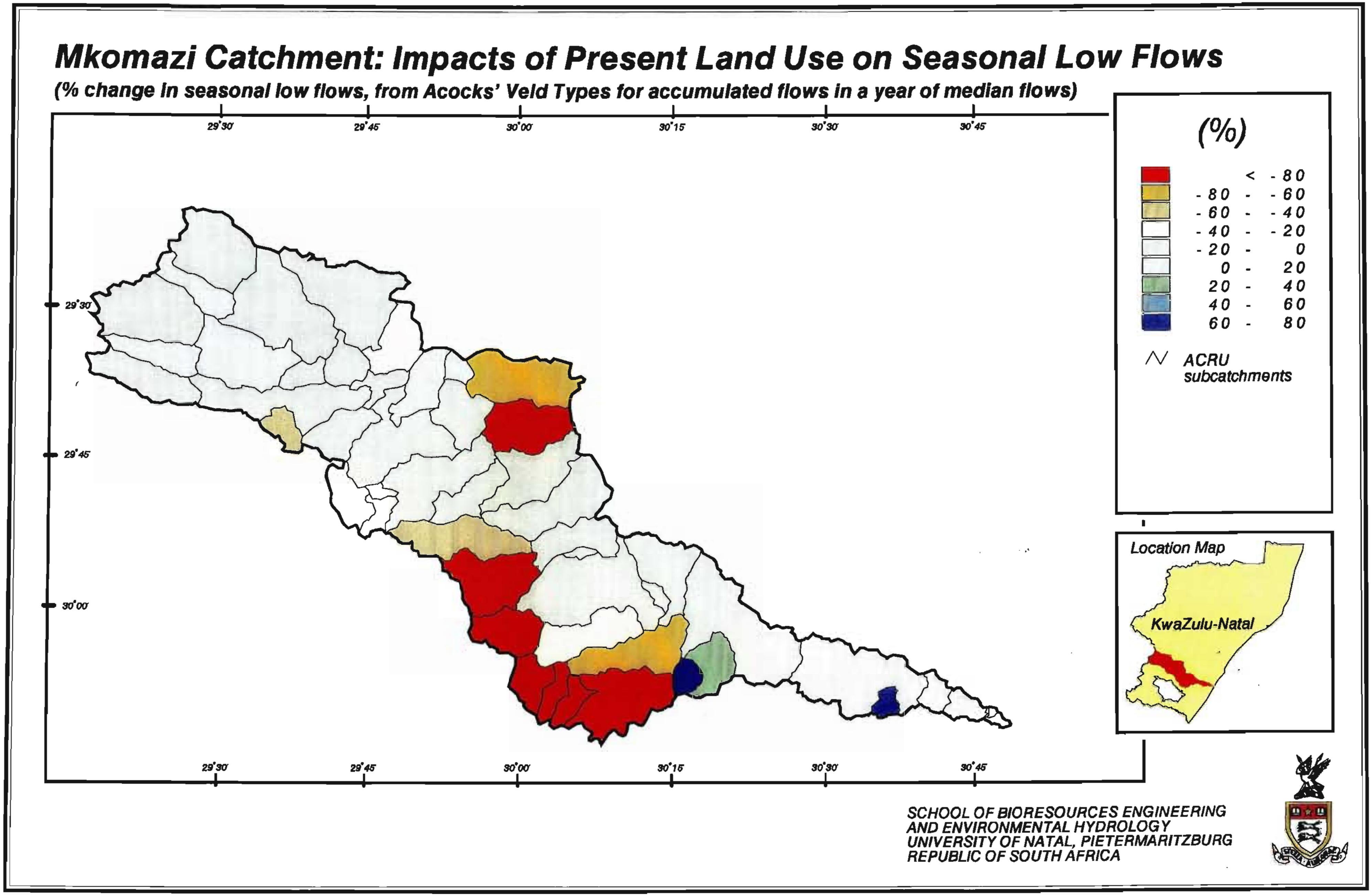

Figure 7.3 Mkomazi Catchment: Impacts of present land use on seasonal low flows

during the low flow season in a year of median flows. Again the SCs at greatest risk are those where both afforestation and irrigation are practiced (SCs 26, 30, 33, 40, 41, 42, and 43 with reductions of 83%, 87%, 96%, 94%, 93% and 94% respectively), with the Donnybrook / Ixopo region experiencing nearly 95% reductions in seasonal low flows compared to the seasonal low flows under baseline land cover conditions. The reductions in *annual* streamflows in a year of median flows from the Donnybrook / Ixopo SCs (41 and 42) were shown in Section 6.2.1 to be a similar percentage reduction (SC41: 96% and SC42: 97%) to those in the *low flow season.* The impacts of present land use during the low flow season in these SCs are such that there is virtually no available water according to simulations except for the seepage releases from dams.

Some SCs indicate increases in seasonal low flows from the baseline land cover, notably those that were delineated (Section 4.7.1) to assess the impacts of subsistence agriculture (SCs 15 and 38) and degraded land (SCs16 and 39). The increase is also evident for SC46, where natural coastal forest and thornveld has been replaced by thicket and bushland. These SCs experienced increases in *annual* flows from the baseline land cover (*cf.* Section 6.2.1) in a median year and some of the increase is represented in the low flow season.

7.4.2 Impacts of Smithfield Dam on seasonal low flows

Water resource managers require information regarding the impacts of dam operations on downstream flows in order to devise dam operating rules that the meet the needs of downstream users, including the environmental Reserve. The proposed Phase 1 of the MMTS, which will store water in the Smithfield Dam for transfer to the Mgeni Catchment, was described in Section 4.11.2. It is anticipated that the transfer will have greatest impact in the low flow season.

The evaluation of the impacts of Phase 1 of the MMTS on seasonal low flows in the year with median flow conditions was carried out following the procedure described in Section 7.4.1. The impacts of the transfer on the seasonal low flows of the Mkomazi were assessed by the change in seasonal low flows simulated under the Phase 1 of the MMTS scenario from the seasonal low flows simulated under present land use conditions. This was achieved by expressing the seasonal low flows simulated under the Phase 1 of the MMTS as a percentage of the seasonal low flows simulated under the present land use conditions.

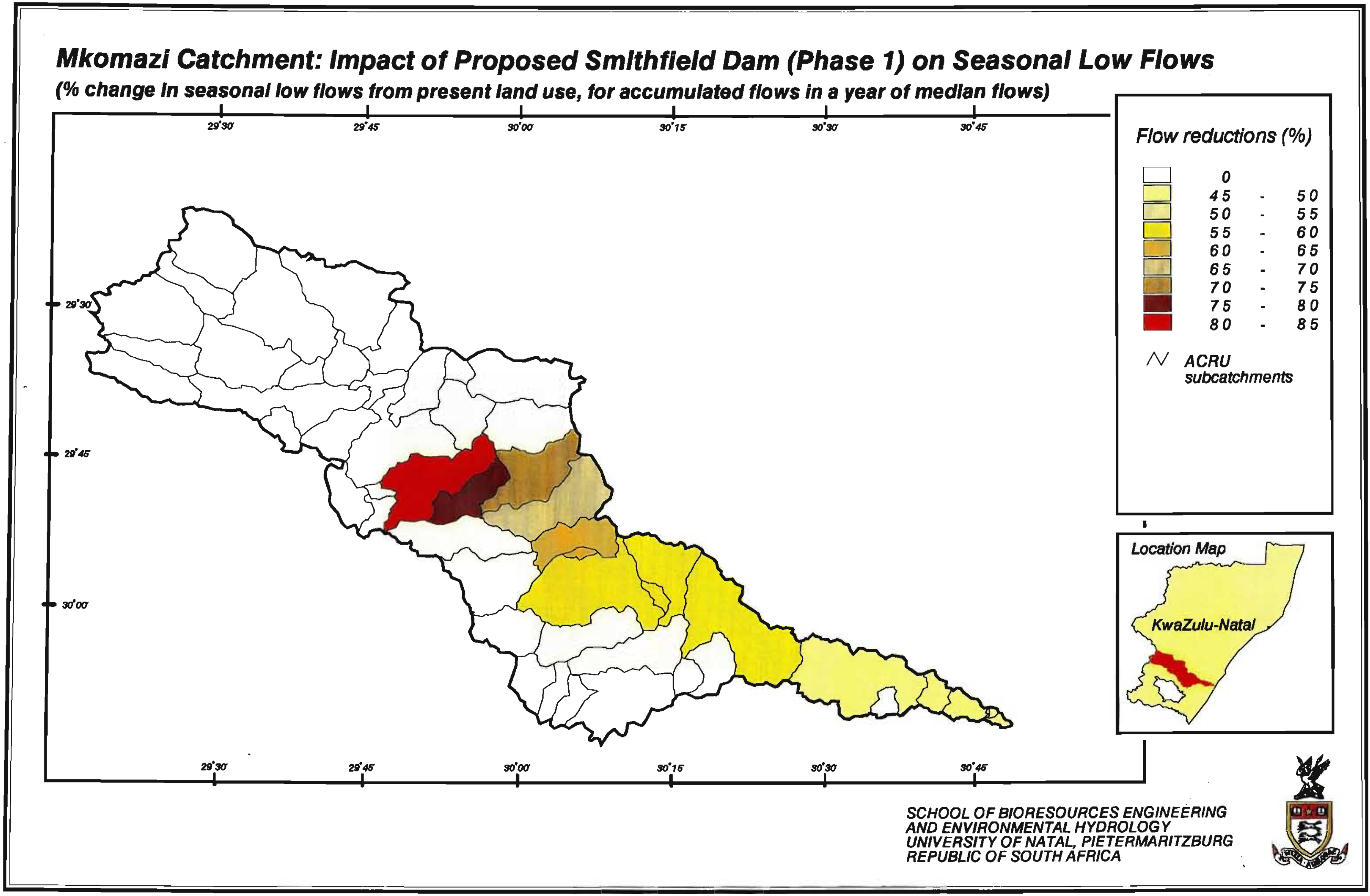

Figure 7.4 Mkomazi Catchment: Impacts of Smithfield Dam (Phase 1) on seasonal low flows

With the exception of this inter-basin transfer, all other land uses and cover remains the same as under present land use conditions.

The impacts of Phase 1 of the MMTS on the simulated seasonal low flows of the Mkomazi, in a year of median flows are shown in Figure 7.4. In a year of median annual flows, the reductions in seasonal low flows from those without the dam in place range from 48% (at the estuary) to 81% (at the site of the Smithfield Dam). This could have critical implications for the efficacy of determining sufficient and times releases to satisfy the requirements of all downstream users in the low flow season.

7.5 Implications of More Extreme Streamflow Scenarios and Sequences for Water Resource Management

Assessment of water resources under different climatic, and hence hydrological, conditions reveals that the impacts of low flow years in the Mkomazi could have significant influence on streamflow generation, especially where the land use has already been altered from natural conditions. In high flow years, streamflow generation in the Mkomazi Catchment shows greatest *relative* increases in those areas that are, at present, commercially utilized. However, those subcatchments that are already heavily utilized by afforestation and, particularly by irrigated land use, are unlikely to be able to support any further large-scale commercial agricultural development.

In a year of median flows, seasonal low flows also experience greatest reductions in the subcatchments where afforestation and irrigation are practiced and the study indicated that there is virtually no available water for further development within in those subcatchments. As expected, transferring water from the Mkomazi Catchment results in greater reductions of mainstream seasonal low flows with Smithfield Dam in place. This feature could intensify the difficulties associated with maintaining some semblance of the natural flow regime in the release of environmental flows from the proposed Smithfield Dam. These features are likely to be further exacerbated in years with lower than average flows.

7.6 Conclusions Regarding the Impacts of Land Use Change on the Available Water Resources of the Mkomazi Catchment

This and the preceding Chapter have investigated the impacts of land use change and development on the water resources of the Mkomazi Catchment under a number of different scenarios in order to establish which areas of the catchment offer potential utilisation for water resource development. The Mkomazi study has highlighted those areas where current practices already fully utilise water resources and those areas where there is water available for further development. The study has also indicated those areas where water resources are likely to be susceptible to the impacts of development under either present or potential climate change.

* * * * *

As discussed in Chapters 2 and 4, Umgeni Water, the authority responsible for bulk water distribution in the Durban-Pietermaritzburg complex of KwaZulu-Natal has indicated that it views the Mkomazi as a catchment where there is still substantial potential for the management of the allocatable water resources. The assessment of the requirements of the different water users in the Mkomazi Catchment is therefore an important consideration in the determination of how much water is available further allocation. The following chapter therefore assesses the water demand of the more predominant water users and in particular focuses on the anticipated environmental demand on the overall water resources of the Mkomazi Catchment.

8 STREAMFLOWS AVAILABLE FOR ALLOCATION IN THE MKOMAZI CATCHMENT

8.1 Introduction

Umgeni Water is faced with the challenge of managing the available Mkomazi water resources to meet the requirements of both the Mkomazi and the Mgeni Catchments. As indicated in Chapter 2, Umgeni Water has determined that while there is little further scope for water conservation and demand management within the Mgeni Catchment, the implementation of strategies to regulate streamflow reduction activities within the donor catchment of the Mkomazi could augment the Mgeni system (Gillham and Haynes, 2000).

The NWA classifies commercial afforestation as the principal streamflow reduction activities within South African catchments. Abstractions for irrigated crops are considered not to be streamflow reduction activities within the NWA because they do not intercept rainfall and therefore do not, *per se*, reduce runoff to streams. However, there is potential application for management strategies that address this highly consumptive water use and irrigation water is controlled through other legal acts. A further stipulation in the NWA, *viz.* that some river water must be reserved for ecological functioning and sustainability, places a new dimension to the allocation of available water resources for the nation's catchments. Managers of the Mkomazi Catchment are obliged to ensure that the ecological reserve receives priority over any other sector demand, except that reserved to meet basic human needs.

8.2 Water Sector Demands on the Mkomazi Catchment Streamflows

In this chapter the water demands of the principal water use sectors in the Mkomazi Catchment are assessed in order to quantify the volumes of water required by each sector. This was achieved by performing a number of *ACRU* simulations, each of which investigated the impacts of one water sector's use explicitly and then comparing the results with a baseline land cover simulation (the *ACRU* Acocks' simulation described in Section 4.11.1) to derive the water use for that particular sector. This was carried out for both pre- and post-MMTS conditions, in order to ascertain the impacts of various water demands on the availability of Mkomazi streamflows for potential further allocation. Chapters 6 and 7 have already highlighted the impacts of different land use and development scenarios on the generation of streamflows in the Mkomazi Catchment at a subcatchment scale. It was concluded in Chapters 6 and 7 that, although some subcatchments experienced substantial streamflow reductions as a result of intensive agriculture, particularly irrigation, the ***annual quantity*** of mainstream Mkomazi River flows are not severely impeded, even with the operation of the MMTS. In this chapter, the intention is to assess the impacts of different water use sectors and to ascertain the availability of flows at sites of specific interest on the Mkomazi River (the IFR and EFR sites). The locations of the Mkomazi IFR sites are shown on Figure 4.2.

In previous chapters, analyses of the impacts of development on Mkomazi streamflows were assessed at the percentile value of *ACRU* simulated output. This is considered to be *statistically* appropriate, given the highly variable climatic conditions affecting rivers in South Africa. Nonetheless, water managers in South Africa frequently assess water demand as a portion of the Mean Annual Runoff (MAR). Additionally, the monthly quantities of water assessed by the BBM methodology (*cf.* Section 8.2.6) as the Mkomazi instream flow requirements, termed the environmental demand in this chapter, were also expressed as a portion of the MAR. For these reasons, the sections in this chapter describe the Mkomazi annual streamflows in terms of the central distribution around the mean of the values in the *ACRU* simulated output. In Chapters 9, 10 and 11, and for reasons that will become evident, any statistical analyses will be made at the percentile value of the simulated output.

Sections 8.2.1 to 8.2.6 briefly describe the explicit impacts of water use by the principal present and future demand sectors (domestic, livestock, industrial, forestry, irrigation, inter-basin transfer and environmental) on the water resources of the Mkomazi Catchment. There are other water consumers within the Mkomazi Catchment (*e.g.* a small extent of indigenous forest in the middle catchment), *cf.* Figure 4.10 and Appendix A, Table A1), however any additional demand imposed on the catchment water resources are expected to be of little consequence. Furthermore, work initiatives to clear riparian invasive vegetation have already been initiated in the Mkomazi

Catchment and consequently water consumption by this land cover was omitted from this assessment.

Each section 8.2.1 to 8.2.6 describes the information required and applied to assess the particular water demand. Each sector demand for the 52 *ACRU* subcatchments (*cf.* Section 4.7.1) was evaluated as a measure of the extent of water use from a baseline land cover (Acocks' Veld Types) in order to have an equivalent comparison. Assessment was made of the water demand by each water use sector on the mean annual accumulated streamflows upstream of IFR Sites 1, 2, 3, and 4 for present sectors (domestic, irrigation, forestry and environmental) and for the future sector (Phase 1 of the MMTS). The only significant industrial demand in the Mkomazi is that of the Sappi-Saicorr paper mill (*cf.* Section 8.2.2) and although the mill abstraction is downstream of all the IFR sites, assessment of this demand is included in this chapter for completeness. The assessment of the water sector demands on the Mkomazi Catchment streamflows resulted in percentages of water demand pre- and post- Phase 1 of the MMTS, per water use sector, on the mean annual accumulated streamflows, as well as the availability of annual accumulated streamflows for allocation upstream of the four IFR sites. The results are given in Table 8.1, which will be referred to throughout this chapter.

Table 8.1 The percentages of water demand pre- and post- Phase 1 of the MMTS per water use sector on mean annual accumulated streamflows and the availability of annual accumulated streamflows for allocation, upstream of IFR Sites 1, 2, 3, and 4 in the Mkomazi Catchment

Water use sector	**Water demand on accumulated streamflows prior to phase 1 of MMTS (%)**				**Water demand on accumulated streamflows post phase 1 of the MMTS (%)**			
	IFR 1	**IFR 2**	**IFR 3**	**IFR 4**	**IFR 1**	**IFR 2**	**IFR 3**	**IFR 4**
Domestic	0.32	0.45	0.50	0.61	0.32	0.45	0.50	0.61
Forest	1.81	4.41	5.17	5.33	1.81	4.41	5.17	5.33
Irrigation	0.85	3.15	3.15	3.91	0.85	3.15	3.15	3.91
Environmental	30.73	27.27	29.32	27.38	30.73	27.27	29.32	27.38
MMTS	0.00	0.00	0.00	0.00	0.00	21.48	20.04	17.51
Allocatable	66.29	64.72	61.86	62.77	66.29	43.24	41.82	45.26

8.2.1 Domestic demand, livestock abstractions and subsistence agriculture

As already indicated in Chapter 4, the Mkomazi Catchment is sparsely populated, with no major urban areas except for the coastal town of Umkomaas. Nonetheless, the majority of the existing populace has inadequate access to potable water and many rural communities rely on direct river abstractions for household, livestock and subsistence water use. Studies conducted in the Mkomazi Catchment by the University of Southampton, in England indicate that present water use by rural communities may be as low as 11 to 16 litre per person per day (INCO-DC, 2000). However, this quantity of water is expected to increase with the implementation of planned rural water supply schemes (*cf.* Section 4.5). Estimates of the basic human water needs vary from between 25 to 50 litre per person per day (Roberts, 1998, pers. comm.), and it is expected that water use by Mkomazi rural inhabitants will increase with improved water supply.

Domestic water demand for the Mkomazi Catchment was sourced from DWAF's Mkomazi Water Demand and Reconnaissance Study provided by Umgeni Water (DWAF, 1998a). The Study defines quantities of water for low, medium and high demand scenarios for domestic use, based on determinations by Meigh *et al.* (1998). These values are given in Table 8.2. Population density and distribution within the Mkomazi Catchment was accessed from the 1996 census information provided by Umgeni Water.

Table 8.2 Domestic water consumption rates (after, Meigh *et al.*, 1998)

Demographic Sector	**Consumption scenario (litre per person per day)**		
	High	**Medium**	**Low**
Urban	200	150	100
Rural	60	30	8

The livestock census (commercial and communal animals per magisterial district) was obtained from the KwaZulu-Natal State Veterinary Services, at the Department of Agriculture and Environmental Affairs (DAEA). The quantities of water required for livestock consumption are assessed by the DAEA according to animal mass and are listed in Table 8.3.

Table 8.3 Livestock water consumption rates (after DAEA, 2000)

Small Livestock Units	**Consumption (litres per day)**	**Large Livestock Units**	**Consumption (litres per day)**
Sheep	25	**Cattle**	50
Goats	25	**Mules**	50
Pigs	25	**Horses**	50

Some manipulation of the information provided in both censuses was necessary to reconcile the categorisation of population and livestock densities, given respectively by enumerator and by magisterial district, with the Mkomazi *ACRU* subcatchment configuration. This was achieved by overlaying the respective enumerator and magisterial districts with the subcatchment boundaries and capturing the relevant population and livestock statistics. The resultant distribution of both present population and livestock, as assessed from the information provided by both censuses is given in Appendix B, Table B1.

Table 8.4 summarises the distribution of both present population and livestock upstream of each of the four IFR sites. On first appearance the population figures appear to be rather low. However, as discussed in Section 4.5 DWAF (DWAF, 1998b) describes the distribution of rural population as ranging from moderate to sparse, with greater concentration in the lower catchment. As expected, the urban population density per subcatchment is greater than that of the rural population. However, there are uncertainties as to the definitions of "rural" and "urban" used by the census collection as subcatchments that would be expected to have no apparent urbanisation (*i.e.* SCs 1, 2, 5, 6, and 11 in the upper Drakensberg) have been ascribed as having an urban population component. Notwithstanding any possible anomalies associated with the population figures in Appendix B, Table B1, and in Table 8.4, the figures were derived from the best information available (*i.e.* the 1996 population census). Furthermore, the domestic demand of Mkomazi streamflows is so inconsequential that even if the population distribution was underestimated by 500% the percentage demand imposed on the

Mkomazi Catchment water resources by the domestic sector would be little more than 3% of total catchment flows (*cf.* Table 8.1).

Table 8.4 Distribution of present population and livestock upstream of the four IFR Sites in the Mkomazi Catchment

IFR Site	**Population**		**Livestock**	
	Urban	**Rural**	**Large Units**	**Small Units**
1	1793	7292	44742	25144
2	1104	4661	32919	14690
3	463	1330	13219	2340
4	3206	8371	26495	5144

The *present* water consumption of the Mkomazi Catchment inhabitants was assumed to be that of the medium scenario shown in Table 8.2. Adequate domestic water supply to rural communities for basic health, for animal husbandry and community / small-scale subsistence farming was one of the main issues of concern identified for the Mkomazi Catchment in Chapter 4. Consequently, for the purposes of this study, these three demands on Mkomazi water resources have been categorised together and are referred to as the domestic demand.

The portion of the domestic demand sector, as a percentage of accumulated mean annual streamflows upstream of each of the four IFR sites on the Mkomazi River, is shown for pre- and post-MMTS conditions in Figures 8.1 and Figure 8.2 respectively. It is clear that the present domestic requirements of the catchment are of little consequence to the Mkomazi's water balance at any of the IFR sites on the river. Furthermore, Table 8.1 indicates that the domestic water demand on available water resources is only 0.61% of annual accumulated flows even in the lowermost region of the catchment at IFR site 4.

8.2.2 Industrial demand

Coincident with the sparse urban population of the Mkomazi Catchment there is little industrial focus and development within the catchment. The notable exception to this is

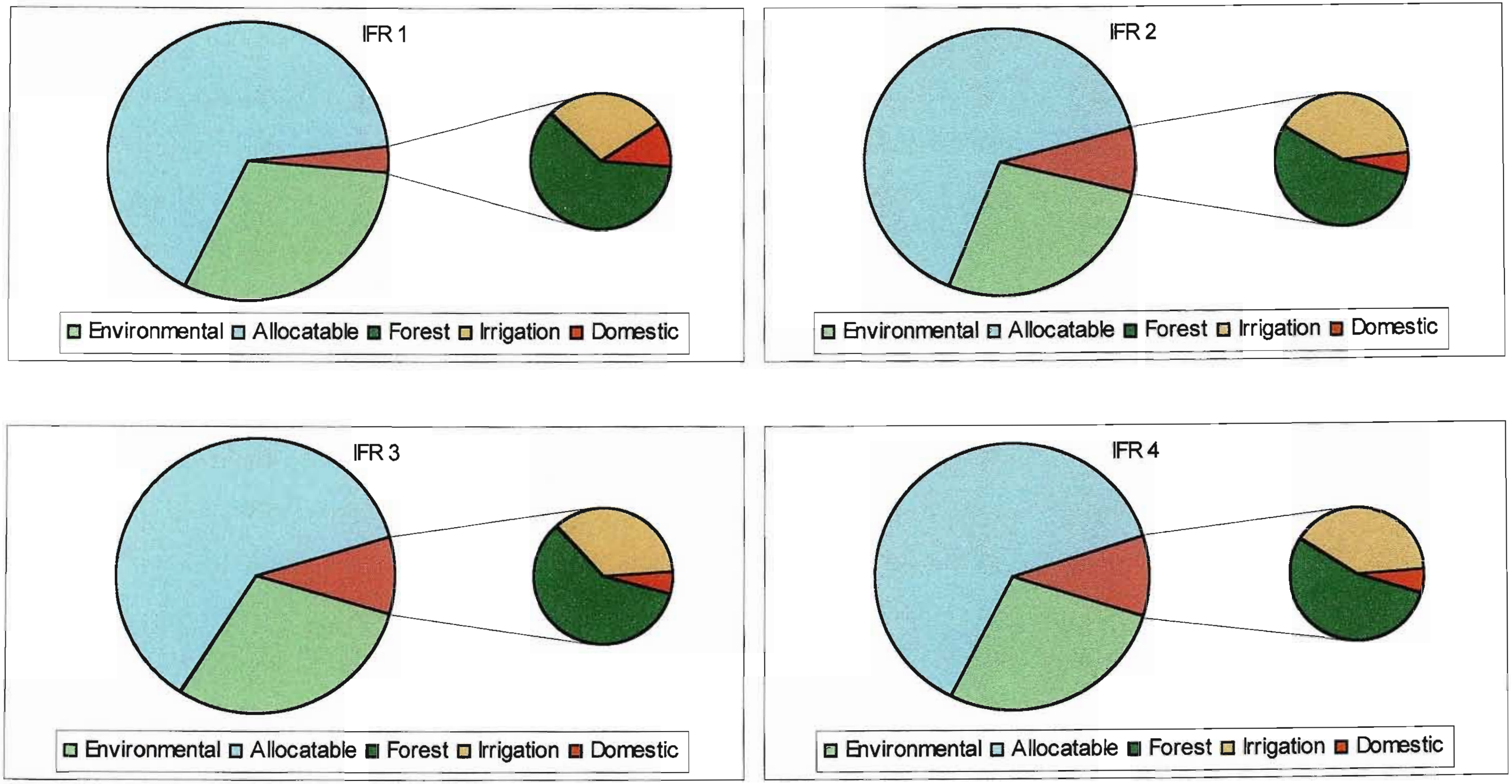

Figure 8.1 Present water demand per sector on annual accumulated streamflows and availability of annual accumulated streamflows for allocation, upstream of IFR Sites 1, 2, 3 and 4 in the Mkomazi catchment

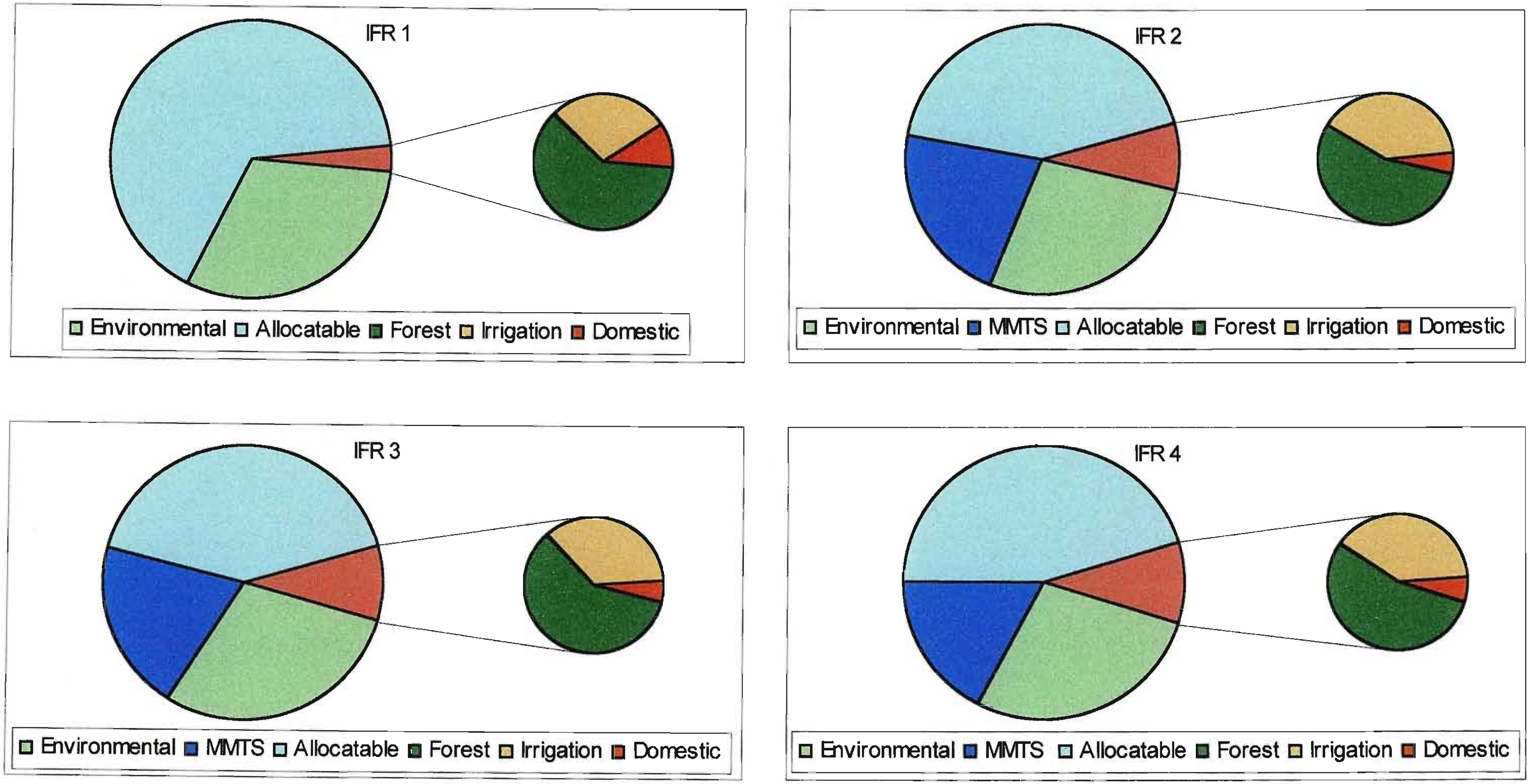

Figure 8.2 Post-MMTS water demand per sector on annual accumulated streamflows and availability of annual accumulated streamflows for allocation, upstream of IFR sites 1, 2, 3 and 4 in the Mkomazi catchment, where MMTS represents the water demand of Phase 1 of the Mkomazi Mgeni Transfer Scheme

the operation of the Sappi-Saicorr paper mill at the Mkomazi estuary. The Sappi-Saicorr mill lies within *ACRU* Subcatchment 49, and consequently impacts on only the three most downstream subcatchments of the Mkomazi configured catchment (*cf.* Figure 4.7). However, Sappi-Saicorr abstracts 54.7 x 10^6 m^3 per annum (representing 4.36% of accumulated mean annual streamflows at SC 49) from the Mkomazi River with none of the flow returned after use. Consequently the abstraction is perceived to be a critical factor in determining whether the estuarine flow requirement is met. In Chapter 4, it was indicated that general opinion is that the estuarine flow requirement is met if the flow requirement at IFR Site 4 is met. However, this factor does not account for the Sappi-Saicorr abstraction.

Recently (September 2000), the Institute for Natural Resources at the University of Natal in Pietermaritzburg was appointed to prepare the Sappi-Saicorr application for authorisation to construct two temporary barrages in the Mkomazi River to store water in dry seasons. It is outside the scope of this dissertation to deliberate over either Sappi-Saicorr's future water demand or the impacts of the construction of the barrage on downstream flows or the estuarine environmental flow requirements. However, Figure 8.3 indicates that Sappi-Saicorr's requirements are nearly one third of the baseline water resources (*i.e.* streamflows available under Acocks' Veld Types) towards the end of the low flow season in September in the year of lowest flows in 5 years (1:5 year). The impact of this requirement under present land use conditions and post Phase 1 of the MMTS will further deplete the downstream Mkomazi water resources and consequently, the estuarine flow requirements.

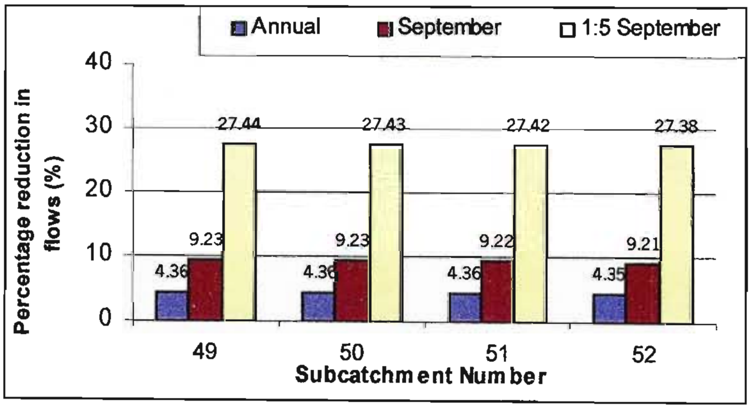

Figure 8.3 Percentage reduction in downstream flows from a baseline land cover in the Mkomazi as a result of the Sappi- Saicorr water abstractions

8.2.3 Forestry demand on water resources

The information required to simulate the Mkomazi forest demand was described in Section 4.8.1, 4.8.2 and 4.9.3 for forest distribution and water use respectively. Chapters 6 and 7 described the impacts of afforestation on the Mkomazi streamflows at subcatchment scale and highlighted the areas that are already water stressed by this land use. However, Figures 8.1 and 8.2 show that the present forestry demand does not appear to adversely impact on the *annual* quantity of water resources in the mainstream Mkomazi River. The areal extent of commercial plantation cover for each of the river reaches upstream of the four IFR sites is given in Table 8.5.

Table 8.5 Distribution of commercial plantation upstream of the four IFR sites in the Mkomazi Catchment

Land cover	**Areal extent of upstream land cover (ha)**				
	IFR 1	**IFR 2**	**IFR 3**	**IFR 4**	**Total**
Forest	7769	22678	11392	12241	54080

Figures 8.1 and 8.2 also show that afforestation places greatest demand on the water resources of the middle catchment and the area upstream of IFR Site 2, where there is greatest commercial plantation coverage (*cf.* Figure 4.10, Appendix A, Table A1). This can also been shown by the difference in percentages given for the forest demand in Table 8.1 which is greatest between IFR Site1 (1.81%) and IFR Site 2 (4.41%).

8.2.4 Irrigation abstractions

The information required to simulate the Mkomazi irrigation abstractions was described in Sections 4.8.1, 4.8.2 and 4.10.2. The Mkomazi irrigation demand on mean annual accumulated streamflows upstream of each of the four IFR sites is, quantitatively, slightly lower than that of the forestry demand (*cf.* Figures 8.1 and 8.2 and Table 8.1). However, the areal extent of irrigated land cover for each of the river reaches upstream of the four IFR sites given in Table 8.6 shows that the total extent of irrigated land cover upstream of IFR Site 4 is only 23% of that of commercial plantation.

Table 8.6 Distribution of irrigated land cover upstream of the four IFR sites in the Mkomazi Catchment

Land cover	**Areal extent of upstream land cover (ha)**				
	IFR 1	**IFR 2**	**IFR 3**	**IFR 4**	**Total**
Irrigation	862	5930	1331	4205	12328

It was shown in Chapters 6 and 7, that irrigation abstractions upstream of IFR Site 3, and in particular upstream of IFR Site 4, imposed undesirable stress at the subcatchment scale. However, the impacts appear to be localised and do not detract substantially from the availability of mainstream flows for potential further allocation. Hence, the irrigation demand on Mkomazi flows is greatest on the river reach between IFR Site 1 (0.85%) and IFR Site 2 (3.15%), rather than on the river reach between IFR Site 3 (3.15%) and IFR Site 4 (3.91%) (*cf.* Table 8.1).

8.2.5 Inter-basin transfer demand

The information required to simulate Phase 1 of the MMTS operation was described in Section 4.11.2. Phase 1 of the MMTS operation described in Chapters 4, 6 and 7, transfers 217 x 10^6 m^3 of water per annum from the Mkomazi into the Mgeni Catchment. Figure 8.2 shows that the impact of this demand on the availability of streamflows is greatest at IFR Site 2. The demand imposed by Phase 1 of the MMTS operation on mean annual accumulated streamflows upstream of IFR Site 2 is 21.48% of available water resources (*cf.* Table 8.1).

8.2.6 Environmental demand

The Mkomazi instream flow requirements were estimated by a BBM workshop in 1998 (DWAF, 1998b). The volumes of flow specified as requirements for each month of the year for drought flows and for maintenance flows (*cf.* Sections 3.7 and 4.10.1) are shown in Appendix B, Tables B2, B3, B4 and B5. The BBM IFR Tables represent the results of the BBM workshop as reported to DWAF in 1998 and were provided to the BEEH by Umgeni Water (Umgeni Water, 1999).

Each of the IFR Tables gives the total annual volumes of both low flows and high flows recommended for maintenance and drought flow requirements at the four respective IFR sites. The Tables also give percentages of "virgin" (*i.e.* natural) MAR for total low flow and high flow requirements at each IFR site. The concepts and principles adopted by the BBM process were described in Section 3.7. The following Sections 8.2.6.1 to and 8.2.6.3 described the assessment of the natural MAR at the Mkomazi IFR sites (a) by the BBM process and (b) from the *ACRU* simulated streamflows under the baseline conditions applied in this study. Section 8.2.6.4 describes the application of the information in the BBM IFR Tables in this study.

8.2.6.1 Generation of natural streamflows at the Mkomazi IFR sites by the BBM process

The natural MAR at each of the four IFR sites given in the BBM IFR Tables was derived by the BBM hydrologist from representative daily streamflow time series which were generated for the IFR sites using a spatial interpolation technique described by Hughes and Smakhtin (1996). The technique is based on flow duration curves (FDCs) for each calendar month of the year and on the assumption that flows occurring simultaneously at sites in reasonably close proximity to each other, correspond to similar percentage points on their respective flow duration curves (DWAF, 1998b).

The four IFR sites on the Mkomazi River are all located between the two DWAF gauged sites U1H005 and U1H006 (*cf.* Figure 4.2) and the interpolation technique assumes that the flow regimes at the IFR sites are similar to the recorded flow regimes. The representative daily streamflow time series for the IFR sites were generated by the BBM hydrologist for the BBM workshop by two steps:

Step 1:
Generation of FDC Tables for the gauged sites and for the IFR sites for each month of the year.

For the gauged sites this was achieved for the BBM workshop process by application of the available observed streamflow records. For the ungauged IFR sites, the final FDC Tables applied in interpolation technique were generated using the FDC Table from the nearest gauged site, together with a corresponding correction factor to account for the differences between natural MARs at the gauged site and those assessed at the IFR site (DWAF, 1998b).

A correction factor was considered unnecessary for IFR Site 1 because of its close proximity to U1H005 and because the estimated natural MAR at the gauged site (661 x 10^6m^3, Water Resources 90 (WR90), (Midgely *et al.*, 1994; cited in DWAF, 1998b) was assessed by the BBM hydrologist as being within 5% of the historical estimate (640 x 10^6m^3, WR90, Midgely *et al.*,1994; cited in DWAF, 1998b).

The WR90 provides monthly flow time series information for virgin flow conditions in the Quaternary catchments, QCs, for a standard 70-year period (1920 – 1990), simulated using Pitman's monthly rainfall-runoff model. IFR Sites 2 and 3 are located close to the QC boundaries. The estimates of the natural MARs used for the FDC Tables for these IFR sites were derived from a reconciliation of information sourced from the WR90 and from an update of the Pitman model simulations for a period from 1925 to 1995) acquired from BKS PTY LTD (DWAF, 1998b). The BKS simulations were performed for the two DWAF gauging sites, for three of the proposed dam sites in the catchment (Impendle, Smithfield and Ngwadini, *cf.* Figure 4.2) and for the catchment estuary. The estimate of the natural MAR used for the FDC Table at IFR Site 4 was calculated by interpolation between the BKS natural MAR estimates at the Ngwadini site and the estuary (DWAF, 1998b)

Step 2:

Simulation of a daily streamflow time series using the FDCs established for the IFR sites by step 2.

This procedure comprised:

(a) Assigning a weighting factor for both gauged sites (UH1005 and UH1006) to account for the degree of similarity between the flow regime at the gauged site and the flow regime at the IFR site.

(b) Identifying the percentage point position of the gauged site's streamflow on the gauged site's FDC for each day of each month and then ascertaining the flow value for the equivalent percentage point from the IFR site's FDC.

(c) The weighted average of the estimated IFR site flow value is assumed to be the final IFR site's flow value for the particular day identified (DWAF, 1998b).

Therefore, the generation of the BBM daily time series of natural flows at each of the four IFR sites was derived from the two DWAF streamflows records (at UH1005 and U1H006) and from the reconciliation of simulations for natural flow conditions at different locations within the catchment, using the monthly time step Pitman model.

8.2.6.2 Generation of natural streamflows at the Mkomazi IFR sites using the *ACRU* baseline land cover simulation

The procedure applied to generate the daily time series of natural streamflows at each of the four IFR sites using the *ACRU* baseline land cover simulation was described in full in Section 4.11.1. To recap, the baseline streamflows applied for the assessment of land use and catchment development impacts described in this study were generated by applying the hydrological attributes of Acocks' Veld Types (Acocks, 1988) in the *ACRU* model simulations.

8.2.6.3 Comparison of the methodologies used to generate natural streamflows at the IFR sites

As expected, there are discrepancies between the mean annual streamflows generated by the *ACRU* baseline land cover simulation and the natural MAR estimates given in the BBM IFR Tables. This is a result of a number of factors, the most pertinent of which are:

(a) The *ACRU* baseline simulation was performed for a subcatchment configuration specifically discretised to assess the streamflows at each of the four IFR sites, whereas the BBM process applied a spatial interpolation technique to assess representative streamflows.

(b) The *ACRU* baseline simulation generated daily streamflows at each of the four IFR sites, whereas the BBM process generated daily streamflows from FDCs derived from observed streamflow records (which had missing, and in the case of U1H006, erroneously recorded data) and from FDCs derived from streamflows generated by a monthly time step model.

(c) The baseline land cover (Acocks' Veld Types) applied in the *ACRU* baseline simulation was selected for its appropriateness to represent natural land cover conditions, whereas the BBM process derives natural streamflows from the observed record at the two gauging sites as well as from the WR90 natural flows. Chapter 5 discussed the attributes and limitations of the availability of record length as well as the quality of the streamflow record at both of the DWAF gauged sites. The automation of gauging records at U1H005 commenced in 1960 and at U1H006 in 1962. However, while the recording gauge U1H005 is generally perceived to be reliable (*cf.* Section 5.2) and the streamflows represent relatively undeveloped catchment conditions, the recording gauge at U1H006 produces unreliable high flow measurements (DWAF, 1998b) and the streamflows represent anthropogenically perturbed conditions (*cf.* Section 5.3). Moreover, WR90 natural flows are estimated by adjusting the historical QC flows to account irrigation abstractions and streamflow reductions incurred by afforestation (assessed from water use curves). This practice has limitations and consequently the WR90 estimates of natural flows are considered to be low.

A comparison of the assessment of the quantity of mean annual streamflows generated by the *ACRU* baseline land cover simulation and the natural MAR given in the BBM IFR Tables at each of the four IFR sites is provided in Table 8.7. Table 8.7 shows that the greatest discrepancy between the two methods used to generate natural streamflows is at IFR Site 4, with the *ACRU* simulated streamflows being 14% higher than those used by the BBM process. This difference reflects the unreliability of the gauging equipment at U1H006 to accurately record high flow measurements as discussed in Section 5.3.

Table 8.7 Comparison of mean annual streamflows generated by the *ACRU* baseline land cover simulation and the "virgin" MAR given in the BBM IFR Tables at each of the four IFR sites in the Mkomazi Catchment

Method of generation	**Mean Annual Streamflows (10^6 x m^3)**			
	IFR 1	IFR 2	IFR 3	IFR 4
ACRU baseline	708	1013	1087	1243
BBM Process	690	909	1004	1064

8.2.6.4 Application of the information in the BBM IFR Tables to assess the environmental demand

In this study the total mean annual volumes for both the recommended low flow and high flow requirements given in the BBM Tables (*cf.* Appendix B, Tables B2, B3, B4 and B5) were expressed as a percentage of the *ACRU* baseline land cover simulation described in Sections 4.11.1 and 8.2.6.2. This was performed in order that an equivalent comparison of this demand could be made with those of the other water use sectors described in Sections 8.2.1 to 8.2.5.

The maintenance flows in the IFR Tables were assumed to equate to flows required in years with mean annual streamflows. Drought flows were assumed to equate flows required in years with flows the annual streamflow depth of which is exceeded in four years out of five (1:5 year). The totals of monthly low flows and high flows for maintenance flow requirements were combined and expressed as a percentage of the *ACRU* baseline land cover simulated streamflows generated at each of the IFR sites and assumed to be the portion of the environmental demand required at the respective sites.

The percentages of the environmental demand on the mean annual accumulated streamflows of the Mkomazi at each of the four IFR sites, and which were assumed to be the same under both the pre- and the post- Phase 1 of the MMTS operation, are given in Table 8.1.

The portion of annual streamflows required for the environmental demand is shown in Figures 8.1 and 8.2 to be greater than that of any other demand, including the inter-basin transfer demand of Phase 1 of the MMTS, at any of the IFR sites (*cf.* Table 8.1). While similar portions of annual streamflows are required at each of the four sites, the environmental demand at IFR Site 1is the highest, reflecting the high measure of protection required for the water resource at this site.

8.3 Availability of Mkomazi Streamflows for Allocation

Figures 8.1 and 8.2 confirm that there is substantial water in the Mkomazi Catchment system to meet present *annual* consumptive demands, the environmental demand and the planned inter-basin transfer. Even after the inter-basin transfer has been satisfied, there is close to 45% of the mainstream accumulated streamflows available for further development (*cf.* Table 8.1). However, this quantifies the *annually* available streamflows.

The flow values in each of the BBM Tables for IFR Sites 1, 2, 3 and 4 (*cf.* Appendix B, Tables B2, B3, B4 and B5) were included in an additional ***basic*** investigation of the availability of Mkomazi streamflows for allocation at a *subcatchment* scale. The assumptions were that:

(a) ***present*** land use conditions prevailed and that

(b) the annual flow requirements (*i.e.*. the total monthly low flow and high flow requirements) specified in the IFR tables were met as a subcatchment pro rata demand, *i.e.* the required streamflows at each IFR site, as a percentage of the baseline land cover, was contributed to by each upstream SC with the equivalent percentage of its annual accumulated streamflows.

For example, for each of the SCs upstream of IFR Site 1, the portion of its streamflows required to contribute to the annual flow requirements at the IFR site was ascertained as being 30.73% (*cf.* Table 8.1) of the *ACRU* baseline streamflows from each upstream SC. The corresponding quantity was then deducted from the quantity of streamflows generated under present land use conditions at each SC and the value remaining was ascertained to be the quantity of streamflows available at each SC for further allocation.

8.3.1 Availability of streamflows for allocation in a year of mean annual flows

The allocatable streamflows in a year of mean flows for each SC are shown in Figure 8.4, which indicates that under present land use (*i.e.* pre-MMTS) most of the Mkomazi Catchment does have substantial water resources for further water allocations. It is pertinent to note that the greatest quantities of allocatable water resources are available downstream from the site of the proposed Smithfield Dam. Figure 8.4 indicates that those subcatchments already commercially utilised by afforestation and / or irrigation (*cf.* Figure 4.10) have least water available for allocation to further streamflow reducing activities. Furthermore, commercial agriculture areas in the lower Mkomazi (*i.e.* SCs 41 and 42) would not meet the IFR requirements ***if*** those SCs had to provide an equitable share towards the requirements at IFR Site 4.

8.3.2 Availability of streamflows in an average September

In low flow months, when there is likely to be greatest pressure on water availability as a result of drier climatic conditions, exacerbated by irrigation demands, the impacts of present land use and fulfilling the environmental demand are considerably greater. Figure 8.5 indicates that in an average September, the month with generally the lowest flows, the stress on the availability of streamflows would be evident for the majority of the tributaries as well as for much of the Mkomazi River. Indeed, much of the upper Mkomazi Catchment would have virtually no more water available for further development.

8.3.3 Availability of streamflows in a September with only 1:5 year flows

The stress placed on available water resources is all the greater for the scenario for low flow months (*e.g.* September) in low flow years (*i.e.* 1:5 year). Figure 8.6 shows that the entire Mkomazi Catchment is likely to have very little water to allocate to further water users under these conditions, once environmental demands have been met.

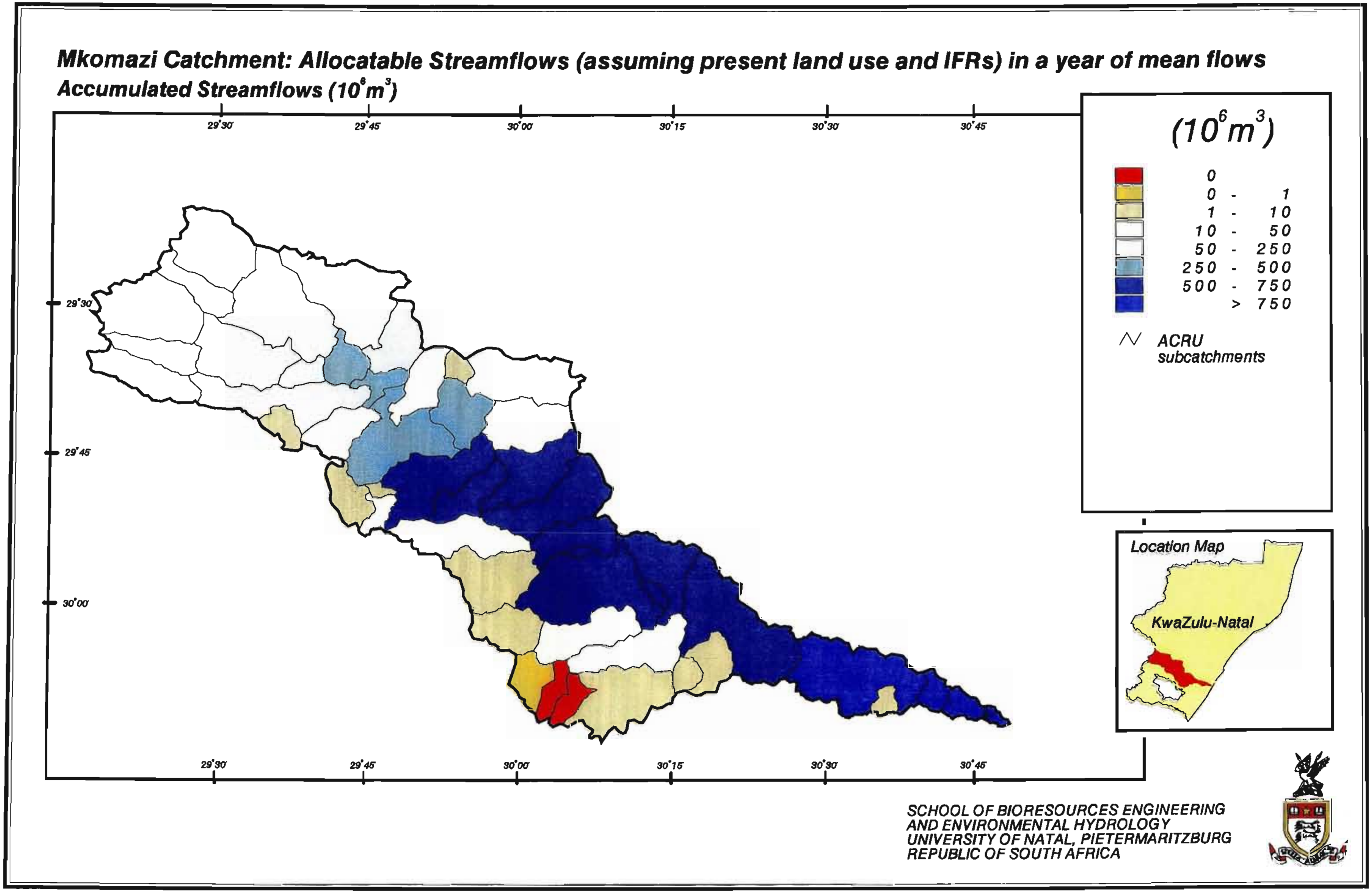

Figure 8.4 Mkomazi Catchment: Allocatable streamflows, assuming that instream flow requirements are met, under present land use in a year of mean flows
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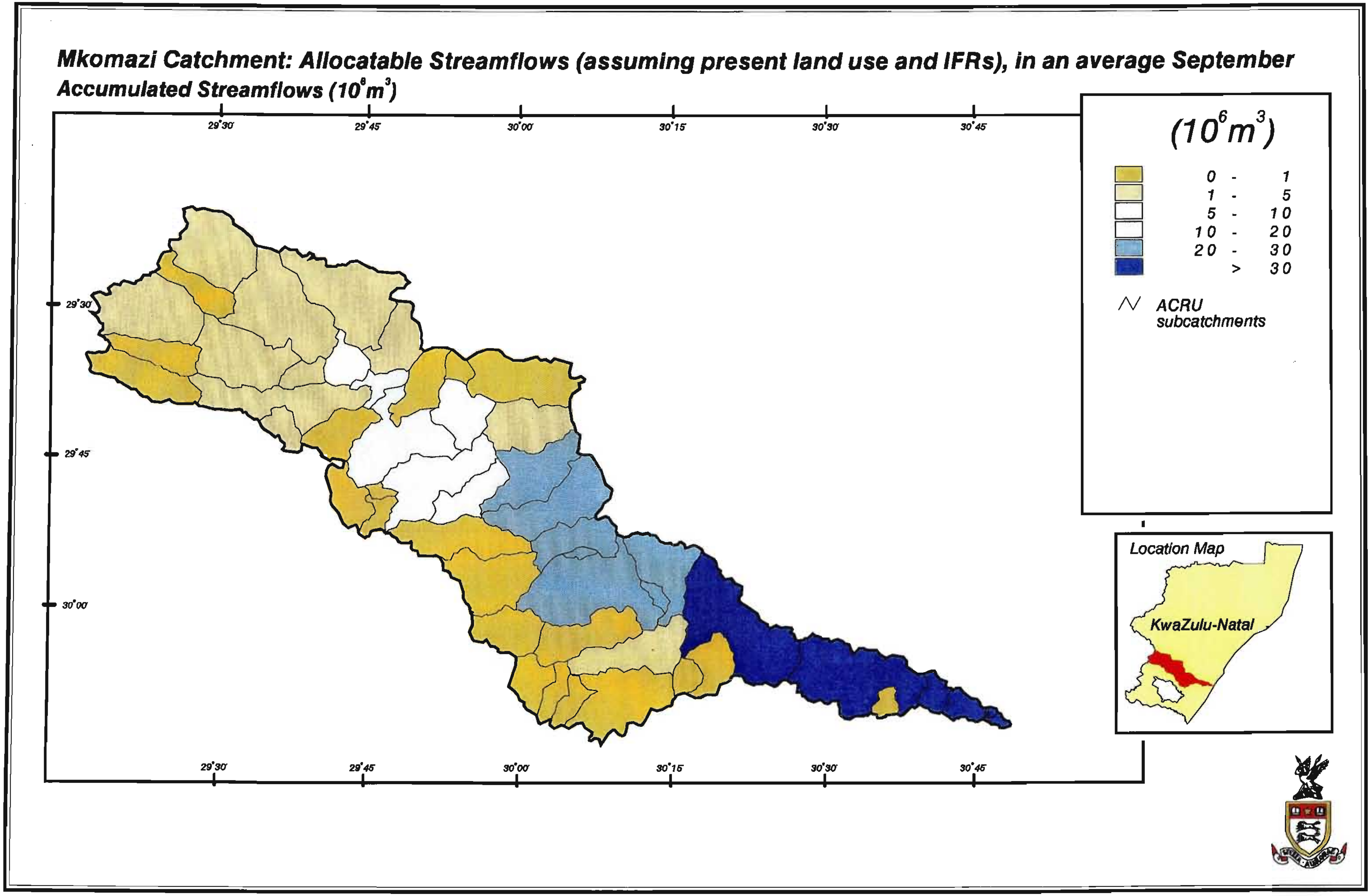

Mkomazi Catchment: Allocatable Streamflows (assuming present land use and IFRs), in an average September

Accumulated Streamflows ($10^6 m^3$)

Figure 8.5 Mkomazi Catchment: Allocatable streamflows, assuming that instream flow requirements are met, under present land use in an average September

Mkomazi Catchment: Allocatable Streamflows (assuming present land use and IFRs) in a 1:5 September

Accumulated Streamflows ($10^6 m^3$)

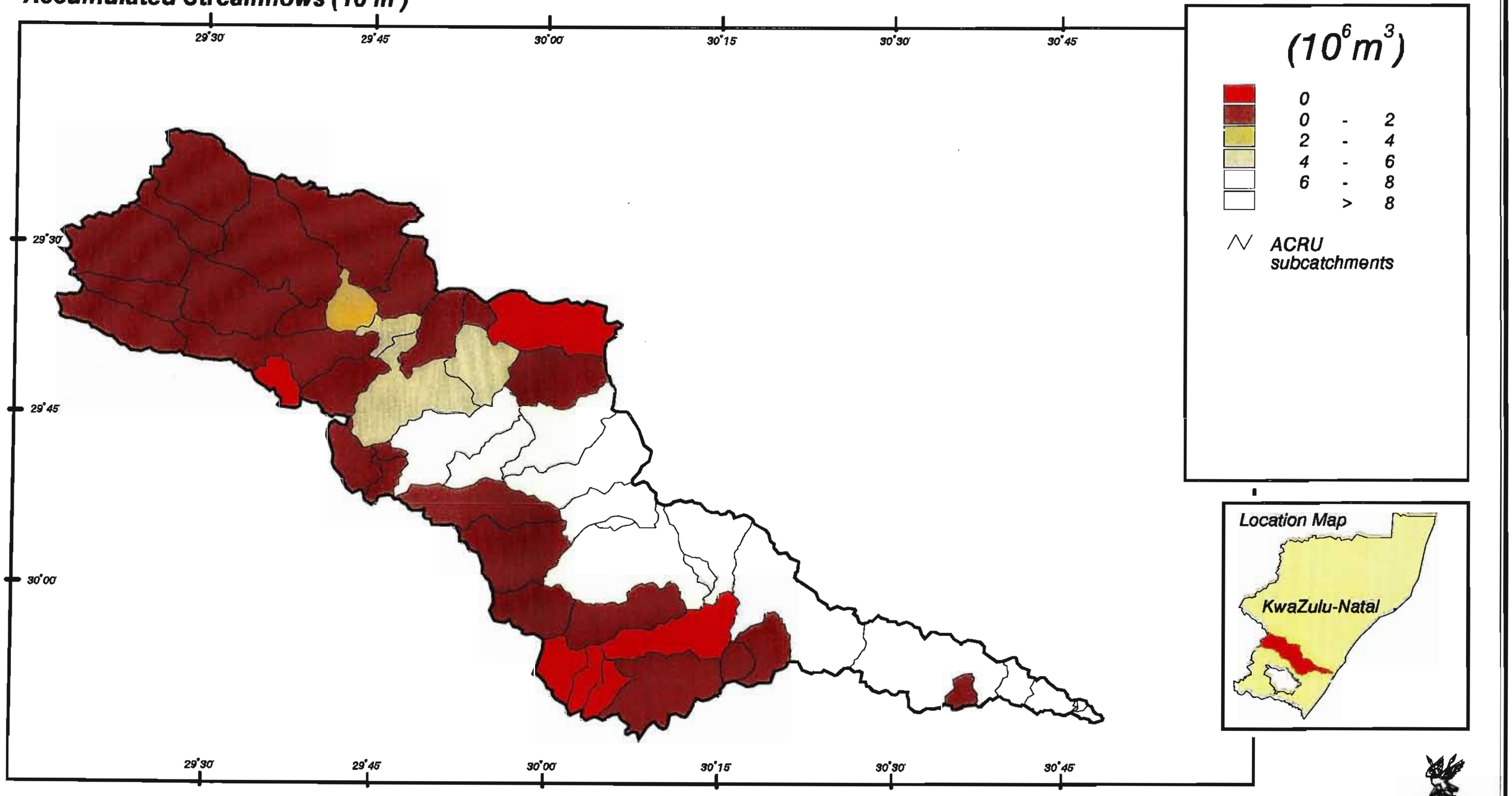

Figure 8.6 Mkomazi Catchment: Allocatable streamflows, assuming that instreamflow requiremnts are met, under present land use in a 1:5 September

8.4 Conclusions

In general, these elementary water demand scenarios indicate that the annual streamflows in the Mkomazi River are more than adequate to meet not only present catchment demand and the environmental requirements, but to also supply Phase 1 of the planned transfer of catchment water resources to the Mgeni system. However, there may not be sufficient streamflows generated in the Mkomazi, even under present land use, to sustain further development in low flows. Successive phases of the MMTS planned for additional inter-basin transfer would impose even further stress on water resources during low flows and periods of hydrological drought. Whilst it is recognised that the analysis was performed on essentially simple rules, this factor emphasises the need for effective operating dam rules with all stakeholders' needs being accounted for.

* * * * *

Notwithstanding the extent of surplus streamflows available for further allocation, this chapter has indicated that the greatest single source of demand on the Mkomazi Catchment water resources emanates from the reservation of instream flows for environmental requirements. This principal water use is further investigated in terms of the BBM workshop process, the alteration of the natural flow regime of the Mkomazi streamflows and the preliminary management targets for the Mkomazi ecosystems in the following three Chapters.

9 DETERMINING THE ENVIRONMENTAL DEMAND OF THE MKOMAZI CATCHMENT: THE BBM WORKSHOP REVISITED

9.1 Introduction

The previous chapter identified the environmental demand, in terms of the reservation of instream flows, as being the dominant water use sector of the Mkomazi Catchment water resources. The instream flow requirements for the Mkomazi River were assessed in March 1998 (DWAF, 1998b) by an IFR workshop using the Building Block Methodology described in Section 3.7 and Section 8.2.6. The workshop defined and determined the management class (*cf.* Section 2.5.1) of representative reaches and focussed on four unique sites at which flow characteristics would be required to maintain the integrity of the aquatic ecosystem.

Four macro-reaches were identified for the Mkomazi River, distinguished by the different habitat, instream and riparian characteristics of each. These macro-reaches are upstream of, though not coincident with, the four IFR sites shown on Figure 4.2. The upper part of the Mkomazi Catchment is largely undeveloped, and the upper reach of the river is in good condition. The present state class of the macro-reaches in which both IFR Sites 1 and 2 are situated was assessed by the workshop participants as being category C/B. However, it was regarded by the participants as important that habitat, instream and riparian integrity of these macro-reaches be protected from degradation. Hence, the workshop set a protective management class of category B for the macro-reaches upstream of both IFR Sites 1 and 2. Although IFR Site 3 is less than 20 km downstream from IFR Site 2, the macro-reach within which it is situated is impacted by irrigated agriculture and consequently suffers some degradation in flows, both quantitatively and qualitatively. For that reason, it was suggested by the BBM process that the management class of this macro-reach be improved from the present class of D/C to class B. As indicated in Chapters 6, 7 and 8, the impacts of agriculture and forestry in the lower part of the Mkomazi Catchment are ameliorated in the downstream reaches of the Mkomazi River by the magnitude of the mainstream flows. Notwithstanding this factor, the present state of the river where IFR Site 4 is situated was assessed by the workshop as being class C, and the management class was set as class B. Hence, the entire Mkomazi River management class is assessed as B.

The workshop produced four IFR tables detailing the streamflows required in terms of magnitude, frequency and duration at each of the four sites for each calendar month. Streamflows were prescribed to facilitate maintenance of the management class (the maintenance flow requirement) and to stress the river in drought years (the drought flow requirement) since stress and variability is considered an essential feature of the river system (DWAF, 1998b). The values for each site are provided in Appendix B, Tables B2, B3, B4 and B5.

9.2 Revisiting the Mkomazi BBM Workshop Process

Prior to any BBM workshop, the hydrological specialist generates representative time series of natural and present-day flow regime conditions of the river being assessed (*cf.* Section 8.2.6.1). The generation of this information can be an arduous task, not only because IFR sites invariably are not coincident with existing flow measurement sites, but also because historical flow records are frequently impacted by upstream land use developments, including water abstractions (Hughes, 1999a). A further difficulty associated with the generation of representative time series is that there are often constraints in the time allocated to the task, typically as little as six days for a relatively large river system with say five IFR sites to be assessed (Hughes, 1999a). The generated values are used as a reference time series of flows by the hydrological specialist at the workshop in order to assist the other workshop specialists to set the ecological flows expected to occur within the natural flow regime.

Whilst these factors are not detrimental to the overall BBM process *per se*, they are indicative of the magnitude of the complexities and challenges facing experts in the science of instream flow assessment. The following sections therefore revisit the Mkomazi BBM workshop table values to ascertain whether the streamflows prescribed for each of the four Mkomazi IFR sites are achievable, not only for baseline land use conditions, but also under the development scenarios, described in Section 4.3 *viz*:

(a) present land use conditions, defined in accordance with Thompson's 1996 classification and interpretation of the LANDSAT TM 1996 image (*cf.* Section 4.8),
(b) present land use, but including potential impoundment in accordance with Phase 1 of DWAF's Mkomazi-Mgeni Transfer Scheme (MMTS) (*cf.* Section 4.11.2),

(c) present land use, but with the climate perturbed in accordance with the climate change scenarios for a doubling of CO_2 conditions as generated by the HadCM2 General Circulation Model (excluding sulphate forcing), *i.e.* the second version of the Hadley model developed by Murphy and Mitchell (1995)(*cf.* Section 4.11.3) and

(d) present land use, but with the climate perturbed for a doubling of CO_2 conditions as described in (c) and including Phase 1 of the MMTS described in (b).

9.3 Assessment of the BBM Mkomazi IFR Table Values

The Building Block Methodology adopts a holistic approach to setting the environmental requirements of aquatic ecosystems. The process integrates some components of the habitat, hydraulic and historical flow methodologies described in Chapter 3. However, due to time constraints and a lack of information, the process by which the values in the BBM tables are determined is limited, prescriptive and to a large extent subjective. In addition to the difficulties inherent in generating an historical time series of flows within a short space of time, there is frequently insufficient habitat and hydraulic data available for making informed judgements regarding the quantities of water required to sustain particular species and their different life cycles. Furthermore, the hydrological specialist does not have the benefit of applying historical streamflows generated explicitly at the IFR sites. With these factors in mind, the achievability of the values determined as instream flow requirements for the four Mkomazi IFR sites is investigated in Sections 9.3.1 to 9.3.4.

9.3.1 Assessment of wet and dry season low flows (baseflows)

As described in Section 3.7, the BBM methodology recognises that wet and dry season low flows form the base "building block" (baseflows) of any streamflow regime and the ecological importance of the baseflow regime for aquatic ecosystems is described in Section 3.7. The conservation of dry season baseflows, particularly following a water resource development such as an impoundment, is considered critical to the streamflow regime, since water is typically most needed by aquatic ecosystems in the dry season.

The *ACRU* simulated daily streamflows generated at each of the four IFR sites were ranked for each calendar month and converted to percentages of time the flow was equalled or exceeded for each of the scenarios described in Section 4.3. The relationship between the ranked flows and the percentage of time the flows were equalled or exceeded can be illustrated as a flow duration curve. An example of a typical flow duration curve for the month of November under baseline conditions (Acocks' veld types) at IFR Site 4 is provided in Figure 9.1. The percentage of time the flows equalled or exceeded the baseflow values provided in the BBM Tables was assessed for each month using a computer program developed in the BEEH at the University of Natal in Pietermaritzburg.

In addition to the MMTS scenarios under both present land use and climate change conditions described in Chapter 4, whereby some water was released from the Smithfield Dam as normal or compensation flow, it was also considered appropriate to assess the Smithfield Dam simulations without any compensation flows. This factor was considered pertinent to providing a more realistic base on which to plan future dam operating rules in the allocation of the Mkomazi water demand.

The percentage of time that the BBM Table baseflow requirements would be equalled or exceeded under different land use and development scenarios, on a month by month basis, for each of the four IFR sites are shown in Figure 9.2 for maintenance flow requirements and in Figure 9.3 for drought flow requirements.

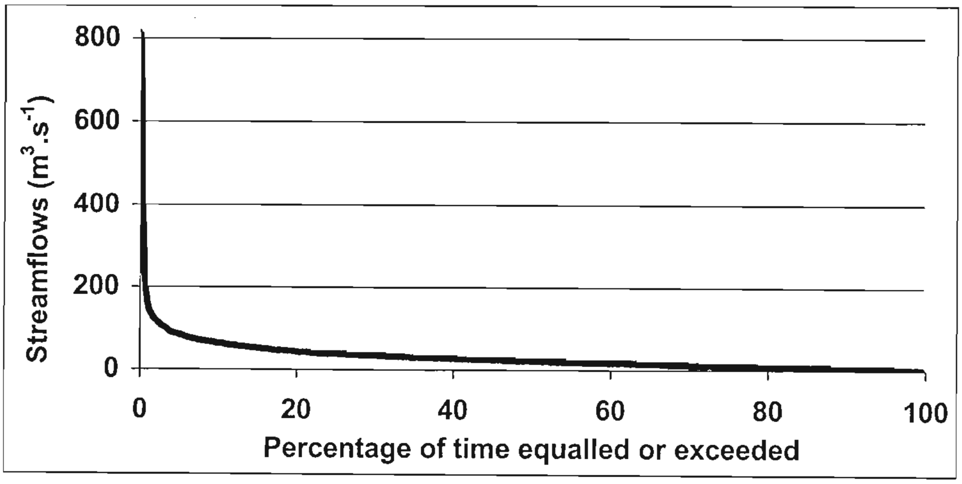

Figure 9.1 Flow duration curve of streamflows at Mkomazi IFR Site 4 for the month of November using Acocks' veld types as baseline land cover.

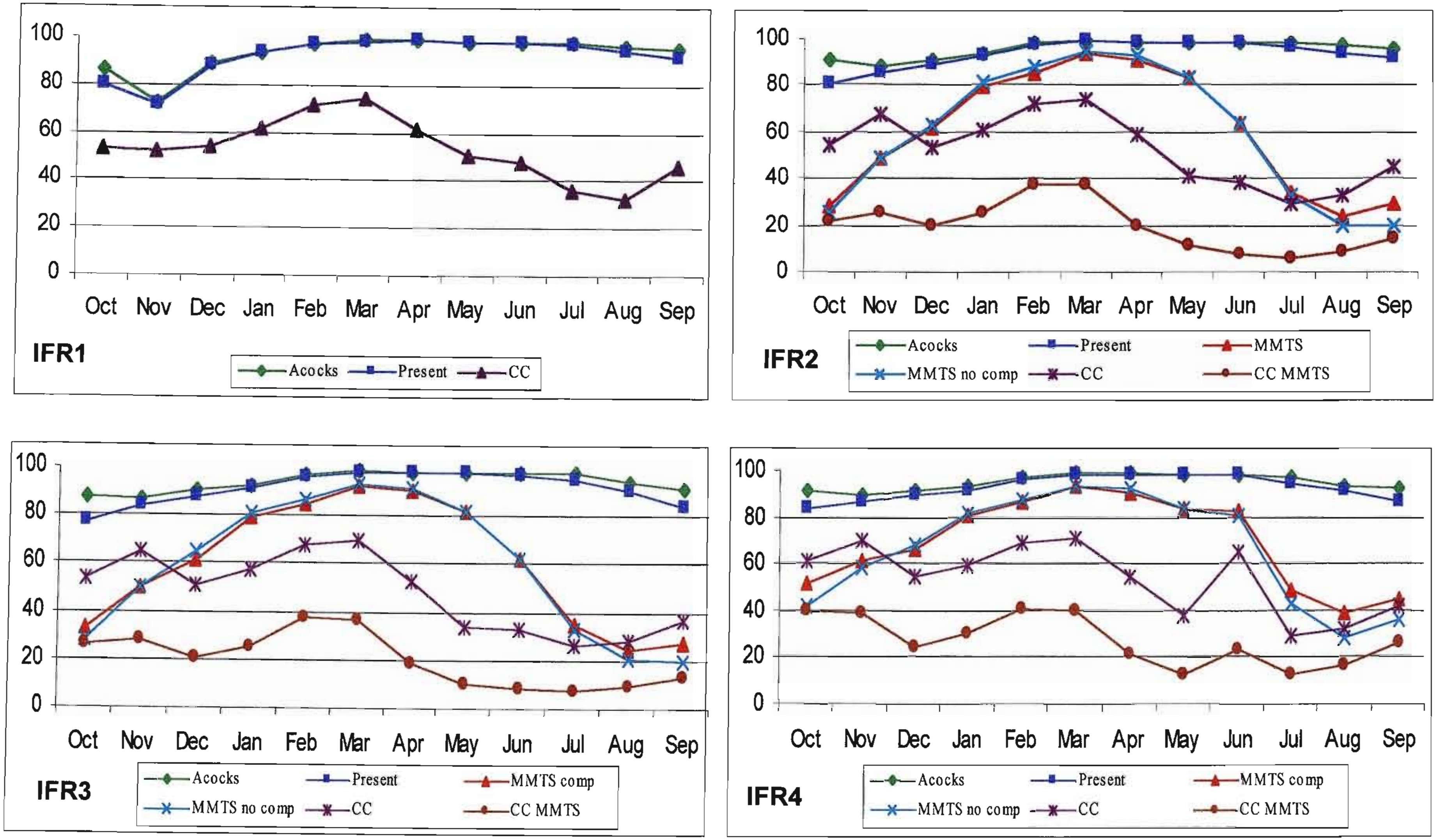

Figure 9.2 Percentage of time that the Mkomazi BBM Table maintenance baseflow requirements are equalled or exceeded at IFR Sites 1 2, 3 and 4, for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use, with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use, without and with the operation of Smithfield Dam respectively.

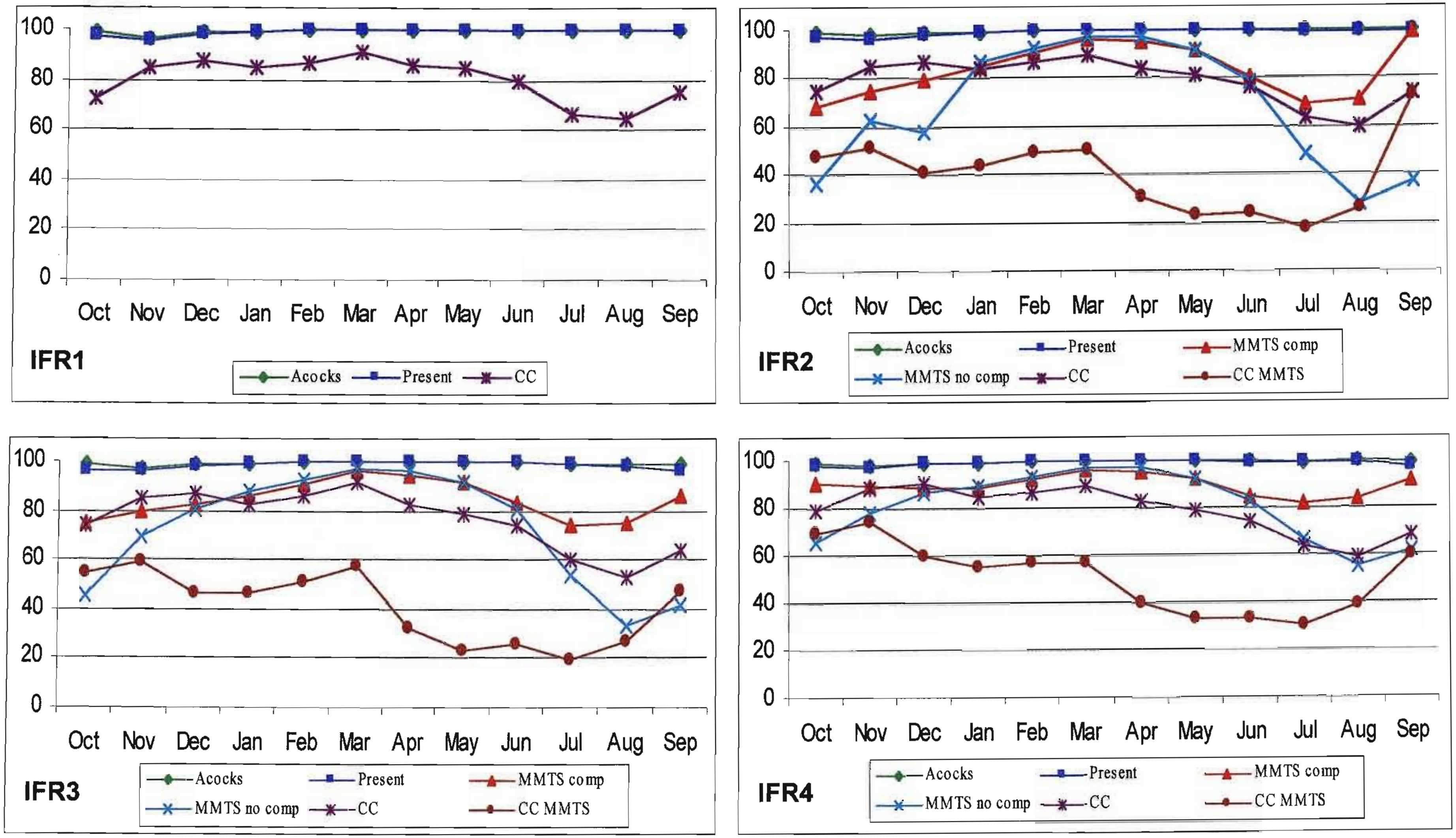

Figure 9.3 Percentage of time that the Mkomazi BBM Table drought baseflow requirements are equalled or exceeded at IFR Sites 1 2, 3 and 4, for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use, with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use, without and with the operation of Smithfield Dam respectively.

9.3.1.1 Baseflow requirements at IFR Site 1

IFR Site 1 is upstream of the proposed Smithfield Dam. Hence only the Acocks' veld types, present land use and climate change scenarios were assessed.

Figure 9.2 shows that, with the exception of the dry season months of August through October, there is little difference between baseline land cover and present land use in meeting maintenance baseflow requirements. Under both land cover conditions the BBM recommended maintenance baseflow requirements will be equalled or exceeded more than 90% of the time for most months of the year. Climate change conditions will reduce flows more substantially in dry season months, with the maintenance baseflow requirement being equalled or exceeded only 32% of the time during August.

The percentage of time that the drought baseflow requirements (Figure 9.3) recommended at this site are equalled or exceeded, is greater than that for the maintenance flow requirements, for each month and for all scenarios. Furthermore, there is no discernible difference between the attainment of baseflow requirements from either baseline and / or present land cover.

Moreover, the results show that the percentage of time at which the required baseflows would be equalled or exceeded for each month, under either baseline or present land use conditions, is higher than that assessed by the BBM workshop (*cf.* Appendix B, Table B2). This can be attributed to the *ACRU* generated series simulating higher daily natural flows than the time series used at the BBM workshop.

9.3.1.2 Baseflow requirements at IFR Site 2

The percentage of time that the BBM recommended maintenance baseflow requirements would be equalled or exceeded under either baseline land cover or present land use at IFR Site 2 (Figure 9.2) is very similar to that at IFR Site 1, apart from November which shows a very slight increase. Both climate change scenarios indicate the same trends as at IFR Site1. The operation of the MMTS with climate change would severely impact baseflows in both wet and dry seasons. Figure 9.2 shows that there is no discernible difference between the two scenarios with the Smithfield Dam in meeting the maintenance baseflow requirements, either with or without the normal flow releases being implemented. In the wet season, baseflows are maintained by the overflow from the dam and in dry seasons no releases are made in any event. Thus, the percentage of time at which maintenance baseflow requirements would be equalled or exceeded is virtually identical, irrespective of whether or not releases from the dam are included in the simulation. This suggests that the normal flow releases currently included in the MMTS scenarios as compensation for downstream use are inadequate for environmental requirements.

For all scenarios the drought baseflow requirements (Figure 9.3) are more likely to be achieved than the maintenance baseflow requirements (Figure 9.2). However, the impact of not releasing normal flows from Smithfield Dam would severely reduce the occurrence of flows meeting even the drought baseflow requirements in all but the wettest months.

At the end of the dry season the impact of climate change on the occurrence of flows meeting both the maintenance and drought baseflow requirements is generally less than the impact of the MMTS. This is because no releases from the dam are implemented in dry months.

These results again show that the percentage of time that the required baseflows would be equalled or exceeded for each month, under either baseline or present land use conditions, is higher than that assessed by the BBM workshop (*cf.* Appendix B, Table B3) for the same reasons as given in Section 9.3.1.1.

9.3.1.3 Baseflow requirements at IFR Site 3

The occurrences of flows required to meet the BBM recommended maintenance baseflows at IFR Site 3 are very similar to those occurrences of required flows at IFR Site 2 (Figure 9.2). However, the percentage of time at which flows meeting this requirement are equalled or exceeded at IFR Site 3 is slightly lower than at IFR Site 2 in the dry season for both baseline and present land use.

There are also similarities between the occurrences of flows required to meet the drought baseflows at IFR Site 3 and those occurrences of required flows at IFR Site 2 (Figure 9.3). However, in the absence of climate change, the impact of the Smithfield Dam on the occurrence of downstream flows meeting the drought baseflow requirement at the start (June to August) and after the end (October to December) of the dry season is slightly less than at IFR Site 2, particularly if no normal flows are released. This is partially due to the increased magnitude of streamflows in the Mkomazi River at IFR Site 3. Moreover, under conditions of climate change and with Smithfield Dam in operation, the percentage of time that flows would equal or exceed the required drought baseflows at IFR Site 3 is generally slightly greater than at IFR Site 2, for all months.

The specialists determining the flow requirements have been influenced by the degraded present state of the macro-reach between IFR Site 2 and IFR Site 3, and therefore have been more stringent in their assessment of the maintenance baseflow requirements at IFR Site 3. However, it is also noted that the percentage of time at which the recommended flows are equalled or exceeded under *present land use* at IFR Site 3 is relatively high (78% minimum value for October, *cf.* Figure 9.2). This could be explained by the fact that the BBM Table for IFR Site 3 (*cf.* Appendix B, Table B4), indicates that the values of flows associated with the flow duration curves resulting from the BBM generated time series used are lower than those flows generated by the *ACRU* simulated time series (*cf.* Section 8.2.6.1 to 8.2.6.3).

9.3.1.4 Baseflow requirements for IFR Site 4

Figure 9.2 shows that the occurrences of flows required to meet the BBM recommended maintenance baseflows at IFR Site 4 are generally slightly higher than those occurrences of required flows at IFR Site 3.

Figure 9.3 shows that at IFR Site 4 there would be few months during which the drought baseflow requirements set by the BBM process would not be exceeded 100% of the time under either baseline land cover or present land use. Furthermore, even if no normal flow releases were made from the Smithfield Dam, the drought baseflow requirement recommended by the BBM workshop would be equalled or exceeded at least 55% of the time (August). The impact of climate change on streamflows at IFR Site 4 would result in a reduction in the percentage of time that the drought baseflow requirement is equalled or exceeded, but to no lower than 60% (August).

9.3.2 Conclusions regarding the assessment of the BBM workshop baseflow requirements

The availability of the *ACRU* generated time series of streamflows generated specifically at the four IFR sites enhanced the confidence of these investigations into the monthly baseflows determined as essential to sustain the integrity of the aquatic environment. This study indicates that there is *presently* sufficient water in the Mkomazi River at all IFR Sites to exceed the BBM recommended maintenance baseflow requirements at least 72% of the time (IFR Site 1, November) at the end of the dry season (September to November) and at least 90% of the time for all other months. The latter indicates that these requirements may have been set too low in general to achieve the goal of environmental protection of a higher than present management class. This study also confirms that the BBM recommended drought baseflows have been set at sufficiently low values to ensure that they are equalled or exceeded virtually 100% of the time under present land use conditions.

9.3.3 Assessment of the wet season high flows (freshes and floods)

The baseflow regime provides the basic volume of water over and above which streamflow contributions, in "building blocks" of freshes and periodic floods (high flows), can be generated (Tharme and King, 1998). As described in Chapter 3, freshes act essentially as biological cues for the initiation of different life cycles of instream biota, whereas periodic floods are ecologically important for the maintenance of riparian habitats as well as for flushing river channels. The Mkomazi BBM process determined high flow requirements for the wet season months in terms of magnitude, as an instantaneous peak in $m^3.s^{-1}$, and for a specified duration, in days. The wet season months were defined as October to March for maintenance flow requirements and as November to March for drought flow requirements (*cf.* Appendix B, Tables B2 to 5). The Mkomazi IFR Tables also indicate the monthly volumes of flow required for the high flow events as well as the number of events required within each wet season month.

The *ACRU* simulated daily streamflows generated at each of the four sites were analysed to ascertain the achievability of the high flow events recommended by the BBM workshop process. Ideally, a flood hydrograph of daily flows is required to assess the exceedance of a specified volume of flow for a specified number of consecutive days within which an instantaneous peak flow rate occurs. Unfortunately routing of the flood hydrograph through the Mkomazi Catchment configuration described in Section 4.7.2 was beyond the scope of this catchment case study. A further problem was that, with the exception of IFR Site 3, none of the BBM high flow events recommended in the Mkomazi IFR Tables indicates either the portion of the total volume of flow allocated to *each* particular event, or the recommended duration of *each* event. In addition, some of the flow duration curve percentiles for the individual events are also missing from the BBM Tables for these sites. This information is required before any detailed analyses of the high flow requirements can be made with regard to the *ACRU* simulated daily streamflows generated at each of the four sites. In the interim, and for the sake of completeness of this study, the *ACRU* simulated daily streamflows were analysed on the basis of the relationship between the ranked streamflows and the percentage of time the BBM recommended high flow values were equalled or exceeded, as previously described for the assessment of baseflow requirements in Section 9.3.1. These results were then compared to those available flow duration curve percentiles as assessed by the BBM workshop process.

Because of the large areal extent of the Mkomazi Catchment, it was assumed that the instantaneous peak flows would be represented by a daily flow. This assumption is in keeping with the graphical examples of daily time series presented in the BBM starter document (DWAF, 1998b), which indicate that during wet season months, particularly in wet hydrological years, flows of such magnitude endure for several days. In this study each flood event was identified by means of a percentile on its month's flow duration curve. This analysis will be able to establish whether these percentiles are of similar order of magnitude to the BBM assessment of flow duration curve percentiles. The methodology was applied to the same land cover and land use scenarios investigated for the assessment of baseflows in Section 9.3.1

9.3.3.1 High flow requirements at IFR Site 1

Figure 9.4 illustrates that a number of the recommended high flows at IFR Site 1 will be equalled or exceeded between 20% and 60% of the time only. Under baseline and present land cover conditions, these are the October and November maintenance freshes, the higher drought flood required for February and the higher maintenance floods required for November to March. However, most of these flows are required for only 2 or 3 days

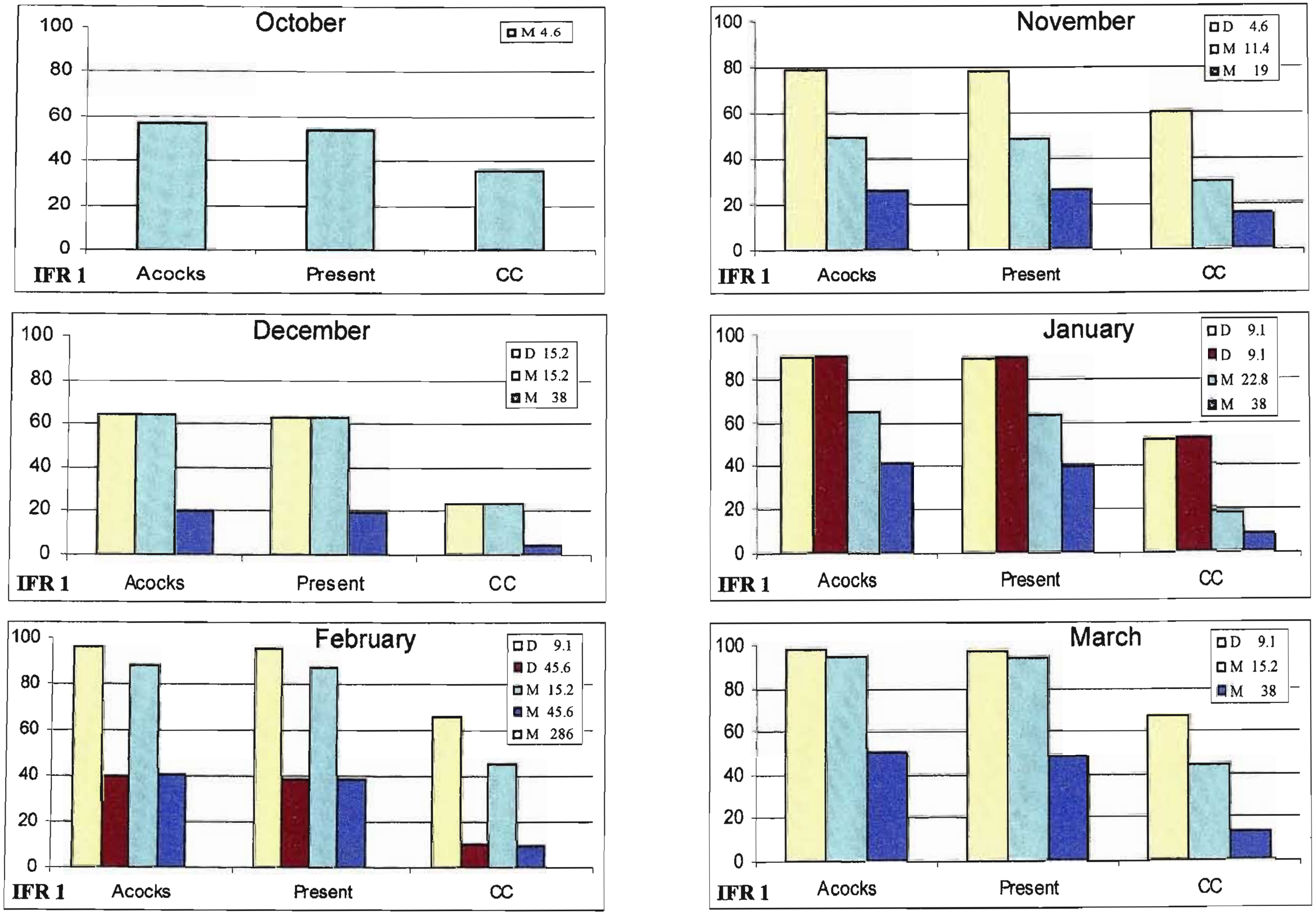

Figure 9.4 Percentage of time that the Mkomazi BBM Table high flow values are equalled or exceeded within each month at IFR Site 1 for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use without and with the operation of Smithfield Dam respectively. D and M represent drought and maintenance high flow values respectively. The values for both D and M represent the flow in $m^3.s^{-1}$.

within each of these months and it is therefore likely that flows to meet these BBM recommended events *would* occur, even under present land use. The occurrence of flows meeting the extreme maintenance flood event of 286 $m^3.s^{-1}$ required in February is equalled or exceeded only 0.32% of the time in the series of *ACRU* generated Acocks' streamflows from 1945 to 1996 at this site. This suggests that this event is unlikely to occur even under baseline conditions. Consequently the recommendation that a one in 5-year flood in February of 380 $m^3.s^{-1}$ should replace the 286 $m^3.s^{-1}$ (Appendix B, Table B2) may need to be reviewed.

There is generally greater expectancy that the drought high flow requirements recommended by the BBM workshop will occur than maintenance high flow requirements under both baseline and present land cover conditions, particularly in the wettest months of January, February and March.

The occurrence of flows to meet the maintenance high flow requirements under climate change conditions is much lower than under baseline conditions and present land use, particularly in December, January and February. This feature confirms the finding in Chapter 6, that climate change is expected to have greatest impact on those Mkomazi Catchment water resources where there is greatest water availability for enhanced plant evapotranspiration.

9.3.3.2 Assessment of high flow requirements at IFR Site 2

Figure 9.5 shows that flows at IFR Site 2 meeting the freshes recommended at the start of the wet season (October to December) for either drought or maintenance flow requirements are equalled or exceeded at least 50% of the time under both baseline conditions and present land use. This suggests that there is sufficient flow in these months to meet the first of season pulse requirements for the 2 or 3-day durations specified. As at IFR Site 1, the occurrence of flows meeting the maintenance fresh requirements is less than that for the drought fresh requirements. In wetter months flows meeting the flood requirements are equalled or exceeded for a greater percentage of time from January to March. However, the BBM workshop flow values may have been set too high for the extreme maintenance flood event in February, since the occurrence of flows meeting 350 $m^3.s^{-1}$ in February is

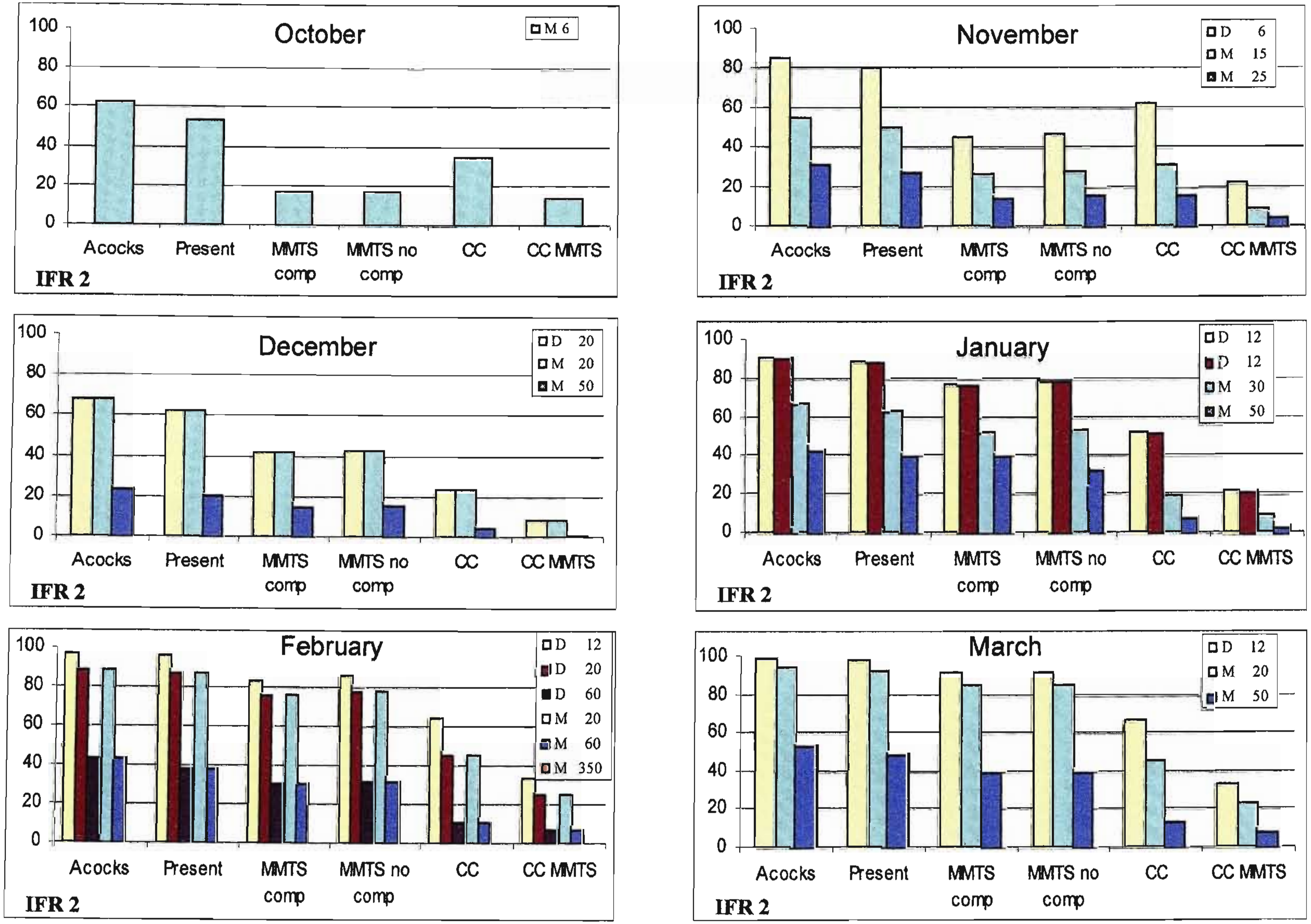

Figure 9.5 Percentage of time that the Mkomazi BBM Table high flow values are equalled or exceeded within each month at IFR Site 2 for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use, with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use, without and with the operation of Smithfield Dam respectively. D and M represent drought and maintenance high flow values respectively. The values for both D and M represent the flow in $m^3.s^{-1}$.

equalled or exceeded only 0.32% of the time in the *ACRU* generated Acocks' streamflows from 1945 to 1996.

The normal flow releases from the operation of MMTS in the wet season are, in fact, overflows from the Smithfield Dam, which would occur when the high flows upstream fill the dam storage. Consequently, there is no discernible difference between the simulated release / non-release scenarios in wet months. From January to March the MMTS flows meeting the high flow requirements recommended by the workshop are exceeded for almost as high a percentage of time as under present land use.

Although at the start of the wet season the impacts of climate change on the high flow requirements are less than the impacts due to the operation of the MMTS, the climate change impacts nevertheless exceed the impact due to the MMTS from December to March.

9.3.3.3 Assessment of high flow requirements at IFR Site 3

The occurrence of flows meeting the high flow requirements at IFR Site 3 (Figure 9.6) is similar to those at IFR Site 2 for all scenarios. There are, however, a few notable exceptions. The percentage of time at which the higher maintenance flood flows would be equalled or exceeded in January and March is less than 30% for all land cover and land use scenarios investigated suggesting that the BBM workshop process exercised stringency in this recommendation. Nonetheless, the flow requirements are for only 3 days within each of these months, implying that these events are still likely to be met for at least baseline conditions and present land use. Similar stringency appears to have been applied to the recommendation for the October maintenance fresh at this site. There are only two drought high flow requirements recommended for February and the higher of these would be equalled or exceeded 31% of the time under present land use, suggesting that there would probably be sufficient flows to sustain the five-day duration of this event.

Again there is no discernible difference between the two MMTS scenarios in the wettest months in meeting high flow requirements. This is because of the overflow releases from Smithfield Dam.

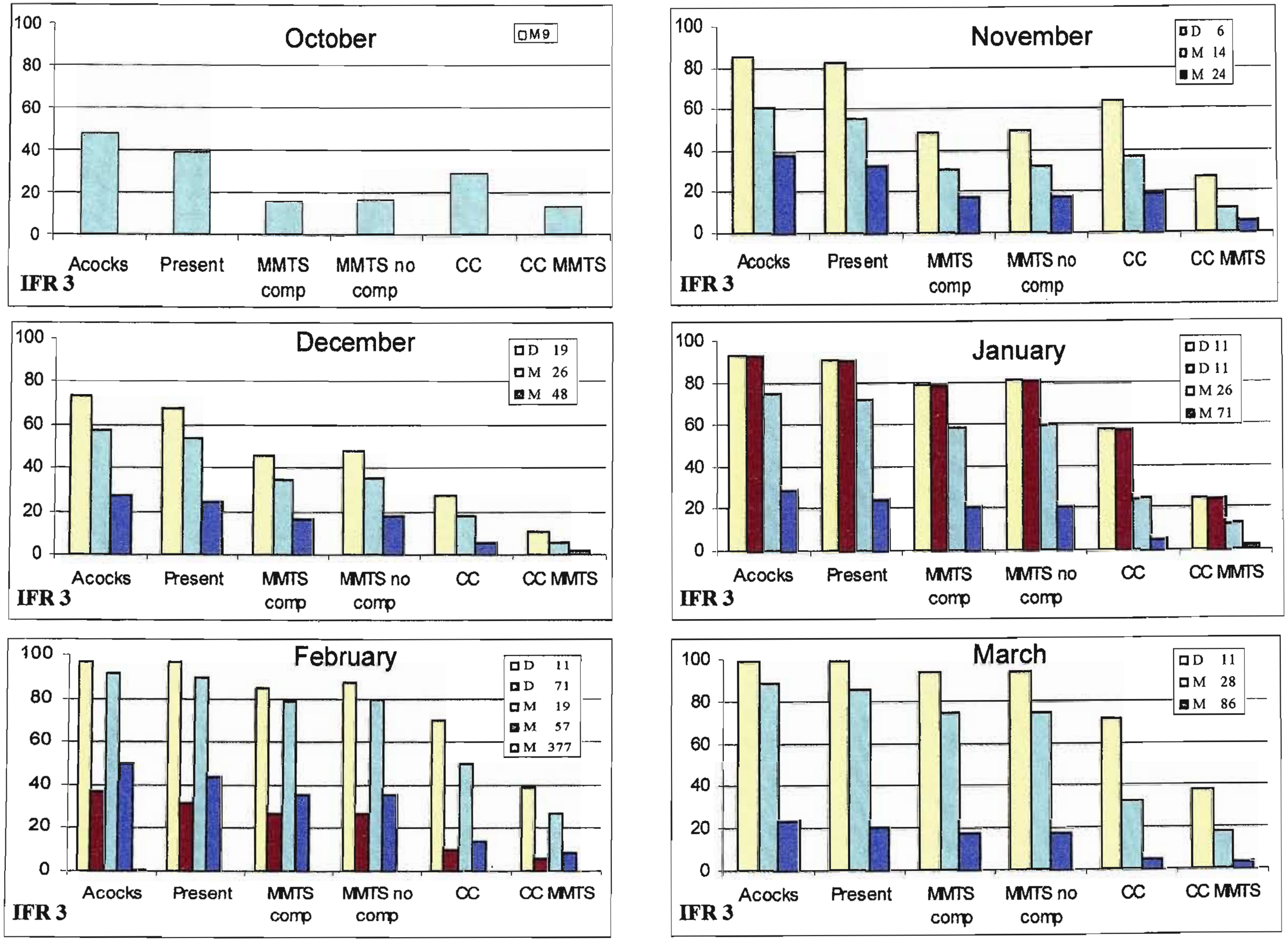

Figure 9.6 Percentage of time that the Mkomazi BBM Table high flow values are equalled or exceeded within each month at IFR Site 3 for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use without and with the operation of Smithfield Dam respectively. D and M represent drought and maintenance high flow values respectively. The values for both D and M represent the flow in $m^3.s^{-1}$.

Under climate change conditions at IFR Site 3, the occurrence of flows meeting the recommended drought fresh requirement would generally be equalled or exceeded 28% of the time in December. Flows meeting the drought flood requirement would be equalled or exceeded 70% of the time in both February and March. Flows meeting the lower maintenance flood requirement would be equalled or exceeded between 25% and 50% of the time in the wettest months (January to March). Flows meeting the drought flood requirement of 71 $m^3.s^{-1}$ would not be equalled or exceeded above 10% of the time in February. However, the specified duration for this event is 5 days implying that this requirement is unlikely to be met on a regular basis. Flows to meet the higher maintenance flood requirement in the wettest months would be equalled or exceeded between 5% and 14% of the time.

The occurrence of flows meeting the extreme flood event of 377 $m^3.s^{-1}$ in February is equalled or exceeded only 0.34% of the time in the *ACRU* generated baseline streamflows 1945 to 1996 at this site, once again indicating that the BBM recommended flow values may have been set too high for this event.

9.3.3.4 Assessment of high flow requirements at IFR Site 4

Generally, the high flow requirements recommended by the BBM workshop are equalled or exceeded for a similar percentage of time in each month at this IFR site compared with the others. Figure 9.7 indicates that streamflows from both baseline and present land cover are virtually sufficient to meet the lower drought flood requirements throughout the months of January, February and March. Moreover, the lower maintenance flood requirements recommended are all but met throughout the months of February and March under both baseline and present land cover conditions.

In February, flows meeting the higher maintenance flood event are equalled or exceeded 52% and 45% of the time under baseline and present land cover respectively, but this is reduced for all other months (minimum 21% in December). Nonetheless, it is still possible that this event may be met under present land use even in December for the 3-day duration specified. The extreme flood event of 400 $m^3.s^{-1}$ required in February is equalled or exceeded only 0.55% of the time in the *ACRU* generated baseline streamflows from 1945 to 1996 at this site. As expected there is no discernible difference between the MMTS

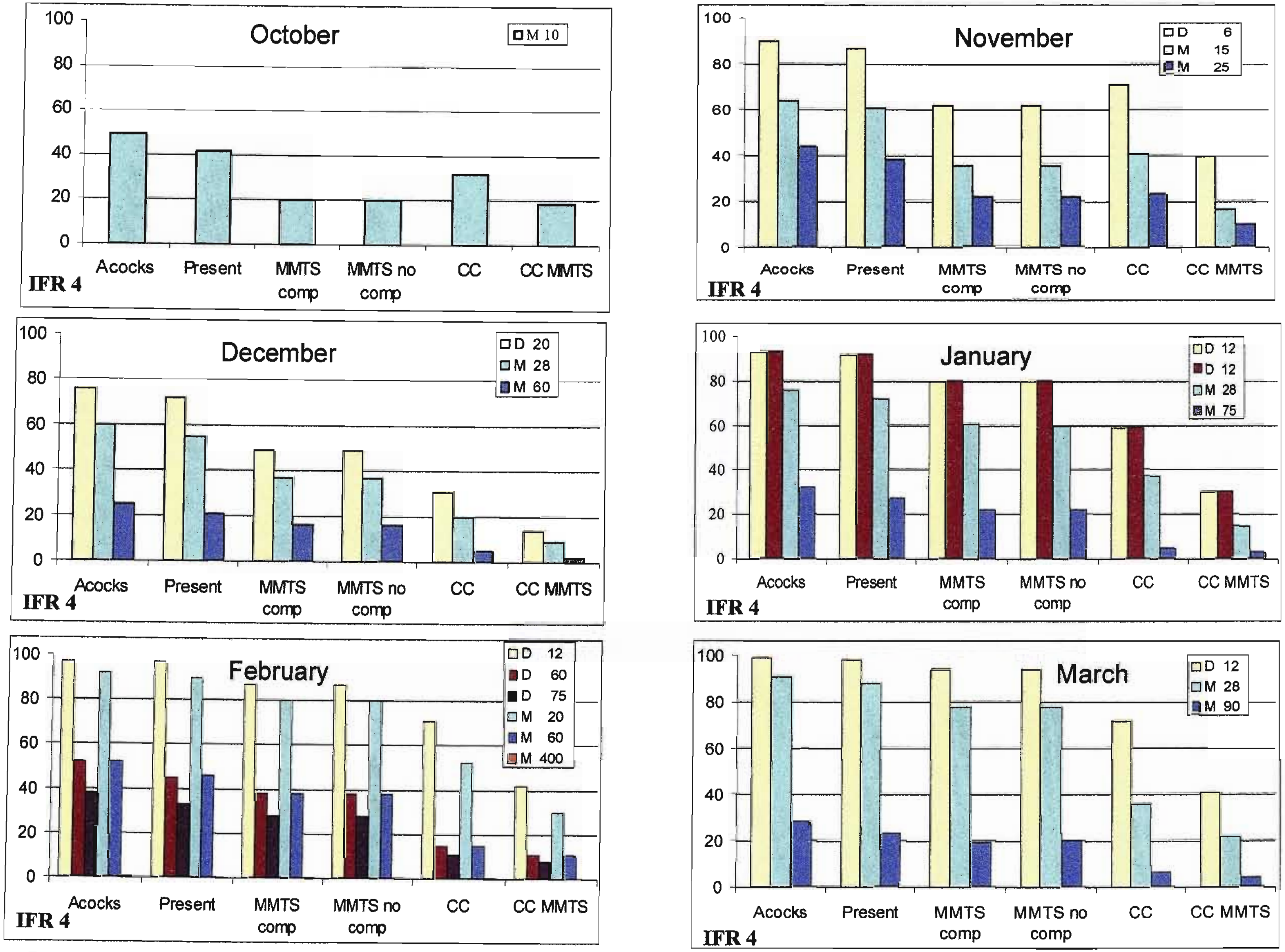

Figure 9.7 Percentage of time that the Mkomazi BBM Table high flow values are equalled or exceeded within each month at IFR Site 4 for various land cover, use and development scenarios, simulated with the *ACRU* model. Acocks and Present represent baseline and present land use respectively. MMTS comp and MMTS no comp represent the operation of Smithfield Dam with present land use, with and without normal flow releases respectively. CC and CC MMTS represent climate change conditions, but with present land use, without and with the operation of Smithfield Dam respectively. D and M represent drought and maintenance high flow values respectively. The values for both D and M represent the flow in m^3.s^{-1}.

scenarios investigated, for the same reasons as given in Sections 9.3.1.1 to 9.3.3.3 given above.

As at the other IFR sites, the impact of climate change conditions on the occurrence of flows meeting the high flow requirements recommended by the BBM process at the start of the wet season is less than that of the operation of the MMTS. In the wettest months, streamflows resulting from climate change conditions would be severely impacted, with virtually no water available for any of the flood events.

9.3.4 Conclusions regarding the assessment of the BBM workshop high flow requirements

The assessment of this study indicates that the high flow requirements determined by the BBM process for all four sites would be equalled or exceeded for a higher percentage of time than the workshop predictions indicate. This is attributable to possible discrepancies between the approaches used by the two studies and to the *ACRU* generated series simulating higher daily natural flows than the time series used at the BBM workshop. Whilst, as would be expected, the specialists have determined higher maintenance than drought high flow requirements, the assessment in this study indicates that their evaluations of the higher drought floods required in only in February are high at all four sites, with low likelihood of occurrence compared to the drought high flow requirements for the other months. The BBM extreme flood events required for channel and habitat maintenance have been set so high that they are likely to occur in the natural flow regime at only very low percentages of time at any of the sites.

The flow requirements for the start of the wet season maintenance fresh in October have been set with lowest achievability at IFR Site 3. This implies that the workshop process was influenced by the degraded present state class of the river reach upstream of this site and recommended flows to improve the management class.

9.4 Conclusions Regarding the Assessment of the BBM Mkomazi Workshop

The BBM process is intended to conserve the trends of the natural flow regime. However, the generally high occurrence of flows under present land use meeting the baseflow requirements indicates that the BBM recommendations may have been set too low to improve the present state class of the river to a higher management class upstream of all four sites. The extreme flood requirements of the wet season appear to have been overestimated since they are represented in the natural flow regime at only very low percentages of time at all four IFR Sites and there may be a need to reassess this requirement.

These factors are indicative of the difficulties in prescribing flows to enhance the river condition to a management class higher than it is at present, while simultaneously ensuring sufficient variability in the flow regime. However, the time series of daily streamflows applied in this study were generated differently to those used in the BBM workshop process (cf. 8.2.6.1 to 8.2.6.3). This is likely to be an important contributing factor to the differences between the two assessments of the instream flow requirements.

9.5 Addendum

Following this analysis, it came to light that the values in the BBM IFR Tables for Sites 3 and 4 (*cf.* Appendix B, Tables B4 and B5) were subsequently refined and amended from those applied in this study. Unfortunately time constraints prohibited the repetition of the analysis in the detail described above. Moreover, the amended tables contain information at a much sparser level than those used in this study.

However, for both IFR Sites 3 and 4 the *refined* flow requirements for both the maintenance and drought baseflows are generally lower than those used in this study. This implies that there would be even greater expectancy that the baseflow requirements at IFR Sites 3 and 4 would be achieved, under each of the scenarios investigated. For both IFR Sites 3 and 4, the *refined* flow requirements for both the maintenance and drought high flows are higher than those used in this study. Consequently, there is less likelihood that these flows would occur under any of the scenarios investigated and, as such, the successful implementation of these refinements may go some way to the enhancement of the river reach upstream of these sites.

Furthermore, the *refined annual volumes* of flows, required at both IFR Sites 3 and 4, are *slightly* higher than those applied in the water allocation study in Chapter 8. The consequence of this is that the annual portion of Mkomazi flows required as a water allocation for the environment would be slightly higher than that reported in this study. However, the order of magnitude of the values reported remains the same.

Finally it would prove extremely useful for further research if the following information could in future always be provided for the BBM recommended high flow requirements:

(a) The full flood hydrograph details for each recommended flood event from which can be obtained the instantaneous peak flow, the average daily flow for each day of the event, and hence the total volume of the event as well as the duration of the event.

(b) The flow duration percentiles for each recommended event (i.e. no missing data).

The provision of the data in (a) above would, in combination with the *ACRU* simulated daily streamflows, allow the probability of occurrence of the event as a whole to be assessed.

* * * * *

The following chapter investigates the hydrological regime of the Mkomazi River to ascertain its natural flow variability, and to assess how much alteration is likely under development of the Mkomazi Catchment.

10 ASSESSING THE ALTERATION OF THE NATURAL FLOW REGIME OF THE MKOMAZI RIVER

10.1 Introduction

Hydrological regimes play an important role in determining the biotic composition, structure, and functioning of aquatic and riparian ecosystems (Richter *et al.*, 1996). As described in Chapter 3, inter-annual variation, reflecting all aspects of the hydrological regime, is essential to maintaining streamflow conditions for the survival of many aquatic and riparian species. Section 3.4.1 described the limitations of applying annual or monthly percentages of historical flows to the assessment of instream flow requirements of aquatic ecosystems. However, the concept of analysing the streamflow regime statistically for hydrologically relevant indicators of variation poses a viable option in planning ecosystem management activities, and in setting and monitoring protection objectives (Richter *et al.*, 1996).

In this chapter the daily streamflow regime of the Mkomazi River at each of the four IFR sites described in Chapters 8 and 9 will be analysed statistically to assess the extent of alteration imposed on the flow regime by anthropogenic development. This will be performed by comparing the *ACRU* daily simulated streamflows under baseline land cover conditions with the *ACRU* daily simulated post-development streamflows.

10.2 Assessment of Indicators of Variability within Hydrological Regimes

The link between hydrological variation and the extent of biotic diversity in aquatic ecosystems is well known (Richter *et al.*, 1997; Hughes, 1999a). This fundamental feature, that variations in river flow control habitat conditions within the channel, floodplain and hyporheic zones, renders historical streamflow records useful, provided that they are of sufficient length and of quality for analysis (Richter *et al.*, 1996; 1997).

A method for assessing the extent of human induced hydrological changes to aquatic ecosystems was proposed by Richter *et al.* (1996), based on the analysis of hydrological data from existing streamflow measurements or, alternatively, from information generated by a hydrological simulation model. The methodology, the Indicators of Hydrologic Alteration (Richter *et al.*, 1996), is a statistical analysis of 32 hydrological parameters, representing 5 groups of streamflow characteristics, which can be attributed to playing major roles in determining the nature of aquatic and riparian ecosystems. A summary of the parameters, and their characteristics, used in the Indicators of Hydrologic Alteration (IHA) is provided in Table 10.1. The analysis statistically characterises inter-annual variation in flow regimes and, because the methodology uses daily mean streamflow rates, it is suitable for detecting the hydrological characteristics relevant to sustaining aquatic ecosystems.

Therefore, the goal of the methodology is to characterise the temporal variation in hydrological conditions using attributes that are hydrologically relevant, yet sensitive to anthropogenic influences such as land use change and modifications such as irrigation abstraction and impoundment. The benefit of the methodology is that it quantifies the hydrological alteration associated with the transition from pre-system impacts (natural flow regime or from current land use conditions) to post-system impacts (simulated modification).

The five biologically relevant groups representing characteristics of the hydrological regime are:

(a) The ***magnitude*** of the water condition, *i.e.* the amount of water passing a point in a river at a point in time, measured in units of $m^3.s^{-1}$. The magnitude of flows is a measure of habitat availability, or suitability, in terms of wetted perimeter area or habitat volume.

(b) The ***timing*** of occurrence, *i.e.* the time of year at which particular flow events such as floods or low flow extremes occur. The timing determines whether certain life-cycle requirements are met and introduces variability in ecosytems through stress and mortality.

(c) The ***frequency*** of occurrence, *i.e.* how often specific conditions such as floods or droughts occur. The frequency can be related to reproduction and / or mortality events for particular species, influencing intra-community population density and distribution.

Table 10.1 Summary of hydrological parameters used in the Indicators of Hydrologic Alteration (IHA) and their characteristics (after Richter *et al.*, 1996)

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

(d) The ***duration*** of occurrence, *i.e.* the length of time over which a particular flow condition lasts. The duration determines whether a particular life cycle can be completed; alternatively, whether it influences the extent to which species can tolerate environmental stress.

(e) The ***rate of change*** is a measure of how quickly streamflows rise and fall between consecutive days. The rate of change can lead to the stranding of individuals in riffles and pools; additionally it influences the ability of riparian vegetation to maintain root contact with river channel water.

Of the 32 parameters, 16 (Groups 2, 3 and 4) focus on the magnitude, duration, timing and frequency of *extreme events* to account for the influence of these events in ecosystems. The other 16 (Groups 1 and 5) are measures of the *mean* of the magnitude; alternatively, the rate of change of water conditions. The following sub-sections describe each of the five fundamental groups and the associated statistical parameters given by Richter *et al.* (1996).

10.2.1 Magnitude of flows (Group 1)

The magnitude of the monthly mean of daily flows represents normal daily flow conditions for the month and is indicative of the general amount of flow required for habitat availability and suitability. Intra-annual similarities in monthly means are a measure of relative constancy within streamflow conditions, whereas inter-annual similarities or variance are measures of the degree to which flows may vary within a particular month.

10.2.2 Magnitude and duration of annual extreme conditions (Group 2)

The magnitude and duration of extreme (highest and lowest) annual conditions are a measure of the different environmental disturbances, or stresses, that can occur throughout the year. The durations were selected by the developers of the methodology to represent natural or human induced cycles and comprise the 1-day, 3-day, 7-day (weekly), 30-day (monthly) and 90-day (seasonal) extremes. The 1-day events are the maximum and minimum values that occur in any given year and the multi-day events are the means of the highest and lowest multi-day average occurring in any given year. The inter-annual variance in the magnitude of these extremes influences the extent to which environmental variation occurs within ecosystems.

10.2.3 Timing of annual extreme conditions (Group 3)

The Julian date of the 1-day annual highest and lowest extreme represents the timing of the highest and lowest extreme conditions within annual cycles and provides another measure of the seasonal nature of environmental stresses or disturbances. The timing of these flows can influence the life cycles of aquatic organisms. The inter-annual variance in the timing of these extremes influences the extent to which environmental variation occurs within ecosystems.

10.2.4 Frequency and duration of high and low pulses (Group 4)

The number of occurrences during which the magnitude of streamflows exceeds an upper threshold or falls below a lower threshold within an annual cycle, and the mean duration of such occurrences (pulses) together reflect the pulsing behaviour of environmental variation within a given year. Richter *et al.* (1996) define the high pulses as those periods within a year when the daily streamflow rises above the 75th percentile of all daily values, and the low pulses as those periods within a year when the daily streamflow falls below the 25th percentile of all daily values.

In this Chapter and in Chapter 11 the term percentile is defined as "the value dividing a set of data arranged in an order of magnitude into one hundred equal parts" (Boxer, 1961). Hence the 25th and 75th percentiles correspond to the first (lowest) and third (highest) quartiles respectively.

10.2.5 Rate and frequency of change in conditions (Group 5)

These parameters measure the rate and frequency of hydrograph changes by measuring the number and mean rate of both positive and negative changes in the streamflow from one day to the next. Measurement of these parameters indicates the fluctuation of the intra-annual cycles of environmental variation and reflects the extent of the rate and frequency of the intra-annual environmental change.

10.3 Assessing Hydrological Alteration

The IHA method of assessing the impacts of land use change or development issues, is based on comparing the hydrological attributes of a site before and after the perturbation (Richter *et al.*, 1996). Two time series of streamflows, either recorded or simulated using a hydrological model, are required, one for the period before the perturbation and the other initiated after the perturbation. The pre- and post-impact representations of the hydrological regime are then characterised and a statistical comparison between the two time series can be made for any of the 32 IHA parameters. The comparison assumes tests of null hypotheses that neither the means nor the distribution of the values in each has changed. However, the developers of the IHA methodology state that the assessment of the effects of the perturbation, by detecting the extent of thresholds of change in the hydrological regime and their potential biological importance, outweighs any consequence attached to hypothesis testing. To warrant the soundness of the statistical comparison derived from the methodology, the developers suggest that a minimum of 20 years of data is required to temper the effects of inter-annual climatic variation on the IHA parameter statistics (Richter *et al.*, 1997). This is based on research by Poff (1996) that showed that the range of estimates of the mean annual 1-day maximum of three streams representing different stream types begins to narrow substantially when based on at least 20 years of record.

However, for southern African conditions, where statistical analyses can be influenced by a particularly wet or dry spell of years, especially where periodic fluctuations with approximately 20-year oscillations have been identified (Tyson, 1987), longer record lengths may be required (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995). Schulze, Dent, Lynch, Schäfer, Kienzle and Seed (1995) have produced a map for southern Africa indicating the minimum record lengths required to ensure that the means of annual rainfall estimates are within 10% of the long term mean 90% of the time. Furthermore, they surmise that for a daily model such as *ACRU* the ideal minimum record lengths require to be double those for MAP. For the region comprising the Mkomazi Catchment, they suggest a minimum MAP record length of 20 years. Hence a 40-year record of simulated daily rainfall would be considered acceptable for statistical analyses.

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

(a) at streamflow gauging station X2H010 on the Noordkaap River in the Northern Province

(b) at Schoolplaats streamflow gauging station C9H008 downstream of the Vaalharts Dam and

(c) at IFR Site 2 on the Mkomazi River, comparing the naturalised streamflow assumed to occur at the IFR site, with streamflow generated using the IFR model developed by Hughes *et al.* (1997) for pre- and post-dam construction.

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

10.4 Assessing the Impacts of Hydrological Alteration on the Mkomazi River

A summary hydrograph of the *ACRU* simulated daily Acocks' streamflows at the four IFR sites on the Mkomazi River for the period October 1945 to September 1996 is shown in Figure 10.1. The 1-day maximum has been omitted so that comparison of the range of the percentiles of the daily flows selected can be seen more easily. As expected, the range between each percentile increases downstream as the magnitude of the streamflows increases. The daily mean is always higher than the daily median value and in periods of extreme flood events (*e.g.* May 1959, and September 1987) is similar to, and sometimes higher than, the 90th percentile. Thus the climatic variability experienced in the Mkomazi Catchment fully substantiates the use of non-parametric statistical parameters for analysing the inter-annual variation of the streamflows occurring at the four Mkomazi IFR sites.

The IHA methodology was applied to an assessment of the impacts of land use change and development on each of the four IFR sites on the Mkomazi River. Because IFR Site 1 is situated upstream of the proposed Smithfield Dam, an assessment was made of the impacts of present land on the natural flow regime. This was achieved by comparing the time series of the *ACRU* simulated baseline streamflows (*cf.* Section 4.11.1) with that of the *ACRU* simulated streamflows for present land use (*cf.* Chapter 4). Each of IFR Sites 2, 3, and 4 are downstream of the proposed Smithfield Dam, and the impacts of Phase 1 of the MMTS (*cf.* Section 4.11.2) were assessed by comparing the time series of the *ACRU*

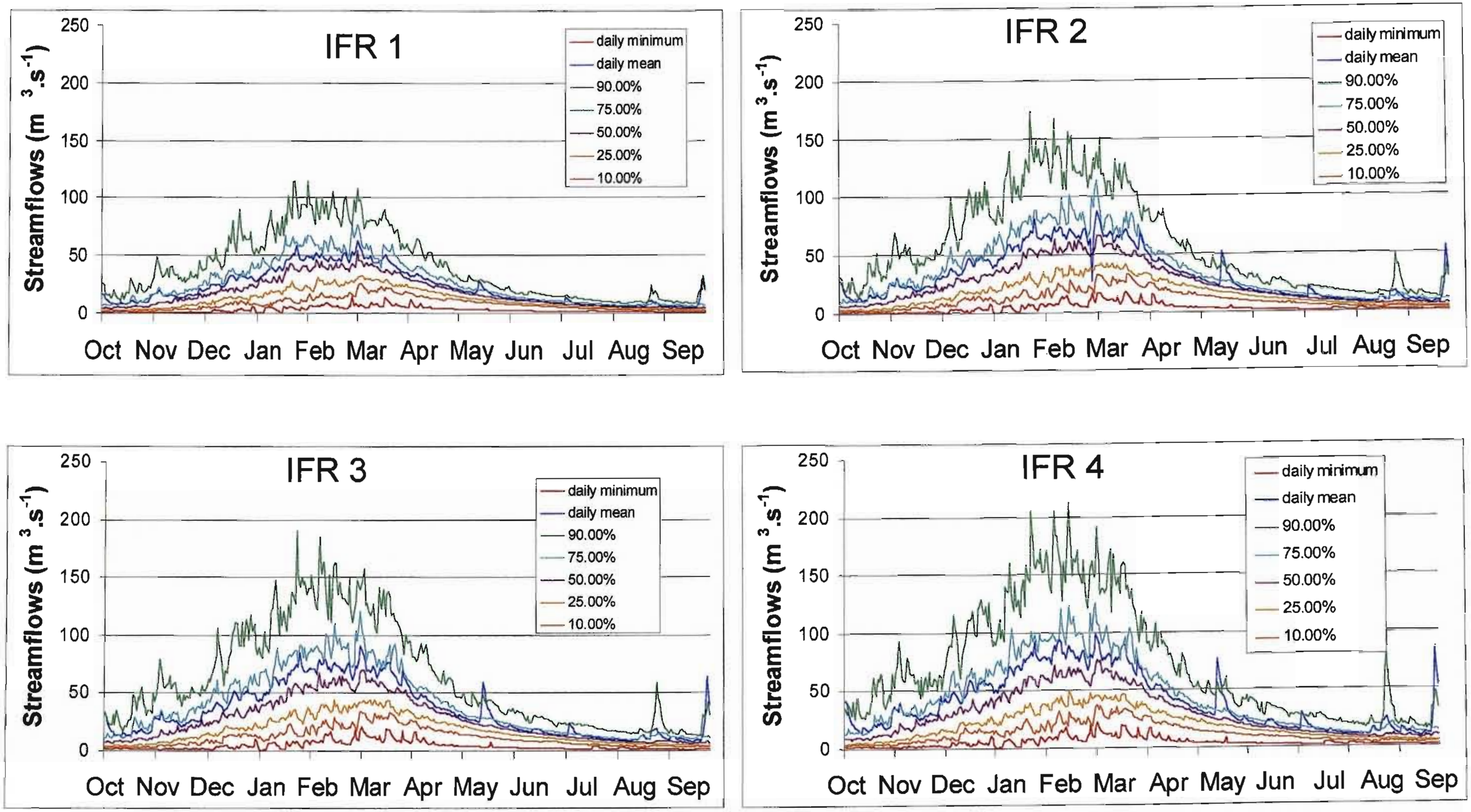

Figure 10.1 Summary hydrographs for *ACRU* simulated daily Acocks streamflows at IFR Sites 1, 2 , 3 and 4 on the Mkomazi River for the period 1945 - 1996.

simulated baseline streamflows with the time series of the *ACRU* simulated Phase 1 of the MMTS streamflows at each site using rainfall data recorded for the period October 1945 to September 1996. In order to compare the impacts of land use on streamflows before the construction of the dam with the impacts of the MMTS on streamflows, each of the comparisons was made by assuming a hypothetical continuous time span from October 1894 to September 1996, separating the two time series of simulated streamflows with "the impact". This was achieved by using the same climatic information for both pre- and post-impact time periods, *i.e.* the climatic information for October 1945 to September 1996 (the post-impact period) was also applied to the October 1894 to September 1945 (the pre-impact period).

For each of the comparisons performed, the IHA methodology was applied using non-parametric statistical analysis, *i.e.* the analyses were based on percentile distributions of data. The IHA parameters are calculated for the 10th, 25th, 50th, 75th and 90th percentiles for each IHA parameter for both the pre- and post impact periods. The results of each analysis are presented in the following formats:

(a) A primary summary scorecard, examples of which are provided in Tables 10.2 to 10.5, for the analysis of the comparisons, and containing the following parameters pertaining to the relevant period of analysis (pre or post impact):

- median annual flow
- annual coefficient of variation
- percentage of floods that occur during a given 60 day period in all years
- length of flood free season.

Columns 1 and 2 show the median for each of the two periods. Columns 3 and 4 show the coefficient of dispersion for each period, defined as (75th percentile – 25th percentile) /50th percentile. Columns 5 and 6 show the deviation of the post- from the pre-impact, defined as [(post-impact value) – (pre-impact value)] / (pre-impact value)]. Columns 7 and 8 calculate a significance count for the deviation values, based on the probability of the dispersion of the value from randomised recalculations of all years of data.

(b) Percentile statistics, an example of which is provided in Table 10.6, for the analysis of all the comparisons: The first five columns show the 10th, 25th, 50th, 75th and 90th percentile values for the pre-impact period. The sixth column shows the value

Table 10.2 IHA Score Card: Mkomazi IFR Site 1

	Pre-impact period October 1894 - September 1945 (51years)	Post-impact period October 1945 - September 1996 (51 years)
Mean monthly flow (m^3)	22.62	22.24
Annual C. V. (%)	0.69	0.69
% of floods in 60d period	0.39	0.39
Flood-free season (days)	21	21

PARAMETER		MEDIANS		COEFFICIENT of DISPERSION		DEVIATION FACTOR		SIGNIFICANCE COUNT	
		Pre	Post	Pre	Post	Medians	Coefficient of variance	Medians	Coefficient of variance
Group 1	**Units**								
October	$m^3.s^{-1}$	6.50	6.00	1.29	1.34	0.07	0.04	0.53	0.86
November	$m^3.s^{-1}$	13.70	13.30	0.88	0.89	0.03	0.01	0.88	0.95
December	$m^3.s^{-1}$	22.40	21.80	0.84	0.83	0.03	0.01	0.76	0.97
January	$m^3.s^{-1}$	37.00	35.90	0.70	0.71	0.03	0.01	0.94	0.97
February	$m^3.s^{-1}$	44.30	42.90	0.64	0.67	0.03	0.04	0.72	0.90
March	$m^3.s^{-1}$	42.00	40.40	0.52	0.53	0.04	0.02	0.58	0.93
April	$m^3.s^{-1}$	27.60	27.20	0.53	0.54	0.02	0.02	0.89	0.93
May	$m^3.s^{-1}$	16.40	16.00	0.57	0.56	0.03	0.01	0.77	0.95
June	$m^3.s^{-1}$	11.10	10.60	0.45	0.46	0.05	0.02	0.72	0.95
July	$m^3.s^{-1}$	7.70	7.40	0.42	0.43	0.05	0.01	0.64	0.97
August	$m^3.s^{-1}$	5.80	5.40	0.68	0.69	0.07	0.02	0.48	0.92
September	$m^3.s^{-1}$	5.20	4.80	1.04	1.06	0.07	0.02	0.85	0.96
Group 2									
1-day minimum	$m^3.s^{-1}$	2.40	1.80	0.51	0.60	0.22	0.17	0.02	0.63
3-day minimum	$m^3.s^{-1}$	2.40	2.00	0.54	0.61	0.15	0.13	0.04	0.79
7-day minimum	$m^3.s^{-1}$	2.60	2.30	0.52	0.61	0.12	0.17	0.06	0.80
30-day minimum	$m^3.s^{-1}$	3.10	2.80	0.83	0.92	0.09	0.12	0.37	0.68
90-day minimum	$m^3.s^{-1}$	5.30	5.00	0.65	0.67	0.05	0.04	0.68	0.86
1-day maximum	$m^3.s^{-1}$	134.20	130.60	0.81	0.81	0.03	0.00	0.86	0.99
3-day maximum	$m^3.s^{-1}$	114.10	109.50	0.77	0.78	0.04	0.02	0.74	0.97
7-day maximum	$m^3.s^{-1}$	85.70	82.10	0.79	0.80	0.04	0.02	0.67	0.91
30-day maximum	$m^3.s^{-1}$	60.60	58.90	0.58	0.58	0.03	0.00	0.84	0.99
90-day maximum	$m^3.s^{-1}$	45.20	43.50	0.53	0.53	0.04	0.01	0.61	0.95
Number of zero days	number	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.12	0.45	0.44	0.07	0.03	0.20	0.90
Group 3									
Date of minimum	day	274	274	0.08	0.07	0.00	0.09	0.56	0.69
Date of maximum	day	40	40	0.15	0.15	0.00	0.00	1.00	0.98
Group 4									
Low pulse count	number	5.50	7.00	0.73	0.57	0.27	0.21	0.00	0.50
Low pulse duration	days	11.80	10.30	0.58	0.56	0.12	0.03	0.09	0.91
High pulse count	number	7.50	8.00	0.53	0.66	0.07	0.23	0.83	0.54
High pulse duration	days	9.80	9.50	1.31	1.13	0.03	0.14	0.81	0.61
Group 5									
Rise rate	$m^3.s^{-1}.day^{-1}$	8.30	5.40	0.51	0.47	0.35	0.07	0.01	0.74
Fall rate	$m^3.s^{-1}.day^{-1}$	-2.30	-2.70	-0.50	-0.55	0.19	0.10	0.08	0.79
Number of reversals	number	103.00	164.50	0.12	0.27	0.60	1.19	0.00	0.00

Table 10.3 IHA Score Card: Mkomazi IFR Site 2

	Pre-impact period October 1894 - September 1945 (51years)	Post-impact period October 1945 - September 1996 (51 years)
Mean monthly flow (m^3)	32.28	22.99
Annual C. V. (%)	0.66	0.89
% of floods in 60d period	0.38	0.38
Flood-free season (days)	21	33

PARAMETER		MEDIANS		COEFFICIENT of DISPERSION		DEVIATION FACTOR		SIGNIFICANCE COUNT	
		Pre	Post	Pre	Post	Medians	Coefficient of variance	Medians	Coefficient of variance
Group 1	**Units**								
October	$m^3.s^{-1}$	10.10	2.50	0.90	1.10	0.75	0.22	0.03	0.51
November	$m^3.s^{-1}$	21.70	6.70	0.70	2.02	0.69	1.89	0.03	0.00
December	$m^3.s^{-1}$	30.90	19.80	0.84	1.59	0.36	0.88	0.03	0.03
January	$m^3.s^{-1}$	52.80	42.00	0.83	1.05	0.20	0.27	0.15	0.41
February	$m^3.s^{-1}$	62.40	47.70	0.64	0.80	0.24	0.24	0.05	0.44
March	$m^3.s^{-1}$	59.60	48.40	0.65	0.76	0.19	0.17	0.11	0.45
April	$m^3.s^{-1}$	37.00	27.00	0.52	0.72	0.27	0.38	0.01	0.12
May	$m^3.s^{-1}$	22.20	12.60	0.47	0.79	0.43	0.70	0.00	0.01
June	$m^3.s^{-1}$	15.20	6.10	0.47	0.98	0.59	1.09	0.02	0.00
July	$m^3.s^{-1}$	10.50	2.60	0.52	1.01	0.75	0.95	0.05	0.04
August	$m^3.s^{-1}$	8.40	2.10	0.82	1.42	0.75	0.73	0.01	0.02
September	$m^3.s^{-1}$	7.70	2.00	1.03	1.17	0.74	0.13	0.00	0.68
Group 2									
1-day minimum	$m^3.s^{-1}$	3.30	1.20	0.72	0.15	0.62	0.79	0.01	0.01
3-day minimum	$m^3.s^{-1}$	3.30	1.30	0.74	0.15	0.61	0.80	0.01	0.01
7-day minimum	$m^3.s^{-1}$	3.80	1.30	0.56	0.17	0.64	0.69	0.02	0.00
30-day minimum	$m^3.s^{-1}$	4.60	1.50	0.67	0.24	0.68	0.64	0.02	0.02
90-day minimum	$m^3.s^{-1}$	7.10	1.80	0.71	0.87	0.74	0.22	0.03	0.40
1-day maximum	$m^3.s^{-1}$	222.30	201.80	0.75	0.75	0.09	0.00	0.58	0.99
3-day maximum	$m^3.s^{-1}$	181.80	164.90	0.87	0.73	0.09	0.16	0.59	0.58
7-day maximum	$m^3.s^{-1}$	129.00	113.60	0.85	0.78	0.12	0.09	0.39	0.68
30-day maximum	$m^3.s^{-1}$	87.30	74.20	0.73	0.83	0.15	0.13	0.17	0.68
90-day maximum	$m^3.s^{-1}$	65.60	52.80	0.64	0.80	0.19	0.25	0.07	0.24
Number of zero days	number	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.07	0.46	0.67	0.48	0.45	0.00	0.05
Group 3									
Date of minimum	day	278.5	274	0.08	0.06	0.02	0.27	0.51	0.20
Date of maximum	day	29	36	0.21	0.18	0.04	0.11	0.65	0.60
Group 4									
Low pulse count	number	6.00	7.00	0.83	0.71	0.17	0.14	0.15	0.63
Low pulse duration	days	11.60	19.00	0.68	0.76	0.64	0.11	0.00	0.69
High pulse count	number	8.00	9.00	0.63	0.69	0.13	0.11	0.35	0.68
High pulse duration	days	9.60	5.70	1.10	1.21	0.41	0.10	0.09	0.71
Group 5									
Rise rate	$m^3.s^{-1}.day^{-1}$	12.30	6.80	0.49	0.51	0.44	0.05	0.01	0.84
Fall rate	$m^3.s^{-1}.day^{-1}$	-3.70	-4.00	-0.45	-0.65	0.10	0.44	0.34	0.07
Number of reversals	number	104.50	169.50	0.14	0.12	0.62	0.20	0.00	0.34

Table 10.4 IHA Score Card: Mkomazi IFR Site 3

	Pre-impact period October 1894 - September 1945 (51years)	Post-impact period October 1945 - September 1996 (51 years)
Mean monthly flow (m^3)	34.66	24.85
Annual C. V. (%)	0.65	0.86
% of floods in 60d period	0.37	0.37
Flood-free season (days)	21	25

PARAMETER		**MEDIANS**		**COEFFICIENT of DISPERSION**		**DEVIATION FACTOR**		**SIGNIFICANCE COUNT**	
		Pre	**Post**	**Pre**	**Post**	**Medians**	**Coefficient of variance**	**Medians**	**Coefficient of variance**
Group 1	**Units**								
October	$m^3.s^{-1}$	11.00	3.40	0.85	1.00	0.69	0.18	0.07	1.09
November	$m^3.s^{-1}$	23.50	8.40	0.68	1.64	0.64	1.42	0.04	0.00
December	$m^3.s^{-1}$	33.20	21.10	0.80	1.50	0.37	0.87	0.04	0.07
January	$m^3.s^{-1}$	56.60	45.10	0.81	0.98	0.20	0.22	0.33	0.93
February	$m^3.s^{-1}$	65.30	52.40	0.67	0.78	0.20	0.17	0.15	1.08
March	$m^3.s^{-1}$	63.90	51.90	0.67	0.74	0.19	0.11	0.22	1.14
April	$m^3.s^{-1}$	39.30	29.00	0.50	0.69	0.26	0.37	0.03	0.23
May	$m^3.s^{-1}$	23.80	14.20	0.44	0.69	0.40	0.57	0.00	0.03
June	$m^3.s^{-1}$	16.20	6.80	0.47	0.95	0.58	1.01	0.04	0.01
July	$m^3.s^{-1}$	11.30	3.20	0.59	1.06	0.71	0.81	0.07	0.06
August	$m^3.s^{-1}$	9.20	2.50	0.86	1.49	0.73	0.73	0.01	0.05
September	$m^3.s^{-1}$	8.30	2.50	1.03	1.04	0.70	0.01	0.00	1.64
Group 2									
1-day minimum	$m^3.s^{-1}$	3.50	1.40	0.64	0.22	0.59	0.66	0.03	0.01
3-day minimum	$m^3.s^{-1}$	3.60	1.50	0.65	0.20	0.58	0.70	0.02	0.01
7-day minimum	$m^3.s^{-1}$	4.00	1.50	0.53	0.25	0.62	0.52	0.03	0.02
30-day minimum	$m^3.s^{-1}$	4.90	1.80	0.63	0.39	0.64	0.38	0.03	0.10
90-day minimum	$m^3.s^{-1}$	7.50	2.20	0.70	0.78	0.70	0.11	0.06	1.08
1-day maximum	$m^3.s^{-1}$	241.40	218.40	0.80	0.72	0.09	0.10	1.05	1.74
3-day maximum	$m^3.s^{-1}$	202.80	178.60	0.89	0.81	0.12	0.10	1.09	1.33
7-day maximum	$m^3.s^{-1}$	144.10	124.40	0.84	0.86	0.14	0.02	0.75	1.62
30-day maximum	$m^3.s^{-1}$	90.80	76.40	0.77	0.88	0.16	0.14	0.37	1.29
90-day maximum	$m^3.s^{-1}$	69.60	55.90	0.64	0.77	0.20	0.20	0.15	0.65
Number of zero days	number	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.07	0.47	0.58	0.43	0.24	0.01	0.34
Group 3									
Date of minimum	day	274	274	0.08	0.08	0.00	0.02	1.19	1.11
Date of maximum	day	36	36	0.22	0.18	0.00	0.16	1.62	1.03
Group 4									
Low pulse count	number	6.50	8.00	0.92	0.53	0.23	0.42	0.24	0.73
Low pulse duration	days	10.90	18.00	0.68	0.64	0.65	0.05	0.00	1.54
High pulse count	number	8.00	9.00	0.63	0.78	0.13	0.24	0.42	1.03
High pulse duration	days	9.30	5.70	1.03	1.35	0.38	0.31	0.17	0.84
Group 5									
Rise rate	$m^3.s^{-1}.day^{-1}$	13.80	7.70	0.46	0.49	0.44	0.05	0.01	1.66
Fall rate	$m^3.s^{-1}.day^{-1}$	-4.10	-4.30	-0.43	-0.63	0.04	0.45	0.96	0.15
Number of reversals	number	106.50	171.00	0.14	0.11	0.61	0.20	0.00	0.70

Table 10.5 IHA Score Card: Mkomazi IFR Site 4

	Pre-impact period October 1894 - September 1945 (51years)	Post-impact period October 1945 - September 1996 (51 years)
Mean monthly flow (m^3)	39.71	29.05
Annual C. V. (%)	0.64	0.78
% of floods in 60d period	0.34	0.34
Flood-free season (days)	11	24

PARAMETER		MEDIANS		COEFFICIENT of DISPERSION		DEVIATION FACTOR		SIGNIFICANCE COUNT	
		Pre	Post	Pre	Post	Medians	Coefficient of variance	Medians	Coefficient of variance
Group 1	**Units**								
October	$m^3.s^{-1}$	13.00	5.50	0.85	1.18	0.58	0.40	0.05	0.25
November	$m^3.s^{-1}$	26.40	12.30	0.68	1.23	0.53	0.81	0.04	0.02
December	$m^3.s^{-1}$	38.00	24.30	0.83	1.36	0.36	0.65	0.04	0.04
January	$m^3.s^{-1}$	62.30	49.20	0.80	1.02	0.21	0.27	0.18	0.34
February	$m^3.s^{-1}$	71.10	56.40	0.77	0.83	0.21	0.07	0.11	0.80
March	$m^3.s^{-1}$	70.60	56.60	0.67	0.77	0.20	0.16	0.10	0.51
April	$m^3.s^{-1}$	43.00	31.90	0.63	0.81	0.26	0.28	0.04	0.35
May	$m^3.s^{-1}$	26.00	15.50	0.49	0.76	0.40	0.57	0.00	0.03
June	$m^3.s^{-1}$	17.70	8.90	0.54	0.87	0.50	0.59	0.02	0.04
July	$m^3.s^{-1}$	12.30	4.60	0.62	0.93	0.63	0.50	0.01	0.08
August	$m^3.s^{-1}$	10.60	4.00	0.93	1.31	0.63	0.41	0.00	0.18
September	$m^3.s^{-1}$	9.90	4.00	0.94	0.96	0.60	0.02	0.00	0.94
Group 2									
1-day minimum	$m^3.s^{-1}$	4.10	1.80	0.57	0.39	0.56	0.32	0.00	0.08
3-day minimum	$m^3.s^{-1}$	4.20	1.90	0.60	0.36	0.55	0.40	0.00	0.03
7-day minimum	$m^3.s^{-1}$	4.70	2.00	0.46	0.37	0.58	0.19	0.00	0.36
30-day minimum	$m^3.s^{-1}$	5.70	2.40	0.51	0.53	0.59	0.04	0.05	0.88
90-day minimum	$m^3.s^{-1}$	8.40	3.10	0.69	0.84	0.63	0.22	0.02	0.36
1-day maximum	$m^3.s^{-1}$	283.40	239.90	0.77	0.77	0.15	0.01	0.22	0.98
3-day maximum	$m^3.s^{-1}$	233.50	197.50	0.86	0.71	0.15	0.18	0.16	0.71
7-day maximum	$m^3.s^{-1}$	167.60	137.90	0.75	0.85	0.18	0.14	0.12	0.71
30-day maximum	$m^3.s^{-1}$	103.70	88.00	0.74	0.83	0.15	0.13	0.22	0.63
90-day maximum	$m^3.s^{-1}$	77.80	61.10	0.67	0.79	0.21	0.18	0.08	0.50
Number of zero days	number	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.08	0.48	0.54	0.38	0.12	0.00	0.60
Group 3									
Date of minimum	day	275.50	273	0.07	0.08	0.01	0.14	0.51	0.66
Date of maximum	day	39	40	0.20	0.19	0.01	0.01	0.88	0.97
Group 4									
Low pulse count	number	7.00	9.00	1.00	0.47	0.29	0.53	0.01	0.04
Low pulse duration	days	10.40	15.90	0.73	0.65	0.53	0.11	0.00	0.75
High pulse count	number	9.50	9.00	0.53	0.58	0.05	0.11	0.60	0.72
High pulse duration	days	7.60	5.60	1.23	1.27	0.25	0.03	0.14	0.90
Group 5									
Rise rate	$m^3.s^{-1}.day^{-1}$	16.30	8.90	0.51	0.42	0.46	0.18	0.01	0.43
Fall rate	$m^3.s^{-1}.day^{-1}$	-5.00	-5.00	-0.42	-0.60	0.02	0.43	0.88	0.12
Number of reversals	number	112.50	170.00	0.14	0.12	0.51	0.17	0.00	0.31

Table 10.6 IHA Percentile Data: Mkomazi IFR Site 1

		Pre-impact period: October 1894 - September 1944 (51 years)						Post-impact period: October 1945 - September 1996 (51 years)					
		10%	25%	50%	75%	90%	$\frac{(75\%-25\%)}{50\%}$	10%	25%	50%	75%	90%	$\frac{(75\%-25\%)}{50\%}$
Group 1	**Units**												
October	m^3.s^{-1}	2.37	3.45	6.45	11.75	19.27	1.29	2.03	3.12	5.99	11.16	18.34	1.34
November	m^3.s^{-1}	4.38	8.67	13.69	20.71	35.74	0.88	4.15	8.30	13.25	20.09	34.96	0.89
December	m^3.s^{-1}	11.22	14.76	22.41	33.52	59.69	0.84	10.59	14.41	21.83	32.53	57.80	0.83
January	m^3.s^{-1}	11.56	25.25	37.02	51.29	76.40	0.70	11.20	24.28	35.87	49.76	74.23	0.71
February	m^3.s^{-1}	16.83	30.48	44.30	58.95	81.65	0.64	17.15	29.30	42.94	58.03	79.13	0.67
March	m^3.s^{-1}	21.98	31.27	41.97	53.06	67.56	0.52	21.49	30.17	40.35	51.63	65.46	0.53
April	m^3.s^{-1}	14.83	19.84	27.64	34.55	46.25	0.53	14.31	19.30	27.20	34.04	45.59	0.54
May	m^3.s^{-1}	9.30	12.67	16.42	21.98	29.12	0.57	9.07	12.43	16.00	21.36	28.59	0.56
June	m^3.s^{-1}	6.03	8.55	11.10	13.58	19.89	0.45	5.59	8.29	10.60	13.21	19.45	0.46
July	m^3.s^{-1}	4.07	6.30	7.75	9.57	13.38	0.42	3.69	5.95	7.36	9.09	12.85	0.43
August	m^3.s^{-1}	3.57	4.52	5.78	8.45	11.11	0.68	3.26	4.24	5.37	7.97	10.60	0.69
September	m^3.s^{-1}	2.92	3.57	5.16	8.94	11.28	1.04	2.60	3.20	4.79	8.26	10.75	1.06
Group 2													
1-day minimum	m^3.s^{-1}	1.04	1.96	2.38	3.18	4.71	0.51	0.73	1.45	1.85	2.56	4.28	0.60
3-day minimum	m^3.s^{-1}	1.10	1.99	2.41	3.29	4.77	0.54	0.79	1.60	2.04	2.85	4.47	0.61
7-day minimum	m^3.s^{-1}	1.40	2.18	2.62	3.55	4.89	0.52	1.06	1.79	2.31	3.20	4.61	0.61
30-day minimum	m^3.s^{-1}	2.00	2.25	3.07	4.78	6.67	0.83	1.68	1.97	2.80	4.55	6.32	0.92
90-day minimum	m^3.s^{-1}	2.83	3.67	5.26	7.08	9.06	0.65	2.51	3.41	4.97	6.75	8.96	0.67
1-day maximum	m^3.s^{-1}	77.31	102.15	134.20	211.18	310.31	0.81	74.56	100.14	130.60	206.00	303.87	0.81
3-day maximum	m^3.s^{-1}	69.72	85.76	114.10	173.45	272.55	0.77	67.58	82.47	109.50	167.94	267.24	0.78
7-day maximum	m^3.s^{-1}	48.97	65.60	85.73	133.12	204.16	0.79	47.05	63.30	82.06	129.23	200.03	0.80
30-day maximum	m^3.s^{-1}	26.41	45.75	60.64	81.04	112.66	0.58	25.40	44.22	58.89	78.60	109.82	0.58
90-day maximum	m^3.s^{-1}	23.64	36.04	45.20	59.90	74.72	0.53	22.74	35.06	43.54	58.35	72.78	0.53
Number of zero days	number	0	0	0	0	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.08	0.10	0.13	0.16	0.21	0.45	0.06	0.09	0.12	0.14	0.19	0.44
Group 3													
Date of minimum	day	238.10	268.75	274.00	297.50	308.80	0.08	237.20	265.00	274.00	291.25	305.90	0.07
Date of maximum	day	312.30	9.75	39.50	63.50	80.90	0.15	312.30	9.75	39.50	63.50	80.90	0.15
Group 4													
Low pulse count	number	2.00	4.00	5.50	8.00	10.90	0.73	3.10	6.00	7.00	10.00	13.00	0.57
Low pulse duration	days	4.45	8.65	11.77	15.46	19.20	0.58	3.81	6.96	10.34	12.74	15.15	0.56
High pulse count	days	4.00	6.00	7.50	10.00	12.00	0.53	4.00	5.00	8.00	10.25	13.80	0.66
High pulse duration	number	3.53	5.42	9.78	18.19	24.95	1.31	3.05	4.96	9.50	15.69	24.20	1.13
Group 5													
Rise rate	m^3.s^{-1}·day^{-1}	4.76	6.17	8.25	10.38	14.48	0.51	2.91	3.80	5.36	6.34	9.93	0.47
Fall rate	m^3.s^{-1}·day^{-1}	-4.34	-2.95	-2.30	-1.79	-1.41	-0.50	-4.90	-3.62	-2.73	-2.11	-1.83	-0.55
Number of reversals	number	91.10	96.75	103.00	109.50	117.90	0.12	141.10	148.50	164.50	193.00	202.60	0.27

of the coefficient of dispersion calculated as (75th percentile – 25th percentile) / 50th percentile. The last six columns show the same values for the post-impact period.

(c) Tables of annual summaries containing all the information given above, on a year-by-year basis: The tables are very large and consequently an example is not provided here. Suffice to say that these tables are particularly useful for analysing the annual variation in the IHA parameter values and comparing these with existing biological data.

(d) Graphs for each of the IHA parameters showing the pre- and post-impact periods, and the lines showing the median and the 25th and 75th percentile levels for each period.

10.4.1 Assessment of the indicators of hydrological alteration at IFR Site 1 on the Mkomazi River

The score card forming Table 10.2 shows that the impact of present land use on the natural hydrological regime at IFR Site 1 results in only slight reductions in the median flows for any calendar month. There is no discernible difference in the baseflow contribution and the period of lowest flows is 21 days under both baseline and present land use conditions.

There is little impact on the magnitude of multi-day extremes of streamflows, although the relative reductions in the multi-day minima are greater than those in the multi-day maxima. This indicates that while present land use has little substantial influence on the inter-annual variation of extreme events in the upper Mkomazi streamflows, extreme seasonal low flows have been abated. These factors concur with the findings in Chapter 6, *viz.* that the impacts of human induced change in the upper Mkomazi Catchment, which includes afforestation and irrigated agriculture as well as subsistence agriculture with degraded land in areas of rural settlement, have little influence on the overall catchment dynamics of the Mkomazi. The dates of the occurrence of both the daily minimum and maximum flows are identical, a result that can be partially attributed to the same climatic conditions being applied to both time series applied.

Figures 10.2 (a) and (b) show an increase in the number of low pulses as a result of present land use, yet the duration of these occurrences is shorter, indicating a change in the pattern

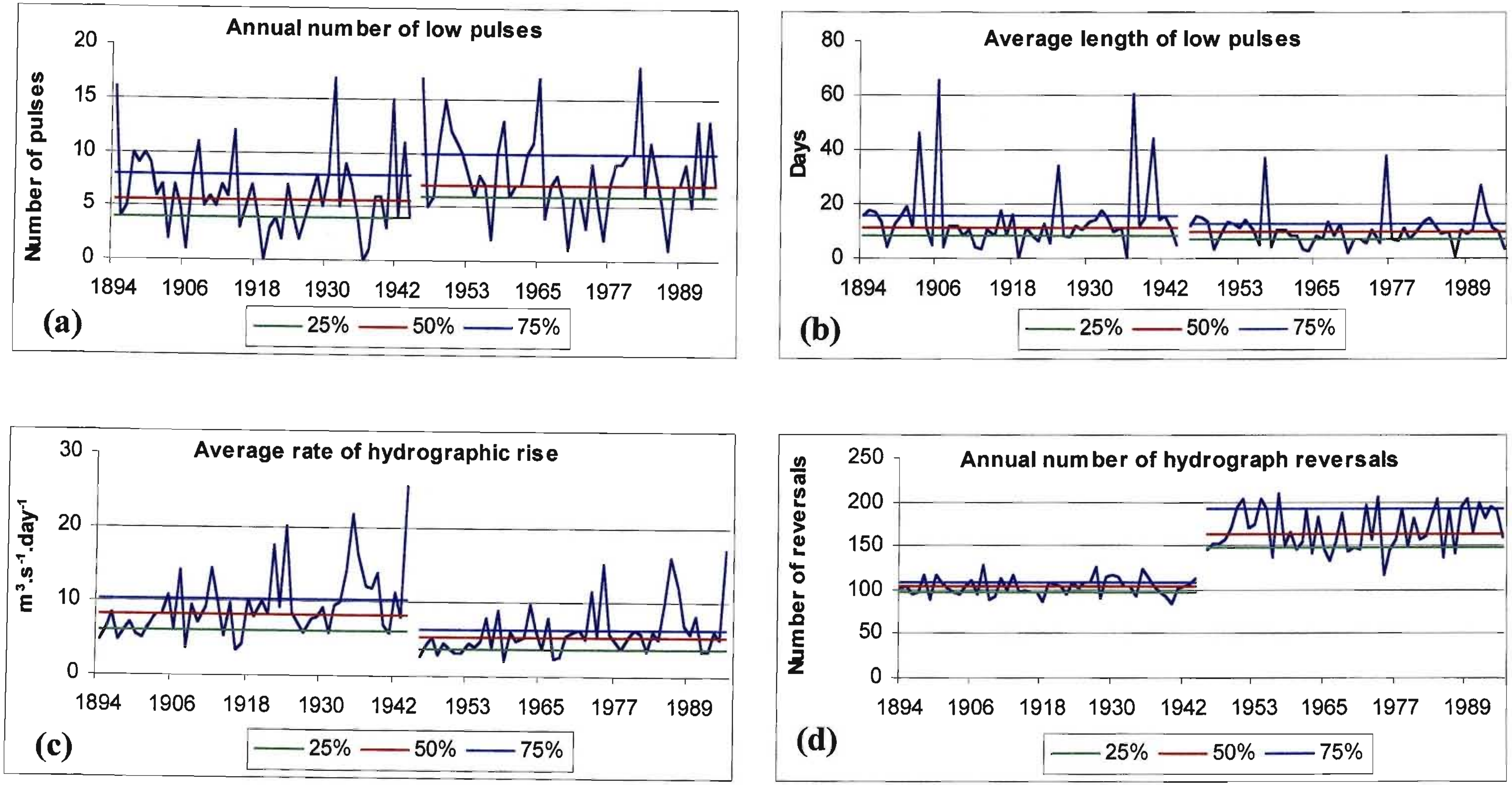

Figure 10.2 Examples of changes in the hydrological regime at IFR Site 1 on the Mkomazi River

of the low flows in winter months. Table 10.2 shows that the number and duration of high pulses are changed only slightly from those under baseline conditions, indicating that flood conditions generally remain unaltered. While the average rate of hydrographic rise, shown in Figure 10.2 (c), is diminished as a result of present land use practices, the number of reversals in the hydrograph as given in (Figure 10.2 (d) shows a substantial increase in both the inter- and intra-annual cycles of variation. This indicates that aquatic ecosystems are subjected to greater environmental stress as a result of present land uses. The IHA methodology program output gave the three greatest changes due to present land use on the hydrological regime at IFR Site 1 as:

(a) changes in the annual number of hydrograph reversals
(b) changes in the annual number of hydrograph falls and
(c) changes in the average rate of hydrographic rises.

10.4.2 Assessment of the indicators of hydrological alteration at IFR Site 2 on the Mkomazi River

Table 10.3 shows the impacts on the hydrological regime at IFR Site 2 as a result of changes in present land use practices from baseline conditions, and the construction of the Smithfield Dam for Phase 1 of the MMTS. Abstracting water to transfer to the Mgeni Catchment considerably reduces winter and early spring monthly streamflows at IFR Site 2. For example, Figure 10.3 (a) indicates that the 75th percentile of the average flow for July is reduced to below the 25th percentile previously experienced. This could impact severely on the health of the aquatic ecosystem at this site. The presence of the high peak at the end of each of the time series shown for July in Figure 10.3 (a) indicates the unseasonally high generation of streamflows resulting from a relatively heavy rainfall event and snowmelt in July 1996.

The baseflow contribution at IFR Site 2 is depressed, with all daily and multi-day minimum flows being reduced after the construction of the dam. This results in diminished intra-annual seasonal variation in winter streamflows. There is some reduction in the daily and multi-daily maxima flows and the timing of wet season is delayed. The number of low pulses, and the duration over which they occur is greater (Figure 10.3, b) after the construction of the dam. Except for a reduction in low flow years, the number of high pulses is very similar to those under pre-dam construction conditions (Figure 10.3, c), yet

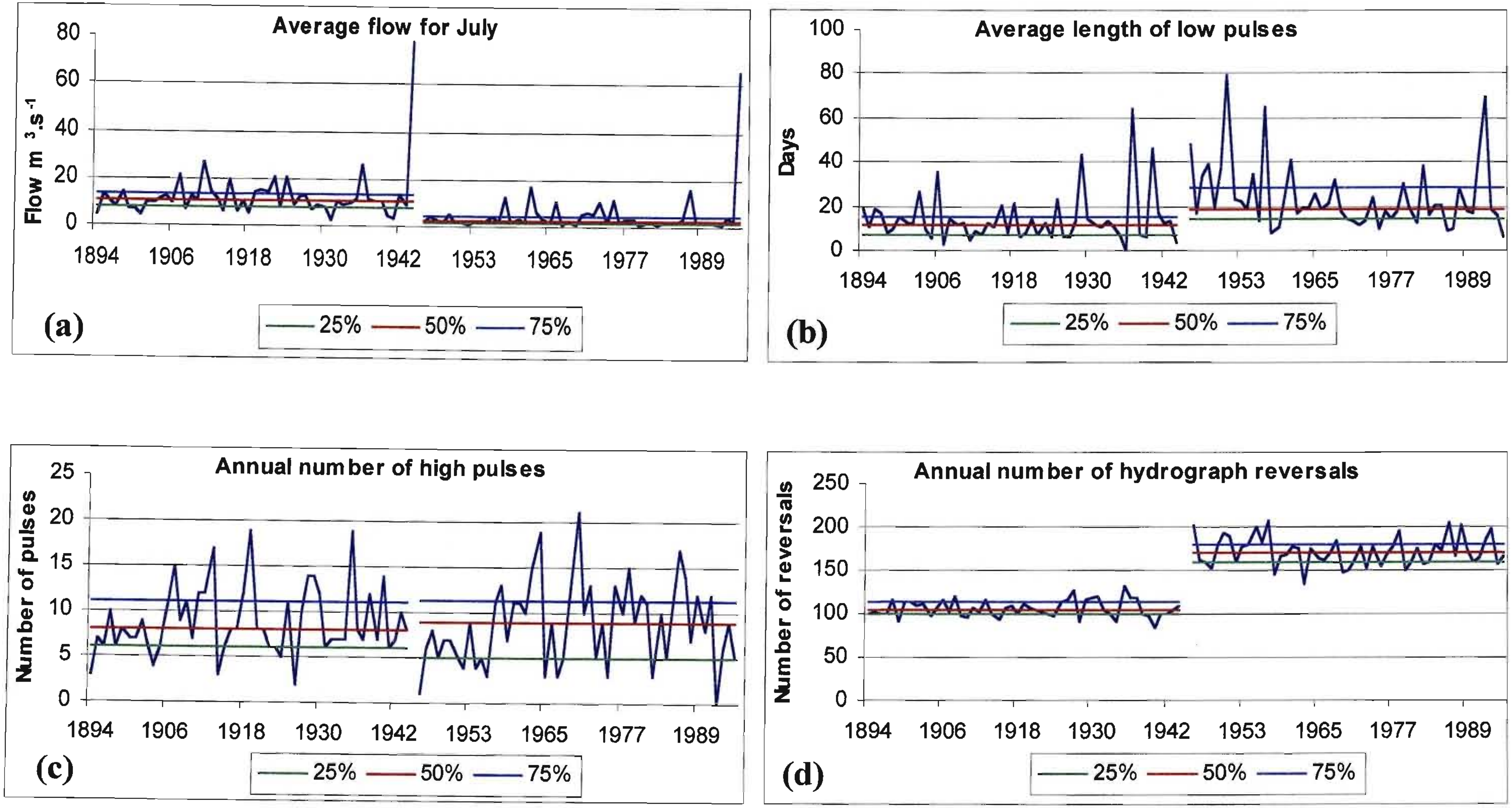

Figure 10.3 Examples of changes in the hydrological regime at IFR Site 2 on the Mkomazi River

their durations are shorter and the flood free season increases from 21 days to 33 days (Table 10.3). Winter low flows experience substantial modification in magnitude, occurrence and frequency as a result of present land use and Phase 1 of the MMTS.

The operation of Phase 1 of the MMTS with present land use reduces the rate of hydrographic rise because of attenuation of moderate to high flows by the dam in wet season months, and similarly the rate of hydrographic falls increases as a result of the attenuation of flows and irrigation abstractions in winter low flow months. Consequently, the number of hydrograph reversals is very much increased in post-dam construction conditions, as in Figure 10.3 (d), implying that the operation of Phase 1 of the MMTS with present land use would exert both additional intra- and inter-annual variation in the conditions to which aquatic organisms have become adapted at this site.

The IHA methodology program output gave the three greatest changes of development with the Smithfield Dam on the hydrological regime at IFR Site 2 as:

(a) changes in the average flow for July
(b) changes in the average flow for August
(c) changes in the average flow for October.

10.4.3 Assessment of the indicators of hydrological alteration at IFR Site 3 on the Mkomazi River

The impacts of the operation of Phase 1 of the MMTS with present land use on the change in the hydrological regime at IFR Site 3 are indicated in Table 10.4. The trends in the modification to the regime are similar to those at IFR Site 2, since the two sites are only some 20 km apart. However, the relative changes in the hydrological regime are generally less severe because contributions from the additional catchment drainage (drainage areas downstream from the dam sites are 886 km^2 and 1274 km^2 for IFR Sites 2 and 3 respectively) mitigate the impacts of the MMTS abstraction. Nonetheless, the greatest monthly flow reduction still occurs in winter, especially from June through September, and the smallest reduction occurs in February, shown in Figure 10.4 (a) and March as a result of overflows from the dam.

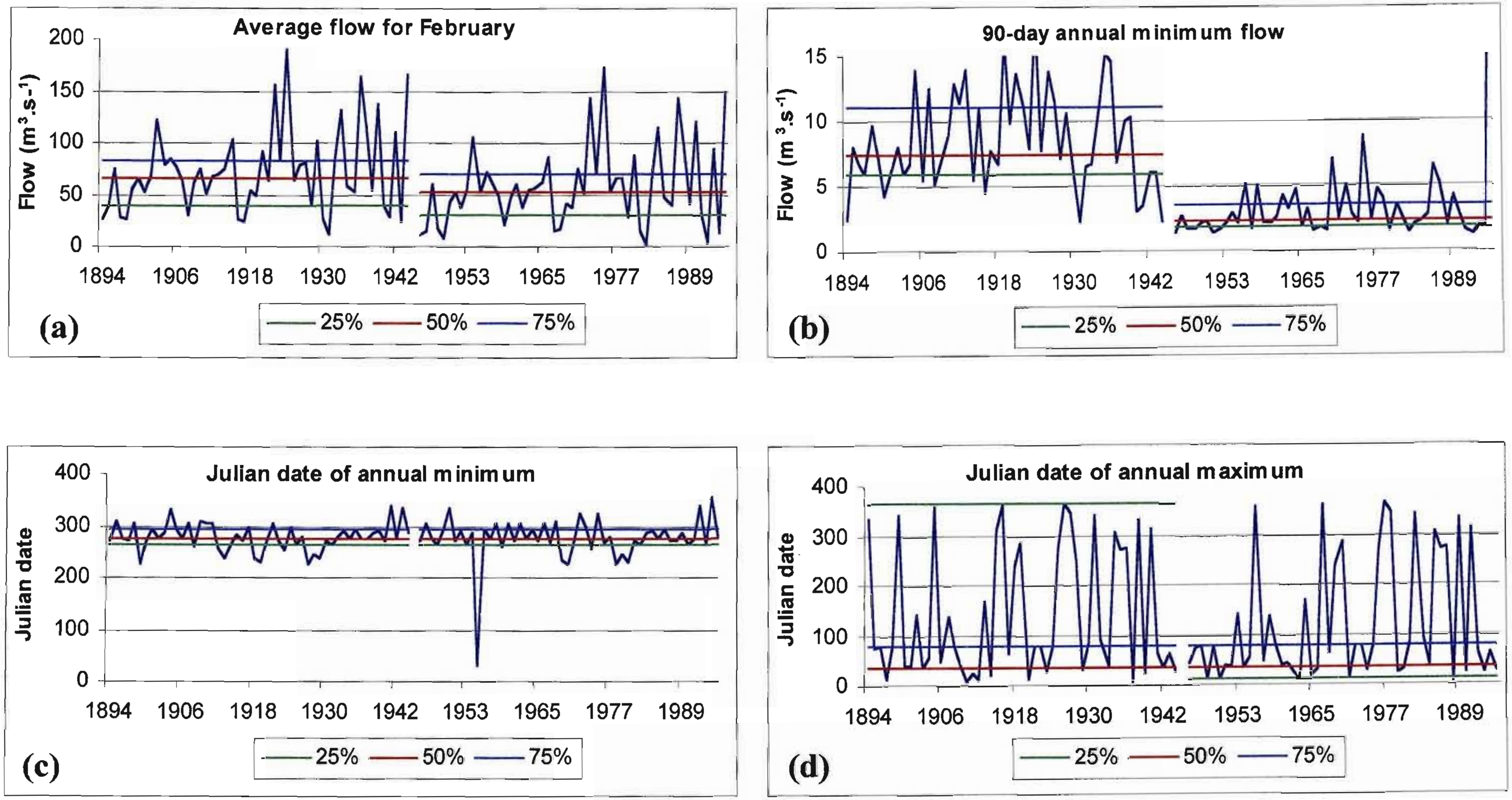

Figure 10.4 Examples of changes in the hydrological regime at IFR Site 3 on the Mkomazi River

Similarly to IFR Site 2, the baseflow contribution is reduced, as are the daily and multi-day minimum flows. This is shown for the 90-day minimum flow in Figure 10.4 (b). The average annual dates of both the daily maximum and minimum remain virtually the same in pre- and post-impact events, as illustrated in Figures 10.4 (c) and (d). However, the post-impact date of daily minimum flow for 1955 occurred in January rather than September / October as would be expected. *ACRU* simulations for January 1955 indicate low streamflow generation as a result of very dry spring / early summer climatic conditions. While the pre-impact time series of flows indicates that 13.75 $m^3.s^{-1}$ were simulated for 1905 (the equivalent year in the pre-impact time series), only 2.74 $m^3.s^{-1}$ were simulated in the post-impact time series of flows as a result of the operation of the dam abstractions and present land use. This was the minimum simulated monthly flow in the time series and consequently the minimum date for 1955 was unseasonally in January. Moreover, the maximum date occurs later in low flow years after the dam construction, as illustrated in Figures 10.4 (d). This will have the effect of increasing the inter-annual variability between the extremes of daily flow in low flow years. Additionally, both the number of low pulses and their durations are increased after the construction of the Smithfield Dam (Table 10.4). Conversely, the duration of high pulses is reduced as a result of attenuation by the dam.

The operation of Phase 1 of the MMTS with present land use influences the rate of hydrographic rise and fall in the same way as at IFR Site 2. Similarly, the increase of hydrograph reversals indicates a substantial change in the intra- and inter-annual stress at this site.

The IHA methodology program output gave the three greatest changes of development with the Smithfield Dam on the hydrological regime at IFR Site 3 as:

(a) changes in the average flow for August
(b) changes in the average flow for July
(c) changes in the 90-day minimum flow.

10.4.4 Assessment of the indicators of hydrological alteration at IFR Site 4 on the Mkomazi River

Table 10.5 indicates that the impact of the operation of Phase 1 of the MMTS with present land use on the change in the hydrological regime at IFR Site 4 is less than that at IFR Site 3. Nonetheless, monthly streamflows are still reduced more in winter months than summer months. As indicated by the daily and multi-day minima, baseflows are still reduced with the number of flood-free days increasing from 11 to 24 in the post-impact period. Seasonal low flows are reduced to a greater extent than seasonal high flows as shown by Figures 10.5 (a) and (b). However, the timing of extreme events in post-impact conditions is relatively unaltered by the operation of the Smithfield Dam, which is some 100 km upstream (*cf.* Figure 4.2, and attenuated by the 2268 km^2 drainage area downstream from the dam site.

As at IFR Site 3, the number of low pulses and their durations are increased after the construction of the Smithfield Dam (Table 10.5). Conversely, the number of high pulses and their durations, as shown in Figure 10.5 (c) are slightly reduced as a result of attenuation by the dam and by present land use practices.

The rate of both the hydrographic rises and falls increases at IFR Site 4, and consequently the number of hydrograph reversals, is much higher than that in pre-construction conditions, as Figure 10.5 (d) shows clearly. This implies that the operation of Phase 1 of the MMTS with present land use would exert both additional intra- and inter-annual variation in the conditions to which aquatic organisms have become adapted at this site.

The IHA methodology program output gave the three greatest changes of development with the Smithfield Dam on the hydrological regime at IFR Site 4 as:

(a) changes in the 90-day annual minimum flow

(b) changes in the average flow for July and

(c) changes in the average flow for August.

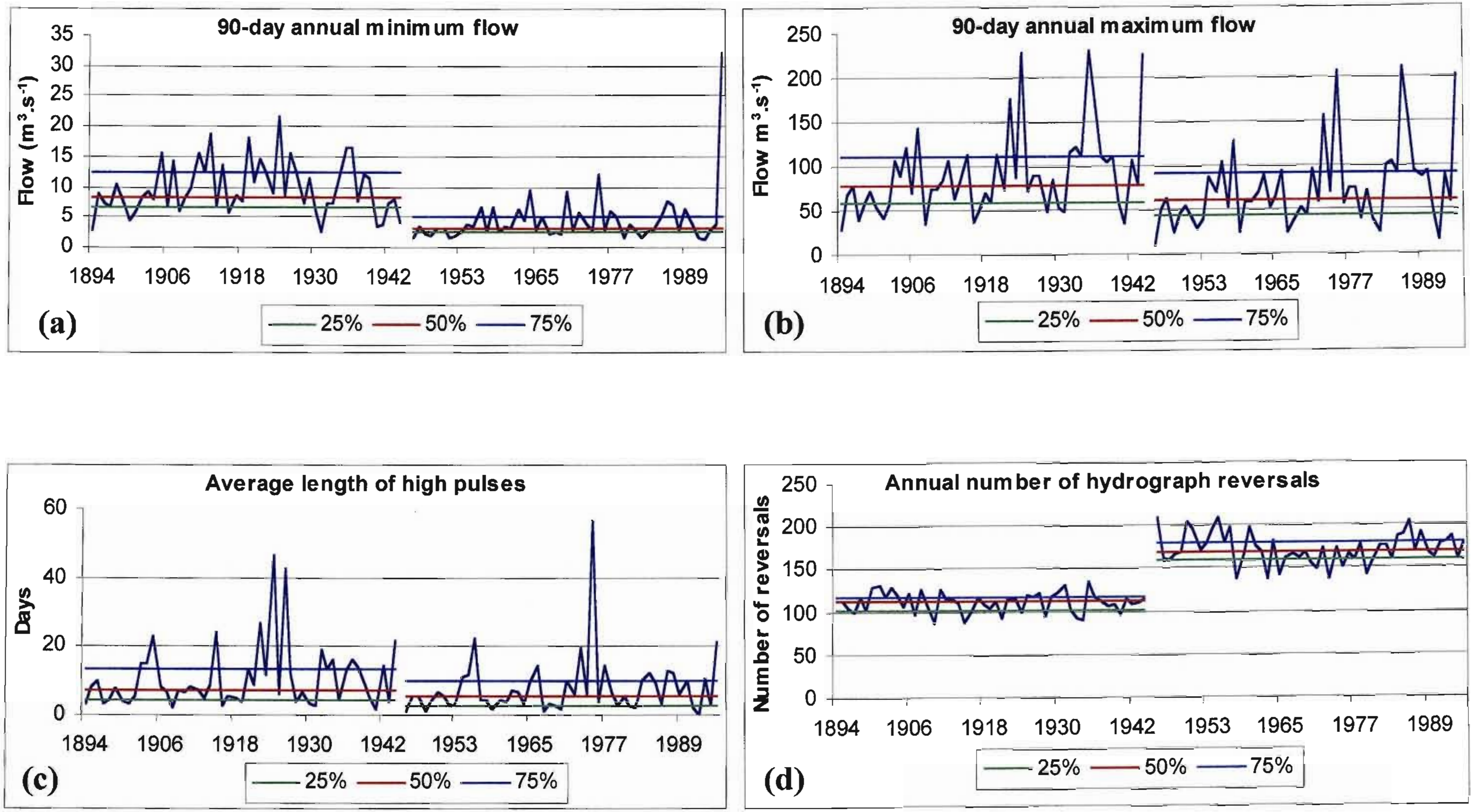

Figure 10.5 Examples of changes in the hydrological regime at IFR Site 4 on the Mkomazi River

10.5 Conclusions regarding the Assessment of the Indicators of Hydrological Alteration

Present land use practices have little influence on the hydrological regime of the upper Mkomazi. For this reason alone, it would appear unlikely that the present class (B/C) of the upper Mkomazi could be improved, *quantitatively*, to a higher management class (B) (*cf.* Section 9.1). However, the abruptness of increased magnitude and frequency of the reversing cycles of hydrograph pulses due to present land use could have affected the health of the river in the upper reaches. Rapid changes between wetting and drying of the littoral zone along the river's edge have been shown to decimate fauna stranded beyond the river-wetted area (Richter *et al.*, 1996).

The operation of the MMTS has raised concerns with the Mkomazi Environmental Task Group that river impoundment and abstractions for inter-basin transfer will alter flood patterns and attenuate low flows downstream. The assessment in this chapter has indicated that Phase 1 of the MMTS with present land use does not appear to substantially alter the magnitude, timing, occurrence or duration of high flow events, given the dam operating assumptions (*cf.* Section 4.11.2). However, the same cannot be concluded for low flow events, which experience considerable modification in magnitude, occurrence and frequency as a result of Phase 1of the MMTS with present land use. These changes need to be addressed by formulating adequate dam operating rules to ameliorate the impacts of reduced habitat refugia for aquatic species.

The construction of the Smithfield Dam to transfer water out of the Mkomazi system will increase the time taken for the hydrograph to be routed downstream. This may affect not only the biological cues required for the successful completion of aquatic species life cycles, but also has implications for the efficacy of dam release rules to satisfy the greatest number of downstream site requirements.

The increased number of the cycles of hydrograph reversals indicates that variability of environmental conditions post-impact is likely to be more extreme than that under natural conditions, and therefore will exert additional stress on those species which have adapted mechanisms to survive under less hospitable conditions. This could also be addressed by effective dam release operating rules to introduce less variability in the hydrograph reversals.

The IHA methodology is a powerful and easily understood analytical approach to the assessment of the extent to which flow regimes are altered as a result of anthropogenic development and it can be applied as an effective ecosystem management tool. It has even greater potential if biological data are available to compare the analysis with community and species population dynamics and distributions.

* * * * *

However, the question still remains as to how much water river systems need. The following chapter will highlight the usefulness of the principles of the IHA, for setting preliminary management targets for the instream flow requirements of the Mkomazi River.

11 PLANNING FOR THE ENVIRONMENTAL DEMAND OF THE MKOMAZI CATCHMENT

11.1 Introduction

Many scientists, internationally and nationally, are challenged by the question of just how much water rivers need to maintain aquatic health and sustain the integrity of their ecosystems. This has become all the more pressing in South Africa, since DWAF has initiated the setting of a preliminary reserve (see Chapter 2). It has been suggested by Hughes (1999b) that there appears to be an ecological / hydrological relationship coincident with the Q75 value of the flow duration curve, *i.e.* the flow value which is equalled or exceeded 75 % of the time. However, there are still uncertainties as to why the instream flow requirement for some rivers is represented at higher than the 75th percentile of time on the flow duration curve. This factor has been attributed to ecological noise and has been the source of recent research to identify eco*logical* reasons for this phenomenon (*cf.* Section 3.10).

The following sections explore a methodology for determining the flow requirements of rivers. The approach is a further examination of the IHA methodology described in Chapter 10, designed principally for wetter conditions than those experienced in southern Africa.

11.2 Range of Variability Approach

The Range of Variability Approach (RVA), a practical application of the IHA methodology described in Chapter 10, was developed by Richter *et al.* (1997) to enable river managers to define and adopt preliminary management targets before conclusive, long-term ecosystem research results are available (Richter *et al.*, 1997).

The fundamental premise of the RVA is that a range of variation in each of the 32 IHA parameters described in Chapter 10 (Richter *et al.*, 1996), *e.g.* the values + or - 1 standard deviation from the mean or the 25th to 75th percentile range, is selected as an initial flow management target. The RVA targets and management strategies should be refined as and when adaptations are required to sustain aquatic ecosystem integrity. The developers have intimated that hydrologists may question the validity of the recommended use of the + / - standard deviation as a default target. However, they emphasise the focus on the need to restore or maintain the regime of natural variability of the hydrological system rather than the need for any particular statistical procedure (Richter *et al.*, 1997).

The approach, therefore, recognises the relationship between the characteristics of river flow and river habitat condition by addressing the critical role of hydrological variability in the natural flow regime. The methodology considers the timing, frequency, duration and rates of change of streamflows required to sustain aquatic ecosystems and was designed to set streamflow-based river ecosystems targets. The developers consider that the approach will be most appropriate when protection of the natural aquatic biodiversity and aquatic ecosystem are the primary management objectives. To this extent the approach addresses the issues identified by DWAF in its assessment of the preliminary reserve (*cf.* Chapter 3).

The developers of the RVA intend that the preliminary assessments are refined by adaptive management strategies resulting from site-specific ecosystem research and monitoring designed to test:

(a) the ability of the designed management system to achieve the desired flow conditions and

(b) biotic and ecosystem response to the targets set (Richter *et al.*, 1997).

11.3 The RVA Methodology

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

The ***first step*** is to characterise the natural range of streamflow variation using the IHA method described in Chapter 10. Richter *et al.* (1997) recommend that the management team should identify a streamflow record of sufficient length (> 20 years) that represents natural, or undisturbed, flow conditions. However, the necessity for a longer length of record for southern African conditions was described in Section 10.3, where it was concluded that a 40-year record of simulated rainfall for the Mkomazi Catchment would be considered appropriate for statistical analysis. Measurements of the central tendency and dispersion are computed for each of the 32 ecologically driven parameters and are used to characterise inter-annual variation.

The developers of the RVA suggest that where inadequate streamflow conditions exist for the period representing natural conditions, existing records may extended using regression relationships between the site of interest and other less perturbed streamflow-gauging sites (Richter *et al.*, 1997). Where no streamflow records exist, use is made of reference catchments with adequate record lengths and with similar climate and geology as well as minimal anthropogenic effects. Adjustment is made to the streamflow data or statistical characteristics to account for differences in catchment area and driving variables such as rainfall. This is the essence of the approach used by Hughes *et al.* (1997) in the generation of representative time series for the BBM methodology where no streamflow records exist close to IFR sites (*cf.* Section 8.2.6.2). Alternatively, a simulation model such as *ACRU* could be applied to generate a daily time series of flows to represent defined baseline natural conditions, as described in Sections 4.11.1 and 8.2.6.3. However, it is imperative that adequate verification of the simulation output is performed to validate the use of the generated time series. This requires adequate streamflow-gauging records to instill confidence in model simulation, as discussed in Chapter 5.

However, because of the uncertainties associated with the prediction of daily streamflow, either by regression techniques, model simulation or the use of reference catchments, the developers of the RVA caution against the use of certain IHA parameters in the RVA. This applies particularly to those parameters sensitive to errors in daily flow estimation, *i.e.* the rates of rise and fall of the daily hydrographs and the frequencies thereof, forming Group 5 in Table 10.1.

The ***second step*** comprises the selection of management targets for each of the 32 IHA parameters. The principal concept is that the targets set should fall within the natural range for that parameter, based on the inter-annual measure of dispersion used in Step 1. On this premise, the management target for any of the 32 parameters is a range of acceptable values. Ideally, the management targets should be based on available ecological information. There is, however a paucity of such information in southern Africa and in such instances the developers recommend that the 25th to 75th percentile range is selected for preliminary targets. Clearly, selection of a target close to the mean or median would severely restrict any other water use in nearly half the years, and where there are human demands placed on water resources such a target may be unacceptable. Monitoring of the ecosystem response to the preliminary targets should identify critical flow thresholds for components of the river ecosystem and allow subsequent refinement of the flow-based management targets (RVA targets).

Using the RVA targets as guidelines, the ***third step*** requires that river managers design a management system comprising a set of rules that allow the targets to be met. To achieve this objective, the management system could include a viable set of reservoir operating rules, including restrictions on abstractions, or restorative land use practices. The RVA targets could be set to be attainable every year (*e.g.* within the upper and lower thresholds). Designing the management system requires the use of historical streamflow values and some measure or quantification of the impacts of human induced activities on the drainage area. Hydrological simulation modelling, such as that described in Chapter 4, provides any number of time series of daily flows for different land use, development and management scenarios. The critical assumption inherent in the management system is that the RVA targets are achievable at the specified targets.

The ***fourth step*** involves the application of a monitoring and ecological research programme to assess the response of ecosystems to the management system described in Step 3. The management plan should include measurable biological goals and an evaluation programme that determines whether the goals are achieved and /or are appropriate. Catchment management strategies in the form of restorative land use programmes (*e.g.* the removal of alien invasive riparian vegetation) and modifications to dam operating rules can be assessed at this stage.

The ***fifth step*** is to characterise the actual streamflow variation using the IHA methodology. Comparison is made of the values of each of the 32 parameters with the RVA target values to identify which targets are met.

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

11.4 Application of the RVA for the Mkomazi Streamflows

The RVA was applied as a preliminary assessment of management targets for the Mkomazi Catchment streamflows at IFR Sites 1, 2, 3 and 4. This comprised the comparison of the hydrological regime at each IFR site under baseline land cover conditions (*ACRU* simulated daily Acocks' streamflows) with post impact conditions. For IFR Site 1 the comparison was made with the *ACRU* simulated daily present land use streamflows, described in previous chapters. For IFR Sites 2, 3 and 4 the comparison was made with the regime after the construction of the Smithfield Dam for Phase 1 of the inter-basin transfer to the Mgeni Catchment (*ACRU* simulated daily MMTS streamflows described in previous chapters). Each comparison was performed in the same manner as that of the assessment of hydrological alteration described in Chapter 10. In the absence of river management plans for the Mkomazi, it was assumed that the upper and lower thresholds of the target range should be set at the 75th and 25th percentiles of the range of natural variation for each of the 32 parameters. This assumption was also considered appropriate to satisfy the Mkomazi BBM IFR workshop determination of a minimum management class B for the entire river.

The RVA output of each analysis was provided in the same form as that of the IHA (Chapter 10) methodology, *i.e.* a primary summary scorecard, percentile statistics, an annual summary and graphs, all calculated using non-parametric statistics. The RVA scorecard provided the following information (Richter *et al.*, 1997):

(a) Columns 1 – 4 show the median, coefficient of variance, and low and high extreme values for each parameter during the pre-impact period.

(b) Columns 5 –8 show the same information for the post-impact period.

(c) Columns 9 – 10 show the low and high RVA targets. By default these are the 25th and 75th percentiles. These percentile are used to set preliminary ecosystem management targets. The user may define different RVA targets, based on appropriateness to local management plans or as additional hydrological and ecological information becomes available. If the target falls outside the range of the pre-impact data, it is replaced by the pre-impact range limit.

(d) Column 11 shows the hydrological alteration, defined as

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

where: **Expected** = the frequency with which annual statistics fall within RVA limits in the pre-impact period, and

Observed = the frequency with which annual statistics fall within the RVA limits in the post-impact period.

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

11.4.1 Results of RVA application at Mkomazi IFR Site 1

The statistics in Table 11.1 show that management plans to enhance the hydrological regime at IFR Site 1 should focus on attempts to increase flows in low flow months. Streamflows resulting from present land use in the winter months of July through September show the highest alteration from the set RVA target range and the greatest number of *below* range years (*i.e.* flows less than the low RVA target of the 25th percentile). This is illustrated in Figure 11.1 (a) for July. Correspondingly, the alteration in the RVA range for the daily extremes, shown in Table 11.1, is greatest for the lower minimum day and multi-day flows, with a substantial increase in the occurrence of the 1, 3 and 7 day minimum flows not meeting the lower threshold. Table 11.1 shows that there is also some depression of baseflows. However, most of the seasonal extremes remain *within* the target range, as shown in Figures 11.1 (b) and (c), and there is no alteration in the timing of the annual extremes as indicated in the stability of the Julian date of occurrence.

Table 11.1 RVA Score Card: Mkomazi IFR Site 1

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

Comparison of Statistics Within, Above and Below RVA Range

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

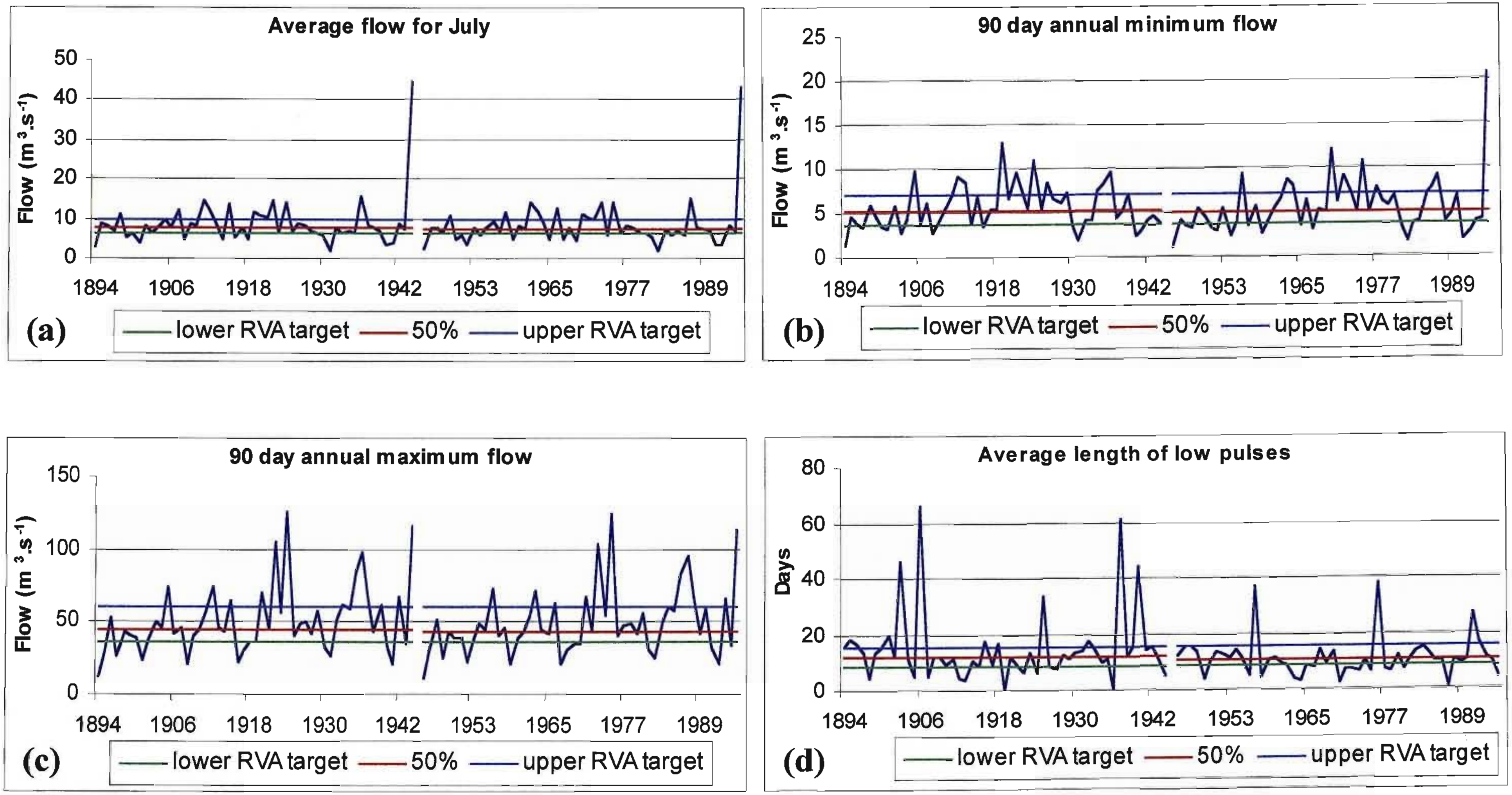

Figure 11.1 Examples of changes in the hydrological regime, together with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 1 on the Mkomazi River

Table 11.1 shows that the number of low pulses increases as a result of present land use, with 21 counts (compared with the pre-impact count of 11) being *above* the upper RVA target. This is exacerbated by the shortening of low pulse durations, more of which (17 post-impact compared to 12 pre-impact) now occur *below* the RVA targets set (Figure 11.1 (d) and Table 11.1), further substantiating the need for management plans to address the performance of present low flows. High pulse counts and their durations are less impacted by present land uses, but together with the alteration in low pulse counts and their durations result in alteration in the annual hydrograph rise and fall rates. This results in all hydrograph reversals occurring *above* the upper RVA target, indicating highly increased cycles of intra-annual environmental variation.

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

Summer high flow months show less alteration than winter low flow months, with only slight reductions in the frequency *within* the target range. Moreover, the daily and multi-day maximum extreme flows are very similar to those under natural conditions.

Based on the RVA anaylsis, it can be recommended that catchment management plans to enhance the conditions of the uppermost river reach of the Mkomazi River to a B management class from a present state class C/B should include objectives to:

(a) restore winter low flows,

(b) elevate the baseflow regime,

(c) decrease the frequencies of low pulses and increase their duration

(d) decrease the frequency of hydrograph reversals resulting from increased shifts between rising and falling flow levels and

(e) adjust the rate at which flows rise or fall *within* days.

The recommendations should be designed to mimic the natural regime by maintaining flows *within* the 25th and 75th percentiles of streamflows from natural land cover conditions. The following Best Management Practices (BMP) could be adopted in catchment management strategies to meet these objectives for the upper Mkomazi:

(a) The removal of alien riparian vegetation to restore the baseflow regime: Alien riparian vegetation is assumed to use more water than the indigenous vegetation with which it competes. In a study on the impacts of the removal of this vegetation, Jewitt *et al.* (2000) found that the most significant improvements in streamflow generation were obtained in the drier winter months.

(b) The initiation of more water use efficient agriculture in periods of low flow, including irrigation scheduling systems (*e.g.* Schulze *et al.*, 1999).

(c) The rehabilitation of degraded land to increase vegetative interception.

If the management class of the Mkomazi River is to be enhanced, careful consideration should be given to the implications of issuing any new afforestation permits or additional licences for irrigation abstraction. Any such deliberations could be negated if plans to construct the proposed Impendle Dam (upstream of IFR Site 1, *cf.* Figure 4.2) came to fruition. However, complex reservoir operating rules would be required to meet the suggested management objectives discussed above. The adoption of any management strategy would benefit greatly from the initiation of a monitoring and research programme to determine the biotic responses to the implementation of the management system (Richter *et al.*, 1997).

11.4.2 Results of RVA application at Mkomazi IFR Site 2

Table 11.2 indicates that the hydrological alteration from the RVA target range set for post dam streamflows at IFR Site 2 is greatest for the winter low flow months of July through October. However, the impact of the catchment development with present land use and Phase 1 of the MMTS is such that the low flow season is extended to include May and June as well as November, and with a substantial alteration of December flows.

Table 11.2 RVA Score Card: Mkomazi IFR Site 2

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

Comparison of Statistics Within, Above and Below RVA Range

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

Figure 11.2 (a) shows that the decrease in July streamflows shifts the majority of annual occurrences to *below* the lower target range (25th percentile), from 12 under natural land cover conditions to 44 in post-dam conditions (*cf.* Table 11.2). For all winter low flow months there are substantial reductions in streamflows *within* the RVA target range, yet only slight reductions in summer high flow months, *e.g.* January and February both decrease from 26 occurrences to 24 and 22 occurrences respectively, whereas the number for March remains the same at 26 occurrences (Table 11.2).

The alteration of daily and multi-day minimum extreme flows as a result of catchment development with present land use and Phase 1 of the MMTS is considerable, with all occurrences of the 1, 3, 7 and 30 day durations falling *below* the lower RVA target. The daily and multi-day maximum extreme flows are far less impacted and most still fall *within* the RVA target range. Figure 11.2 (b) illustrates these factors for the 30-day minimum extreme. Table 11.2 also indicates the extent of suppression of the baseflow regime as a result of the dam, with most occurrences appearing *below* the lower RVA threshold.

With present land use and the operation of Phase 1 of the MMTS, the number of low pulses falling *within* the RVA range is increased (change from 28 to 33, Table 11.2) at the expense of those *below* the lower target (change from 11 to 4). Furthermore, the average length of low pulses is much longer, with most durations being *above* the upper RVA threshold (Figure 11.2, c), (*viz.* 38 occurrences, as shown in Table 11.2. This concurs with the findings described above, that the low flow season is considerably extended under post-dam conditions.

The reverse can be shown in Table 11.2 for high pulses and their durations and in Figure 11.2 (d), where the number of pulses *below* the lower RVA target increases from 5 to 16 after the construction of the dam. The occurrences of average length that are *below* the lower threshold increases from 12 to 21 (Table 11.2). The decline in high pulses and their durations can be attributed principally to the attenuation of high flows by the dam and to the inadequacies of the legal flow releases for downstream use assumed in the *ACRU* model simulation.

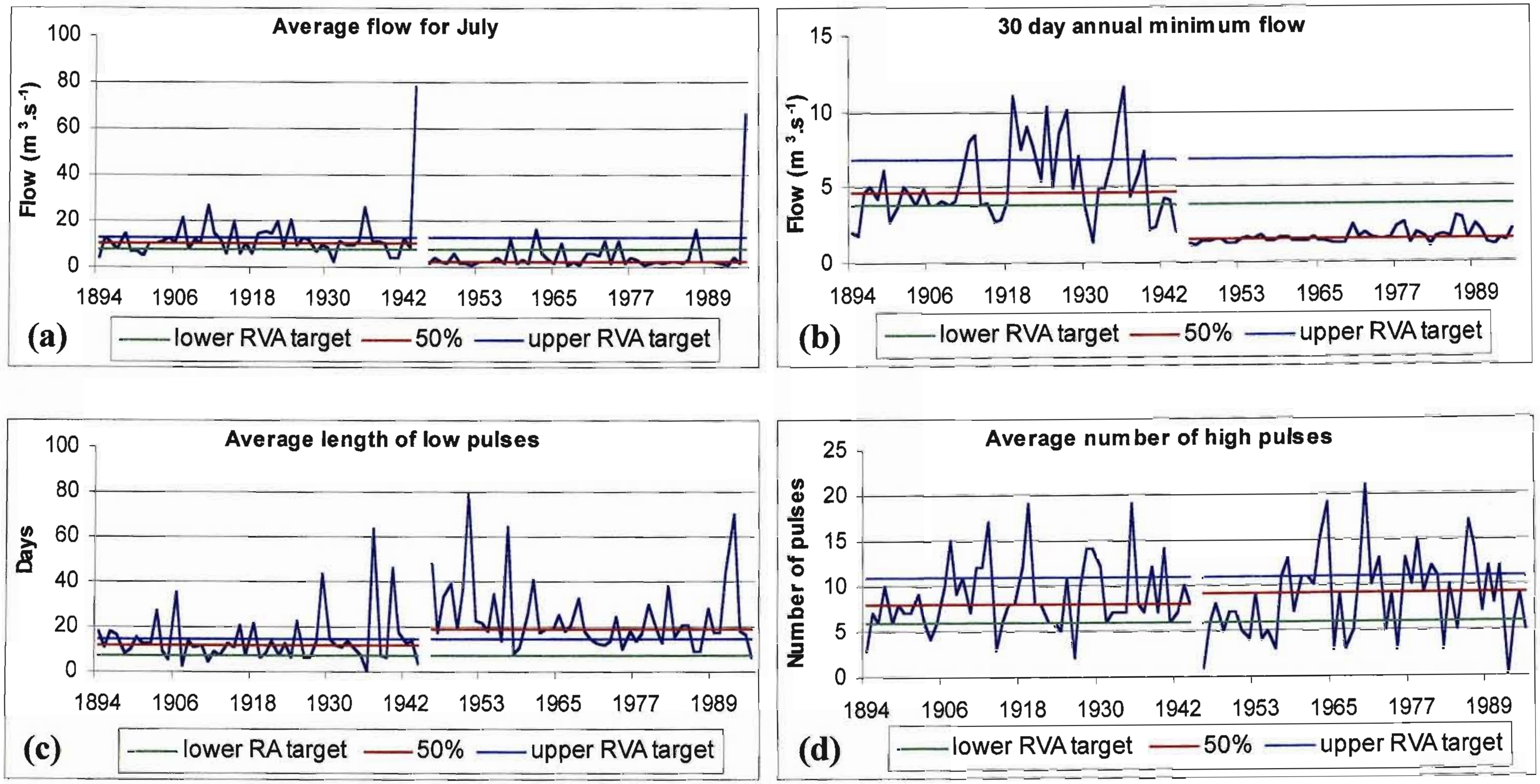

Figure 11.2 Some of the changes in the hydrological regime, together with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 2 on the Mkomazi River

The extent of alteration of the low and high pulses and their durations, under post-dam conditions results in high alteration in the annual rise and fall rates. Under such conditions, all the hydrograph reversals occur *above* the upper RVA target, indicating that the modified regime is characterised by highly abrupt changes.

The RVA analysis generated warnings regarding the interpretation of the frequencies of both high and low pulses, duration of low pulses, number of falls, reversals and the date of the maximum annual daily extreme flow. For example, of the 34 high pulses counts calculated to be *within* the pre-impact target range of 6 to 11, nine counts were equal to the lower threshold. However, as discussed in Section 11.4.1, this factor does not detract from the general trend of reductions in high pulses following the construction of the Smithfield Dam for inter-basin transfer.

Similarly to Mkomazi IFR Site 1, river management plans for the river reach upstream of the Mkomazi IFR Site 2 require the management class to be enhanced from a present state class C/B to class B (*cf.* Section 9.1). The impact of present land use with the proposed Smithfield Dam clearly exerts more influence on downstream flows than present land use conditions on flows at IFR Site 1. Notwithstanding the influence of land use practices on flows upstream of IFR Site 2, management plans for this river reach should clearly look to efficient reservoir operating rules for the Smithfield Dam in order to ameliorate the impacts of the inter-basin transfer on the hydrological regime. Based on the RVA analysis, operating rules should particularly address:

(a) restoration of the winter low flows,
(b) increased releases at the start and end of the low season, to limit the low flow season to a more natural duration,
(c) elevation of the baseflow regime,
(d) decreasing the number of low pulses and their duration,
(e) increasing the number of high pulses and their duration,
(f) decreasing the frequency of hydrograph reversals attributable to the current operating rule of legal flow releases, and
(g) adjustment of the rate at which flows are released *within* days.

Operating release priority rules should be initiated to meet these management objectives. In particular, curtailment of releases for inter-basin transfer may be required at pre-determined levels in the winter low flow season. Lower releases should also be considered in periods *before* low flow periods and *after* water stress months to ensure greater semblance to the natural flow regime. Additionally, restrictions to river abstractions for irrigation in low flow months should be applied. A number of short releases from the Smithfield Dam made in March (when there is no hydrological alteration from pre-dam conditions) for off-channel irrigation storage downstream may compensate for abstraction losses in periods of low flows and increase the high pulses and durations to *within* the RVA target range. However, this would be effective only so far as to the point of off-take for off-storage.

11.4.3 Results of RVA application at Mkomazi IFR Site 3

Table 11.3 shows the results of the RVA analysis for the hydrological alteration from the target range set for post-dam streamflows at IFR Site 3. The winter season months experience greatest hydrological alteration. However, at this site the duration of low flow period is harsher than at IFR Site 2 (20 km^2 upstream from IFR Site 3) with substantial alteration persisting into December. Figure 11.3 (a) shows that the median post-dam streamflow for August is substantially lower than the 25th percentile of streamflows under natural conditions, with 44 post-dam years generating streamflows *below* the lower RVA target range (Table 11.3). The extent of alteration at the end of the low flow season is shown in Figure 11.3 (b) for November flows, indicating that for this month, median flows are *below* the lower target threshold. As at IFR Site 2, all winter months experience substantial reductions in flows that fall *within* the target range, yet only slight reductions in flows that fall *within* the target range in summer high flow months. Moreover, in March there is a slight increase (from 26 to 27, *cf.* Table 11.3) in the occurrence of flows *within* the range.

The alteration of daily and multi-day minimum extreme flows at IFR Site 3, is as great at IFR Site 2, indicating that even with a greater upstream drainage area, the influence of the operation of the MMTS at this site is notable. The alteration from the seasonal low flows of the natural streamflow regime is indicated in Figure 11.3 (c), in which it is shown that most (47) of these annual occurrences are *below* the lower target limit. Most of the daily and multi-day maximum extreme flows still fall *within* the target range (Table 11.3) after the dam construction. This is shown in Figure 11.3 (d) for the 3-day annual minimum

Table 11.3 RVA Score Card: Mkomazi IFR Site 3

		Pre-impact period October 1894 - September 1945 (51 years)				Post-impact period October 1945 - September 1996 (51 years)				RVA TARGETS		HYDROLOGIC ALTERATION
				Range Limits				Range Limits				
Parameter		Medians	Coefficient of Variance	Low	High	Medians	Coefficient of Variance	Low	High	Low	High	
Group 1	**Units**											
October	$m^3.s^{-1}$	11.00	0.85	2.70	162.80	3.40	1.00	1.40	145.20	8.76	16.09	-0.77
November	$m^3.s^{-1}$	2.35	0.68	6.20	80.10	8.40	1.64	1.50	58.00	14.89	30.82	-0.62
December	$m^3.s^{-1}$	33.20	0.80	5.80	165.50	21.10	1.50	1.80	141.70	24.21	50.81	-0.38
January	$m^3.s^{-1}$	56.60	0.81	8.20	173.50	45.10	0.98	1.70	158.10	34.34	80.21	-0.08
February	$m^3.s^{-1}$	65.30	0.67	11.20	191.00	52.40	0.78	2.80	174.30	40.24	83.94	-0.12
March	$m^3.s^{-1}$	63.90	0.67	22.00	241.40	51.90	0.74	3.80	223.90	42.92	85.55	0.04
April	$m^3.s^{-1}$	39.30	0.50	7.60	112.20	29.00	0.69	2.50	101.10	27.52	47.29	-0.23
May	$m^3.s^{-1}$	23.80	0.44	4.00	251.70	14.20	0.69	1.60	235.60	19.21	29.72	-0.65
June	$m^3.s^{-1}$	16.20	0.47	2.60	39.60	6.80	0.95	1.10	27.60	11.81	19.46	-0.88
July	$m^3.s^{-1}$	11.30	0.59	2.70	88.20	3.20	1.06	1.30	74.50	8.17	14.77	-0.85
August	$m^3.s^{-1}$	9.20	0.86	2.50	49.00	2.50	1.49	1.20	32.30	6.72	14.62	-0.81
September	$m^3.s^{-1}$	8.30	1.03	2.50	254.00	2.50	1.04	1.40	240.50	5.57	14.05	-0.77
Group 2												
1-day minimum	$m^3.s^{-1}$	3.50	0.64	1.10	11.30	1.40	0.22	0.60	2.90	2.78	5.03	-0.96
3-day minimum	$m^3.s^{-1}$	3.60	0.65	1.10	11.30	1.50	0.20	0.80	3.00	2.90	5.23	-0.96
7-day minimum	$m^3.s^{-1}$	4.00	0.53	1.10	11.10	1.50	0.25	0.90	3.10	3.28	5.41	-1.00
30-day minimum	$m^3.s^{-1}$	4.90	0.63	1.40	12.40	1.80	0.39	1.10	3.50	4.06	7.17	-1.00
90-day minimum	$m^3.s^{-1}$	7.50	0.70	2.20	17.80	2.20	0.78	1.20	26.90	5.85	11.07	-0.88
1-day maximum	$m^3.s^{-1}$	241.40	0.80	67.70	2728.30	218.40	0.72	19.50	2799.70	165.22	358.02	-0.15
3-day maximum	$m^3.s^{-1}$	202.80	0.89	61.30	2030.70	178.60	0.81	14.30	1992.50	133.85	314.75	-0.04
7-day maximum	$m^3.s^{-1}$	144.10	0.84	54.60	1306.60	124.40	0.86	8.90	1268.30	99.93	221.32	-0.15
30-day maximum	$m^3.s^{-1}$	90.80	0.77	27.70	392.20	76.40	0.88	5.90	371.30	66.55	136.10	-0.23
90-day maximum	$m^3.s^{-1}$	69.60	0.64	23.50	197.90	55.90	0.77	8.00	180.20	52.24	96.80	-0.19
Number of zero days	number	0	0	0	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.47	0.05	0.27	0.07	0.58	0.03	0.51	0.10	0.16	-0.65
Group 3												
Date of minimum	day	274	0.08	227	339	274	0.08	30	355	265	296	0.07
Date of maximum	day	35.3	0.22	6	365	36	0.18	6	365	36.25	275.25	0
Group 4												
Low Pulse Count	number	6.5	0.92	0	22	8	0.53	2	15	4	10	0.23
Low Pulse Duration	days	10.90	0.68	0.00	64.00	18.00	0.64	7.50	65.00	7.59	15.00	-0.52
High Pulse Count	number	8	0.63	2	21	9	0.78	0	21	7	12	-0.26
High Pulse Duration	days	9.30	1.03	2.10	64.50	5.70	1.35	0.00	41.80	4.60	14.17	-0.15
Group 5												
Rise rate	$m^3.s^{-1}.day^{-1}$	13.80	0.46	5.90	42.80	7.70	0.49	1.00	26.20	10.57	16.96	-0.81
Fall rate	$m^3.s^{-1}.day^{-1}$	-4.10	-0.43	-11.10	-1.80	-4.30	-0.63	-14.80	-0.60	-5.01	-3.22	-0.35
Number of reversals	number	106.50	0.14	88.00	136.00	171.00	0.11	133.00	209.00	101.00	116.00	-1.00

Comparison of Statistics Within, Above and Below RVA Range

	Within		RVA Range	Above		RVA Range	Below		RVA Range
Parameter	Expected	Observed	Alteration	Expected	Observec	Alteration	Expected	Observed	Alteration
Group 1									
October	26	6	-0.77	13	5	-0.62	12	40	2.33
November	26	10	-0.62	13	7	-0.46	12	34	1.83
December	26	16	-0.38	13	8	-0.38	12	27	1.25
January	26	24	-0.08	13	9	-0.31	12	18	0.5
February	26	23	-0.12	13	11	-0.15	12	17	0.42
March	26	27	0.04	13	6	-0.54	12	18	0.5
April	26	20	-0.23	13	8	-0.38	12	23	0.92
May	26	9	-0.65	13	6	-0.54	12	36	2
June	26	3	-0.88	13	8	-0.38	12	40	2.33
July	26	4	-0.85	13	3	-0.77	12	44	2.67
August	26	5	-0.81	13	2	-0.85	12	44	2.67
September	26	6	-0.77	13	3	-0.77	12	42	2.5
Group 2									
1-day minimum	26	1	-0.96	13	0	-1	12	50	3.17
3-day minimum	26	1	-0.96	13	0	-1	12	50	3.17
7-day minimum	26	0	-1	13	0	-1	12	51	3.25
30-day minimum	26	0	-1	13	0	-1	12	51	3.25
90-day minimum	26	3	-0.88	13	1	-0.92	12	47	2.92
1-day maximum	26	22	-0.15	13	10	-0.23	12	19	0.58
3-day maximum	26	25	-0.04	13	8	-0.38	12	18	0.5
7-day maximum	26	22	-0.15	13	11	-0.15	12	18	0.5
30-day maximum	26	20	-0.23	13	9	-0.31	12	22	0.83
90-day maximum	26	21	-0.19	13	7	-0.46	12	23	0.92
Number of zero days	0	0	0	0	0	0	0	0	0
Base flow	26	9	-0.65	13	3	-0.77	12	39	2.25
Group 3									
Date of minimum	28	30	0.07	12	12	0	11	9	-0.18
Date of maximum	26	26	0	13	10	-0.23	12	15	0.25
Group 4									
Low Pulse Count	31	38	0.23	10	11	0.1	10	2	-0.8
Low Pulse Duration	27	13	-0.52	12	37	2.08	12	1	-0.92
High Pulse Count	34	25	-0.26	9	8	-0.11	8	18	1.25
High Pulse Duration	27	23	-0.15	13	6	-0.54	11	22	1
Group 5									
Rise rate	26	5	-0.81	13	6	-0.54	12	40	2.33
Fall rate	26	17	-0.35	13	17	0.31	12	17	0.42
Number of reversals	29	0	-1	11	51	3.64	11	0	-1

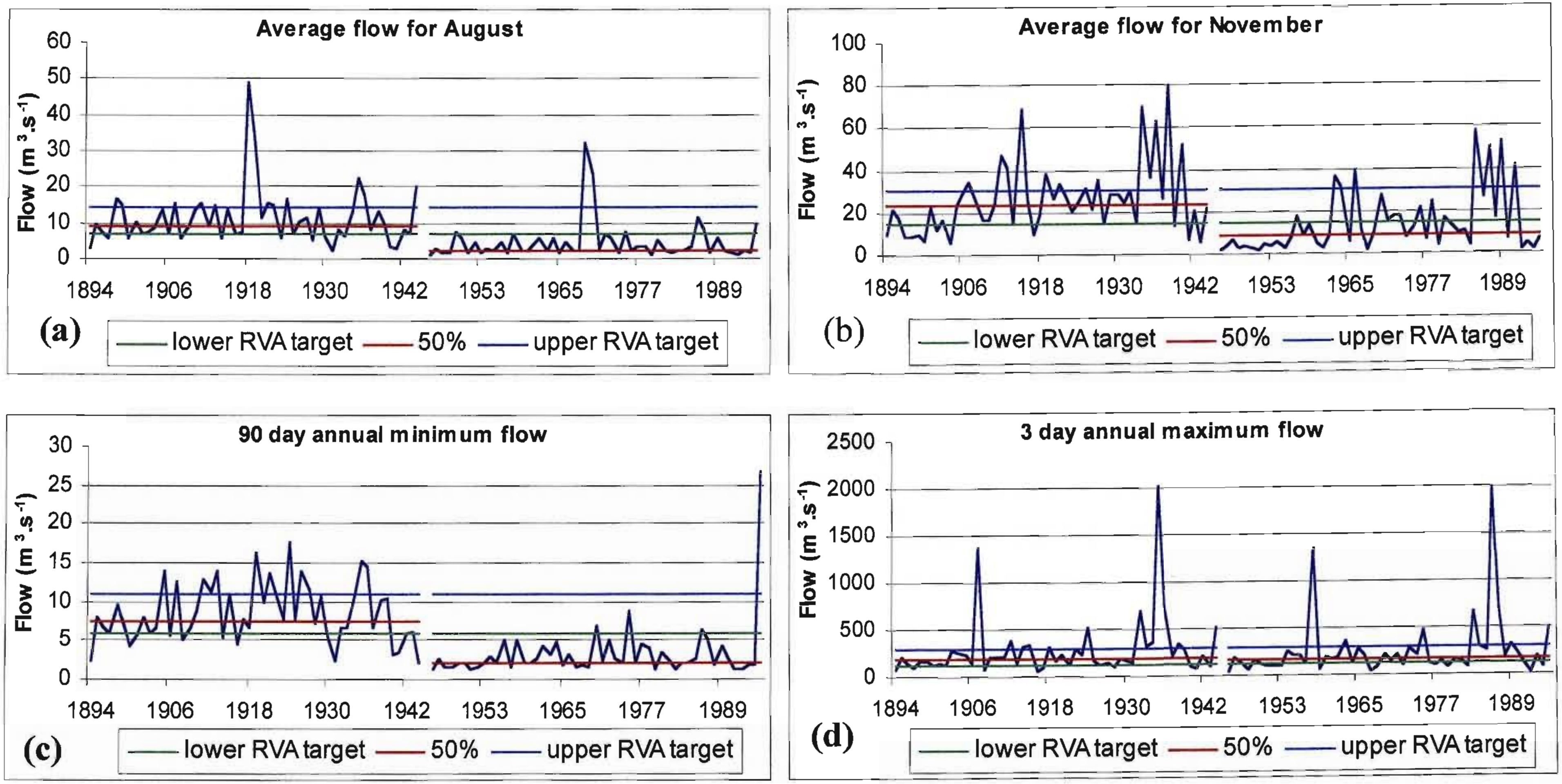

Figure 11.3 Examples of changes in the hydrological regime, together with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 3 on the Mkomazi River

extreme flows. Similarly to IFR Site 2, there is substantial suppression of the baseflow regime with most occurrences (39) appearing *below* the lower threshold.

Table 11.3 indicates that the trend of occurrence of low pulses and their durations being *above* the upper target range at IFR Site 2 is lessened at IFR Site3. This can be attributed to the influence of the catchment drainage area downstream of IRF Site 2 providing a tempering of the impacts of the MMTS. Conversely, the occurrence of high pulses and their durations *below* the lower target range at IFR Site 2 is further exacerbated at IFR Site 3. Clearly, the storage of high flows in the dam, together with inadequate releases of legal flows for downstream use would considerably alter the high flow component of the hydrological regime at this site.

Not surprisingly, the extent of alteration of the low and high pulses and their durations at this site as a consequence of present land use and Phase 1 of the MMTS results in considerable alteration in the annual rise and fall rates. As at IFR Site 2, all the post-dam hydrograph reversals occur *above* the upper RVA target, indicating the extent to which the modified regime is characterised by abrupt changes.

The RVA analysis generated warnings regarding the interpretation of the frequencies and durations of both low and high pulses, the number of falls and reversals and the date of the minimum annual extreme. The most notable of these were that of the 34 high pulse counts calculated to be *within* the pre-impact target range of 7 to 12, 15 were equal to the upper threshold, whereas 13 were equal to the lower threshold. However, this factor does not alter the trend of reduced post-dam high pulses.

River management plans for the river reach upstream from Mkomazi IFR Site 3 require that the management class be increased from a class D/C to a class B (*cf.* Appendix Table B4). It is proposed that this could be achieved by maintaining the streamflow characteristics *within* the 25th and 75th percentiles of the natural flow regime. The impacts of the operation of the MMTS with present land use on the hydrological alteration from the natural flow regime at IFR Site 3 are very similar to those at Site 2. However, the additional alteration of the high pulses and their durations needs to be addressed. The management objectives for efficient operating rules for the Smithfield Dam outlined in (a) to (g) in Section 11.4.2 are also valid for addressing the alteration of the hydrological regime at IFR Site 3.

Together with the recommendation in Section 11.4.2, *viz.* that curtailment of releases from the proposed Smithfield Dam for the operation of the MMTS could be implemented *before*, *during* and *after* winter low flow months, catchment managers could consider restricting other upstream flow reduction activities. This would comprise assessment of the efficacy of increased afforestation, the degree of invasion by alien riparian vegetation, and the prevalence of degraded, unproductive land as described in Section 11.4.1. Restrictions on river abstractions for irrigation in low flow months could be applied, with compensation flows being released from the Smithfield Dam for off-channel storage in March, as suggested in Section 11.4. 2.

11.4.4 Results of RVA application at Mkomazi IFR Site 4

Table 11.4 shows that the alteration of the hydrological regime at IFR Site 4 as a result of present land use and Phase 1 of the MMTS is very similar to that at IFR Site 3 and only salient features are described in this Section.

Months with high flows at this site still show little alteration from the natural flow regime, as indicated in Figure 11.4 (a). There is some abatement of the MMTS impacts on the non-attainment of the RVA targets during the low flow season, with fewer monthly flows occurring *below* the lower target range, *e.g.* 36 at this site (Table 11.4) compared with 44 at IFR Site 3 (Table 11.3) in August. However, the low flow season is still unnaturally extended.

High flow season multi-day maximum extremes show lower attainment of the RVA targets than at IFR Site 3, with more occurrences *below* the lower threshold, *e.g.* 24 at this site (Table 11.4) compared with 18 (Table 11.3) at IFR Site 3 for the 7-day maximum. There is, however, enhanced attainment of the RVA targets for high pulses and their durations. These factors suggest that while the impacts of the Smithfield Dam in attenuating high flows impose hydrological alteration some distance downstream, the contribution of streamflows from the catchment drainage area supplementing this river reach re-introduces some semblance of the natural catchment hydrological dynamics.

Table 11.4 RVA Score Card: Mkomazi IFR Site 4

Parameter		Pre-impact period October 1894 - September 1945 (51 years)				Post-impact period October 1945 - September 1996 (51 years)				RVA TARGETS		HYDROLOGIC ALTERATION
		Medians	Coefficient of Variance	Range Limits		Medians	Coefficient of Variance	Range Limits				
				Low	High			Low	High	Low	High	
Group 1	**Units**											
October	$m^3.s^{-1}$	13.00	0.85	3.40	217.70	5.50	1.18	1.60	197.70	8.98	19.97	-0.65
November	$m^3.s^{-1}$	26.40	0.68	7.00	117.40	12.30	1.23	2.00	86.80	16.86	34.80	-0.65
December	$m^3.s^{-1}$	38.00	0.83	7.00	202.30	24.30	1.36	2.60	172.30	25.77	57.16	-0.35
January	$m^3.s^{-1}$	62.30	0.80	8.80	198.50	49.20	1.02	2.20	180.50	39.41	89.25	-0.12
February	$m^3.s^{-1}$	71.10	0.77	12.30	218.90	56.40	0.83	3.60	197.30	44.00	99.07	0.00
March	$m^3.s^{-1}$	70.60	0.67	22.80	292.70	56.60	0.77	4.40	269.90	46.88	93.88	0.08
April	$m^3.s^{-1}$	43.00	0.63	8.20	135.10	31.90	0.81	3.00	122.30	29.15	56.32	-0.23
May	$m^3.s^{-1}$	26.00	0.49	4.20	340.70	15.50	0.76	1.90	318.10	20.42	33.10	-0.62
June	$m^3.s^{-1}$	17.70	0.54	2.70	53.70	8.90	0.87	1.20	37.80	12.67	22.32	-0.85
July	$m^3.s^{-1}$	12.30	0.62	3.30	125.90	4.60	0.93	1.30	106.90	8.56	16.19	-0.85
August	$m^3.s^{-1}$	10.60	0.93	2.90	57.30	4.00	1.31	1.30	38.50	7.36	17.23	-0.50
September	$m^3.s^{-1}$	9.90	0.94	2.70	352.70	4.00	0.96	1.60	333.20	6.83	16.19	-0.69
Group 2												
1-day minimum	$m^3.s^{-1}$	4.10	0.57	1.20	12.90	1.80	0.39	0.70	4.20	3.24	5.57	-0.96
3-day minimum	$m^3.s^{-1}$	4.20	0.60	1.20	12.90	1.90	0.36	0.90	4.40	3.30	5.82	-0.96
7-day minimum	$m^3.s^{-1}$	4.70	0.46	1.30	12.70	2.00	0.37	1.00	4.50	3.84	5.98	-0.96
30-day minimum	$m^3.s^{-1}$	5.70	0.51	1.60	14.20	2.40	0.53	1.20	5.20	4.84	7.77	-0.92
90-day minimum	$m^3.s^{-1}$	8.40	0.69	2.70	21.80	3.10	0.84	1.40	32.10	6.64	12.47	-0.73
1-day maximum	$m^3.s^{-1}$	283.40	0.77	83.70	3687.20	239.90	0.77	33.90	3742.20	211.50	430.46	-0.19
3-day maximum	$m^3.s^{-1}$	233.50	0.86	70.00	2780.80	197.50	0.71	27.80	2717.00	174.37	375.75	-0.23
7-day maximum	$m^3.s^{-1}$	167.60	0.75	59.10	1803.40	137.90	0.85	17.80	1741.80	127.69	253.01	-0.42
30-day maximum	$m^3.s^{-1}$	103.70	0.74	35.80	538.10	88.00	0.83	13.00	509.80	77.64	154.19	-0.27
90-day maximum	$m^3.s^{-1}$	77.80	0.67	27.50	230.30	61.10	0.79	10.80	211.40	58.22	110.21	-0.12
Number of zero days	number	0	0	0	0	0	0	0	0	0	0	0
Base flow	fraction of total flow	0.13	0.48	0.05	0.25	0.08	0.54	0.03	0.37	0.10	0.16	-0.58
Group 3												
Date of minimum	day	275.5	0.07	227	339	273	0.08	30	355	269.25	296	-0.15
Date of maximum	day	39	0.2	6	365	40	0.19	6	365	36.25	256.25	0
Group 4												
Low Pulse Count	number	7	1	0	21	9	0.47	2	19	4	11	0.21
Low Pulse Duration	days	10.40	0.73	0.00	65.00	15.90	0.65	6.10	66.50	6.33	13.91	-0.31
High Pulse Count	number	9.5	0.53	3	23	9	0.58	0	23	7	12	-0.1
High Pulse Duration	days	7.60	1.23	1.70	46.80	5.60	1.27	0.00	56.70	4.43	13.73	-0.04
Group 5												
Rise rate	$m^3.s^{-1}.day^{-1}$	16.30	0.51	7.00	51.40	8.90	0.42	1.80	32.80	12.69	21.08	-0.77
Fall rate	$m^3.s^{-1}.day^{-1}$	-5.00	-0.42	-14.00	-2.30	-5.00	-0.60	-17.20	-1.00	-6.02	-3.93	-0.31
Number of reversals	number	112.50	0.14	87.00	136.00	170.00	0.12	137.00	210.00	102.00	118.00	-1.00

Comparison of Statistics Within, Above and Below RVA Range

Parameter	Within		RVA Range	Above		RVA Range	Below		RVA Range
	Expected	Observed	Alteration	Expected	Observed	Alteration	Expected	Observed	Alteration
Group 1									
October	26	9	-0.65	13	6	-0.54	12	36	2
November	26	9	-0.65	13	8	-0.38	12	34	1.83
December	26	17	-0.35	13	8	-0.38	12	26	1.17
January	26	23	-0.12	13	9	-0.31	12	19	0.58
February	26	26	0	13	9	-0.31	12	16	0.33
March	26	28	0.08	13	6	-0.54	12	17	0.42
April	26	20	-0.23	13	10	-0.23	12	21	0.75
May	26	10	-0.62	13	7	-0.46	12	34	1.83
June	26	4	-0.85	13	8	-0.38	12	39	2.25
July	26	4	-0.85	13	6	-0.54	12	41	2.42
August	26	13	-0.5	13	2	-0.85	12	36	2
September	26	8	-0.69	13	4	-0.69	12	39	2.25
Group 2									
1-day minimum	26	1	-0.96	13	0	-1	12	50	3.17
3-day minimum	26	1	-0.96	13	0	-1	12	50	3.17
7-day minimum	26	1	-0.96	13	0	-1	12	50	3.17
30-day minimum	26	2	-0.92	13	0	-1	12	49	3.08
90-day minimum	26	7	-0.73	13	1	-0.92	12	43	2.58
1-day maximum	26	21	-0.19	13	10	-0.23	12	20	0.67
3-day maximum	26	20	-0.23	13	10	-0.23	12	21	0.75
7-day maximum	26	15	-0.42	13	12	-0.08	12	24	1
30-day maximum	26	19	-0.27	13	8	-0.38	12	24	1
90-day maximum	26	23	-0.12	13	6	-0.54	12	22	0.83
Number of zero days	51	51	0	0	0	0	0	0	0
Base flow	26	11	-0.58	13	3	-0.77	12	37	2.08
Group 3									
Date of minimum	27	23	-0.15	12	9	-0.25	12	19	0.58
Date of maximum	26	26	0	13	14	0.08	12	11	-0.08
Group 4									
Low Pulse Count	33	40	0.21	10	9	-0.1	8	2	-0.75
Low Pulse Duration	26	18	-0.31	13	32	1.46	12	1	-0.92
High Pulse Count	30	27	-0.1	12	8	-0.33	9	16	0.78
High Pulse Duration	26	25	-0.04	13	6	-0.54	12	20	0.67
Group 5									
Rise rate	26	6	-0.77	13	3	-0.77	12	42	2.5
Fall rate	26	18	-0.31	13	17	0.31	12	16	0.33
Number of reversals	28	0	-1	12	51	3.25	11	0	-1

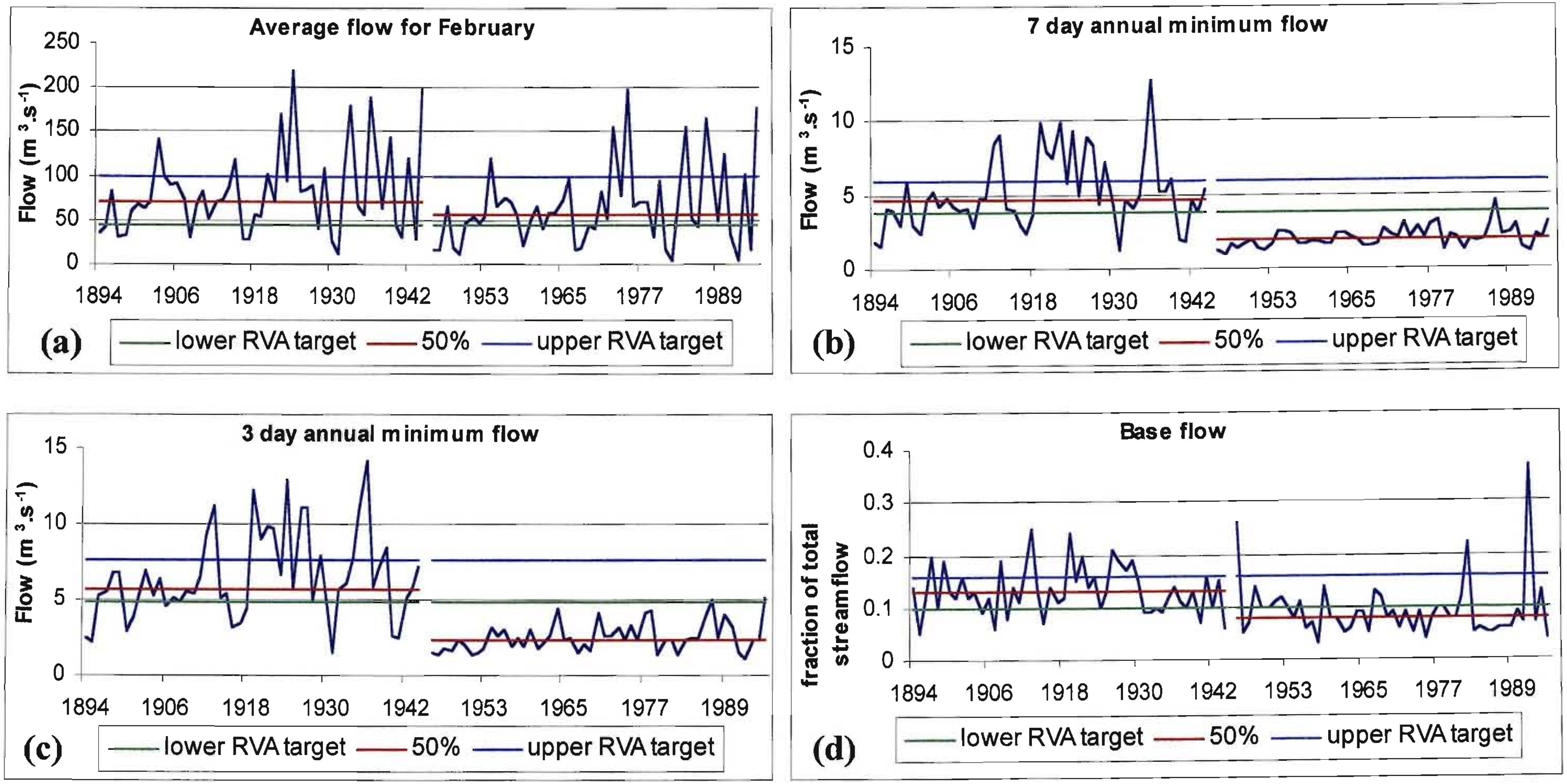

Figure 11.4 Examples of changes in the hydrological regime, together with potential upper (75th percentile) and lower (25th percentile) RVA management targets, at IFR Site 4 on the Mkomazi River

Notwithstanding the enhancement of the low flow component of the hydrological regime, Figures 11.4 (b) and (c) indicate the degree of non-attainment for the 7-, 3- and 1-day annual minimums for post-dam conditions. In all instances 50 of the median occurrences are *below* the lower RVA target (Table 11.4). Figure 11.4 (d) indicates a similar trend for the baseflow component where 37 of the median occurrences resulting from post dam conditions are below the lower RVA target (Table 11.4).

River management issues concerning the modified streamflow regime at this site are similar to those at IFR Site 3. Nonetheless, the shift to the 90-day annual minimum flow being the greatest change in hydrological alteration at this site (see Section 10.4.4) is indicative of the impacts of the land use of the catchment draining into this reach. As discussed in Chapters 6 and 8, irrigated agriculture in these subcatchments severely restricts the generation of downstream flows to the Mkomazi River, particularly in the low flow season. It is therefore recommended that as well as the suggestions for effective operating rules for the Smithfield Dam provided in Sections 11.4.2 and 11.4.3, that catchment managers place high priority on overhauling current irrigation practices (*e.g.* increase application efficiency) to mitigate the impacts of these abstractions on downstream flows.

11.5 Conclusions Regarding the Review of the Applicability of the RVA for Mkomazi Streamflows

The major benefit of the RVA is that preliminary targets, designed to protect natural aquatic biodiversity and aquatic ecosystems, can be set using either historical hydrological data or simulated hydrological information and without the necessity to procure extensive biological data or ecological expertise. The absence of adequate aquatic ecosystem and climatic data, as well as for observed runoff, is common for South African catchments and rivers. Consequently, there is great scope for the application of the RVA in South African catchments where river management objectives for the Reserve have yet to be ascertained. By setting preliminary flow management thresholds which can be modified and refined when ecological data and information becomes available, the approach incorporates flexibility and adaptability. These attributes could prove to be instrumental to resolving water resource management issues.

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

12 DISCUSSION

The results of each component of assessment of the impacts of land use and proposed development on the hydrological dynamics of the Mkomazi Catchment for potential catchment management strategies were discussed separately in Chapters 6 - 11. The purpose of this chapter is to:

(a) integrate the research findings,

(b) identify the shortcomings as well as the benefits of the methodologies available for hydrological modelling to meet the needs of water resources management, and to

(c) present an overview of the implications of the results.

There has been considerable debate in South African hydrological and water resource management groups as to the relative merits of different classifications of "natural" cover to use as a baseline for impacts of land cover assessments. However, as concluded by Schulze (2000), Acocks' (1988) Veld Types remains a respected and credible classification of the vegetation of South Africa. Moreover, Acocks' (1988) has been accepted by the DWAF as the baseline against which hydrological responses can be made objectively (*e.g.* in current streamflow reduction research carried out by CSIR and BEEH under DWAF's auspices). The need for "naturalised flows" as a point of reference, or as a baseline level, was shown to be fundamental to the hydrological modelling applications for water resources management in the Mkomazi Catchment. Such a necessity was confirmed in Chapters 6, 7, and 8 for comparing streamflow reductions resulting from particular land uses and in Chapters 9, 10 and 11 for assessing the extent of hydrological alteration to the natural streamflow regime as a result of catchment development. Therefore, the extensive application of Acocks' as the "baseline" land cover in the Mkomazi case study in this dissertation is not only appropriate, but can be expected to have contributed to the reliability of the results.

Similarly, the basis of the assessment of present land use within the Mkomazi Catchment relied on interpretation of the attributes of the CSIR's National Land Cover map, another respected and valued national asset. The results of the verification study in Chapter 5 provide credibility in the application of this land cover base and confirm the efficacy of the approach and procedures applied in the data acquisition and preparation for the model menu input.

The assessment of catchment development within the Mkomazi (in Chapters 6, 7 and 8) indicates that the upper portion of this catchment, where there is little alteration between the *annual quantity* of streamflows from present land use and those from the baseline cover, has considerable potential to augment the water resources of the neighbouring Mgeni system. The evaluation of water use by various sectors in Chapter 8 indicates that present-day anthropogenic water use in relation to the total annual flows of the Mkomazi River is minimal. Even after the first phase of the inter-basin transfer to the Mgeni, the Mkomazi's water yield is more than sufficient to sustain further development and the main downstream flows show considerable recovery. The environmental demand will account for nearly one third of the annual Mkomazi streamflows, with greatest demand at the uppermost IFR site. The first phase of the MMTS demand will also account for nearly one third of annual streamflows in the upper Mkomazi Catchment. However, the consequence of satisfying these water-sector demands results in nearly one-third of Mkomazi streamflows remaining for further allocation. This is encouraging for Umgeni Water, the regional water board, since they anticipate a water resource management strategy that incorporates the regulation of water allocation and licensing within the Mkomazi Catchment to meet projected water demand in the Mgeni system.

However, the impact of transferring water from the Mkomazi to the Mgeni system will impact heavily on the natural flow regime downstream from the proposed dam site, particularly in low flow months. This factor has been anticipated by the DWAF, who acted to mitigate any harmful flow reductions by initiating the assessment of instream flow requirements for the Mkomazi Catchment. Instream flow assessments are typically applied in order to ameliorate disturbances to, or to sustain the natural flow regime, of those rivers which have already been impounded or where impoundments are planned. The aim of the Mkomazi instream flow study in 1998 was to assess the flow requirements of the extant aquatic organisms and to develop a recommendation for the flows needed to assure maintenance of the riverine ecosystems.

Three different categories of assessment method, each with different approaches, have been reviewed in this dissertation (Chapter 3). Assessments by historical flow and hydraulic methods are related to river size and the attempt to preserve the character of the river. Habitat methods make no assumption regarding the natural conditions, but are based on water depth and velocity requirements of target species. In this way historical flow and hydraulic methods assume that flows lower than those occurring under natural conditions would result in degradation of the ecosystem, whereas habitat methods present the possibility that ecosystems could be *improved* by flows other than those occurring naturally. Moreover, while habitat methodologies are the most complex, they are not necessarily holistic.

The instream flow requirements for the Mkomazi River were assessed by the DWAF using the BBM methodology, a procedure considered by its proponents to be holistic. The BBM workshop process resulted in IFR Tables comprising values relating to the recommended modified flow regime for the Mkomazi River. It was found in this study (Chapter 9) that while the BBM process would conserve the trends of the natural flow regime of the Mkomazi River, several of the workshop recommendations may need to be reassessed if the present state class of the river is to be enhanced. However, it must be borne in mind that the BBM process did not have the luxury of having a time series of streamflows generated at the IFR sites, nor with the detail of the *ACRU* menu configuration.

Notwithstanding this observation, the purpose of the BBM tables is essentially to identify the *minimum flow* required to sustain ecosystems and facilitate maintenance of the river at a pre-defined desired state. The IFR Tables do build seasonality into the recommended regime. However, a concern regarding the IFR Tables is that they may be interpreted as being the *actual* monthly requirements of rivers rather than a *recommended minimum.* As stated by the developers of the BBM, the values relating to the magnitude, timing and occurrence of flows still have to be transformed into a daily hydrograph for efficient dam operating rules using the current catchment climate as a cue for release (Hughes and Ziervogel, 1998). Hughes and colleagues at the IWR, at Rhodes University have made considerable progress in this field with their IFR and DAMIFR models (Hughes *et al.*, 1997 and Hughes and Zeirvogel 1998 respectively). The investigation of operating rules for the proposed Smithfield Dam was outside the remit of this dissertation study and remains a challenge for installed modelling systems such as that now existing for the Mkomazi.

In South Africa the assessment of flow requirements of rivers has become all the more urgent in light of the NWA, which sets aside a Reserve to be met before any other water allocations can be made. With the exception of the rapid desktop methodology described in Section 3.8, the environmental flow assessment methodologies currently employed in South Africa all rely on considerable ecological data, information and expertise. The developers of the BBM and its derivatives, together with the developers of the recently formed DRIFT methodology stand firm in their conviction that determining the link between river condition and river flows requires input from ecological sources and expertise.

According to Richter *et al.* (1997), virtually all methods for determining instream flow needs have the propensity to lead to inadequate protection of ecologically important flow variability, and ultimately to the loss of aquatic biodiversity and ecosystem integrity. Nonetheless, historical flows can be very useful in the determination of the streamflows and characteristics of the hydrological regime required for aquatic ecosystem functioning. The IHA and RVA studies in Chapters 10 and 11 have shown that management targets can be set for river / aquatic ecosystem maintenance without the necessity of having ecological data. However, both the IHA and RVA methodologies focus on ecologically relevant hydrological parameters and the RVA approach prescribes targets that occur within natural streamflow regimes. These methodologies have experienced limited application in the assessment of the streamflow regimes required to sustain aquatic biodiversity and to protect the water resource base of South African rivers. However, the uncomplicated approach could offer water resource managers considerable potential as a preliminary assessment of the ***range of flows*** required for aquatic ecosystem functioning.

It is very important that not only the end-user, *per se*, but also their requirements are identified and defined at the outset of any catchment management study. Identifying the issues of concern for the Mkomazi Catchment set the scope of the study and allowed for the formulation of an approach to address those issues. The application of scenario studies under more extreme climatic (1:5 year) conditions, seasonal low flows and potential climate change was considered essential to clarify which subcatchments and which land uses within the Mkomazi Catchment posed the greatest risk to the efficiency of any management strategies. The success of this study is the assimilation of hydrological criteria into an appropriately configured daily model resulting in an "Installed Modelling

System" for the Mkomazi. The benefit of such a system is that analysis of development scenarios requires relatively little effort and can be expected to produce reliable answers.

13 CONCLUSIONS

Each of the chapters in this dissertation concluded with salient points relating to the topics addressed. Therefore, this chapter is intended as a general conclusion of the findings of the research study.

Water resource managers in South Africa are presently faced with challenges that call for careful planning if the predicted national water crisis by 2025 is to be avoided. The Mkomazi study has indicated that there is a defined need for useful guidance that allows water planners and managers to assess the impacts of potential development on available water resources.

In the past, the construction of large dams was viewed as being synonymous with development. However, this conception has been reviewed and the NWA promotes more conservative water resource management strategies, including the setting aside of a "Reserve" to protect the basic health requirements of humans and the ecological functioning of rivers. The provision of protection for environmental flow requirements by the NWA represents significant recognition of the need to mitigate the detrimental impacts of anthropogenic modification of natural systems and processes. Goals of environmental protection are to be commended. However, where there is potential conflict for water, particularly in water stressed regions where human demands for water supplies are increasing, the levels of environmental protection should be set realistically and holistically.

The characteristics of natural flows, including seasonal variability, pulses and flushing flows for maintenance and drought flow requirements are predominantly addressed for South African rivers by the BBM instream flow assessment methods. However, inadequate data and relative inexperience, or caution on the part of the evaluators, may all contribute to either the under- or over-assessment of the minimum flow required for sustaining the biological and physical river processes. Moreover, the quantification of the Reserve has highlighted the need for more rapid assessment methodologies to be applied. The major response to this need in South African hydrological groups has been an adaptation of the existing methodologies. However, the research component of this dissertation has provided some insight to the trends emerging at tackling some of the complexities of evaluating how much water is required to sustain aquatic ecosystems. Research aimed at enhancing instream flow methodologies for the preliminary Reserve could be directed to make more use of historical flow records and statistical analyses of those flows that occur in the natural flow regime.

The assessment of the availability of water resources within South African catchments has become a major national concern. This has become prominent at a time when water resource managers face a whole gamut of issues relating to the equitable and sustainable development of catchment resources. Decisions must be made not only as to which water use sector receives priority under different climatic conditions, but also which water use represents the best value for money. Ideally, the choice should also represent catchment development that is sustainable for human development, while simultaneously protecting the ecosystems that form the resource base.

The overall aim of the research component of this dissertation was to formulate a modelling approach that would assist the water resource managers of the Mkomazi Catchment in their decision-making processes. The catchment issues have been described as those pertaining to water allocation to meet the needs of not only the Mkomazi system, but also those of the Mgeni system. The processes available for the protection of the Mkomazi's environmental flows have been described, with particular attention given to the impact of the construction of the proposed Smithfield Dam on the variability of streamflows. Water allocations of the Mkomazi streamflows, particularly in periods of low flow, are likely to lead to conflict between different demand sectors unless effective reservoir release operating rules are developed.

While these factors contribute additional complexity to any management strategy, hydrological modelling, in the provision of installed hydrological modelling systems can play an important role in value-based decision-making processes.

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Table A1 Mkomazi subcatchment distribution of present land cover and land use (based on a regrouping of the National Land Cover Classification to LANDSAT TM imagery; CSIR 1996)

SC and QC Numbers		Total Area (km^2)	Forest (km^2)	Plantation (km^2)	Valley Bushveld (km^2)	Dryland (km^2)	Urban (km^2)	Grassland (km^2)	Wetland (km^2)	Channel (km^2)	Dams & Irrigation (km^2)
1	U10B	162.914	0.001	0.401	0.866	0.001	0.001	160.538	0.001	1.095	0.010
2	U10B	63.323	0.001	0.806	0.001	0.001	0.001	61.635	0.001	0.867	0.010
3	U10B	141.668	0.001	6.659	4.196	0.636	15.269	113.357	0.001	1.535	0.032
4	U10B	29.216	0.001	1.952	0.833	0.001	17.551	8.156	0.001	0.712	0.010
5	U10A	142.968	0.237	0.001	0.001	0.001	0.001	141.636	0.001	1.081	0.010
6	U10A	57.758	0.825	0.173	0.001	0.001	0.001	55.799	0.001	0.946	0.010
7	U10A	208.006	0.268	2.804	12.608	5.258	11.196	172.560	0.001	2.712	0.597
8	U10D	47.091	0.001	0.001	0.046	0.007	25.206	20.334	0.001	1.484	0.010
9	U10D	189.227	0.001	0.545	5.806	0.649	0.001	179.017	0.946	1.464	0.801
10	U10D	77.443	0.001	4.191	1.879	19.236	4.029	44.327	0.001	1.137	2.641
11	U10C	93.123	0.208	1.569	0.001	0.001	0.001	89.965	0.001	1.367	0.010
12	U10C	32.865	0.140	0.606	0.001	1.084	0.001	29.126	0.001	0.360	1.546
13	U10C	148.147	0.001	12.190	1.323	4.685	0.318	123.587	0.001	2.144	3.898
14	U10D	29.970	0.001	2.026	0.289	6.071	3.478	17.607	0.001	0.487	0.010
15	U10E	18.867	0.001	0.001	0.001	10.052	0.229	8.378	0.001	0.195	0.010
16	U10E	70.939	1.337	0.422	7.124	1.990	8.517	50.614	0.001	0.924	0.010
17	U10E	69.655	1.214	3.213	3.537	0.350	0.351	59.695	0.001	0.618	0.676
18	U10E	158.546	8.802	27.145	7.589	2.276	22.561	86.517	0.001	3.644	0.010
19	U10F	77.690	5.952	12.981	3.241	2.629	0.299	50.856	0.001	1.021	0.712
20	U10F	55.130	0.561	14.615	2.560	0.001	0.001	35.890	0.001	0.604	0.897
21	U10F	24.124	0.001	12.890	1.071	0.617	0.001	9.009	0.001	0.474	0.060
22	U10F	9.061	1.195	3.146	1.065	0.001	0.206	3.182	0.001	0.256	0.010
23	U10F	145.818	5.155	1.517	3.010	29.196	41.336	63.457	0.001	2.085	0.060
24	U10F	65.329	0.001	3.103	3.517	12.166	30.415	15.622	0.001	0.494	0.010

SC and QC Numbers		Total Area (km^2)	Forest (km^2)	Plantation (km^2)	Valley Bushveld (km^2)	Dryland (km^2)	Urban (km^2)	Grassland (km^2)	Wetland (km^2)	Channel (km^2)	Dams & Irrigation (km^2)
25	U10G	135.996	6.130	27.127	3.031	1.594	0.001	86.816	0.115	1.039	10.143
26	U10G	106.480	0.001	24.295	4.201	3.448	0.001	53.340	0.001	0.812	20.383
27	U10G	116.175	1.678	4.815	16.951	5.594	0.023	86.356	0.001	0.731	0.026
28	U10H	137.541	.0534	27.231	22.246	16.187	0.001	70.052	0.001	0.626	0.663
29	U10H	117.434	3.550	40.945	1.569	9.856	5.566	52.263	0.001	1.497	2.189
30	U10H	122.668	0.001	34.809	2.352	2.595	0.405	53.349	0.001	0.771	28.385
31	U10H	76.546	0.001	30.884	19.460	5.182	0.001	19.376	0.001	1.607	0.034
32	U10J	7.280	0.001	1.408	5.034	0.001	0.001	0.344	0.001	0.48	0.010
33	U10J	76.065	0.001	29.901	0.409	2.642	0.001	29.040	0.001	0.693	13.377
34	U10J	101.097	0.001	7.412	23.039	19.832	34.941	14.257	0.001	1.602	0.010
35	U10J	211.443	10.317	76.603	56.221	7.995	0.001	56.700	0.001	3.595	0.010
36	U10J	11.944	0.001	0.110	7.685	0.447	0.001	3.588	0.001	0.101	0.010
37	U10J	97.829	0.001	28.057	19.877	16.911	2.093	28.899	0.001	1.980	0.010
38	U10L	23.739	0.001	0.001	0.107	5.285	10.473	7.582	0.001	0.28	0.010
39	U10L	56.036	0.001	0.920	24.933	0.195	10.296	19.148	0.001	0.533	0.010
40	U10K	48.362	0.001	31.786	0.001	1.304	0.001	9.739	0.001	0.308	5.221
41	U10K	29.743	0.001	12.016	0.001	1.464	1.497	1.493	0.001	0.134	13.137
42	U10K	30.066	0.001	4.653	0.599	1.994	0.001	12.285	0.001	0.242	10.289
43	U10K	143.620	0.001	21.866	62.541	4.032	0.001	40.647	0.001	1.122	13.410
44	U10K	109.855	0.001	8.487	60.751	11.588	2.322	24.741	0.001	0.863	1.108
45	U10L	226.220	0.001	14.511	129.489	30.601	7.458	40.247	0.001	3.520	0.392
46	U10M	16.759	0.001	0.001	15.160	0.988	0.317	0.001	0.001	0.280	0.010
47	U10M	199.768	0.001	0.001	146.414	10.367	35.697	1.758	0.001	5.517	0.010
48	U10M	25.703	0.001	0.001	24.321	0.001	0.327	0.001	0.001	1.040	0.010
49	U10M	26.233	0.001	0.001	21.620	3.194	0.104	0.001	0.001	1.3	0.010
50	U10M	0.785	0.001	0.001	0.392	0.119	0.152	0.001	0.001	0.1065	0.010
51	U10M	2.297	0.001	0.001	0.623	0.391	0.936	0.001	0.001	.0333	0.010
52	U10M	5.717	0.001	0.001	3.544	0.780	0.821	0.426	0.001	0.132	0.010

NB Where a land use category was absent in a subcatchment, it was assigned a fictitiously small area of 0.001 km^2 (or 0.010 km^2 in respect of the dam and irrigation category) for computational purposes.

Table A2 Month-by-month input variables for the land use categories used in the Mkomazi study

ACRU category	LANDSAT TM Classification	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Forest	Forest	Water use coefficient	0.80	0.80	0.80	0.80	0.70	0.70	0.70	0.70	0.75	0.80	0.80	0.80
		Interception loss	2.50	2.50	2.50	2.00	2.00	2.00	2.00	2.00	2.00	2.50	2.50	2.50
		Roots in topsoil	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80
		Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Forest	Forest and Woodland	Water use coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
		Interception loss	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
		Roots in topsoil	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
		Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Plantation: (Pines: intermediate age, pitted)	Forest Plantation	Water use coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
		Interception loss	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
		Roots in topsoil	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Valley Bushveld	Thicket & Bushland	Water use coefficient	0.65	0.65	0.60	0.55	0.45	0.40	0.35	0.40	0.45	0.55	0.60	0.65
		Interception loss	1.60	1.60	1.60	1.40	1.20	1.10	1.10	1.10	1.20	1.45	1.55	1.60
		Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		Coefficient of I_a	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20
Dryland	Cultivated: permanent - commercial sugarcane	Water use coefficient	0.79	0.80	0.88	0.95	0.98	0.94	0.89	0.85	0.82	0.81	0.81	0.81
		Interception loss	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
		Roots in topsoil	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.25
Dryland	Cultivated: temporary - commercial dryland	Water use coefficient	0.89	1.10	0.96	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.35	0.60
		Interception loss	1.00	1.50	1.40	1.30	1.20	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		Roots in topsoil	0.79	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.25
Dryland	Cultivated: temporary - semi-commercial / subsistence dryland	Water use coefficient	0.80	0.70	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.60
		Interception loss	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.80
		Roots in topsoil	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.25
Urban	Barren rock	Water use coefficient	0.45	0.45	0.45	0.35	0.30	0.20	0.20	0.20	0.30	0.35	0.45	0.45
		Interception loss	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Coefficient of I_a	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Urban	Degraded: Thicket & Bushland	Water use coefficient	0.45	0.45	0.40	0.35	0.25	0.20	0.15	0.20	0.25	0.35	0.40	0.45
		Interception loss	1.40	1.40	1.40	1.20	1.00	0.90	0.90	0.90	1.00	1.25	1.35	1.40
		Roots in topsoil	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
		Coefficient of I_a	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

ACRU category	LANDSAT TM Classification	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jrban	Degraded: Unimproved Grassland	Water use coefficient	0.55	0.55	0.55	0.45	0.20	0.20	0.20	0.20	0.30	0.40	0.50	0.55
		Interception loss	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
		Roots in topsoil	0.90	0.90	0.90	0.94	0.94	0.94	0.80	0.80	0.80	0.80	0.80	0.80
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Jrban	Urban / built-up land: residential	Water use coefficient	0.80	0.80	0.70	0.60	0.40	0.40	0.40	0.40	0.60	0.70	0.80	0.80
		Interception loss	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.00	1.30	1.40	1.40
		Roots in topsoil	0.85	0.85	0.85	0.90	0.95	0.95	0.95	0.95	0.90	0.85	0.85	0.85
		Coefficient of I_a	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.30
Jrban	Urban / built-up land: residential (small holdings: bushland)	Water use coefficient	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
		Interception loss	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
		Roots in topsoil	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
		Coefficient of I_a	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Jrban	Urban / built-up land: transport	Water use coefficient	0.7 0	0.70	0.70	0.60	0.40	0.40	0.30	0.30	0.50	0.70	0.70	0.70
		Interception loss	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.20	1.40	1.40	1.40
		Roots in topsoil	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
		Coefficient of I_a	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
;rassland	Shrubland & low Fynbos	Water use coefficient	0.50	0.50	0.45	0.40	0.30	0.20	0.20	0.25	0.30	0.35	0.45	0.50
		Interception loss	0.80	0.80	0.80	0.80	0.75	0.70	0.60	0.70	0.75	0.80	0.80	0.80
		Roots in topsoil	0.80	0.80	0.80	0.90	0.90	1.00	1.00	1.00	0.90	0.90	0.80	0.80
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
;rassland Coastal forest nd thornveld)	Unimproved grassland	Water use coefficient	0.85	0.85	0.85	0.85	0.75	0.65	0.60	0.65	0.75	0.85	0.85	0.85
		Interception loss	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
		Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		Coefficient of I_a	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
;rassland Highland ourveld and .ohne sourveld)	Unimproved grassland	Water use coefficient	0.60	0.60	0.60	0.45	0.20	0.20	0.20	0.20	0.30	0.50	0.60	0.60
		Interception loss	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Roots in topsoil	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.90
		Coefficient of I_a	0.15	0.15	0.15	0.20	0.25	0.25	0.25	0.25	0.25	0.20	0.20	0.15
;rassland Ngongoni veld)	Unimproved grassland	Water use coefficient	0.65	0.65	0.65	0.55	0.50	0.30	0.30	0.30	0.45	0.55	0.60	0.65
		Interception loss	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
		Roots in topsoil	0.90	0.90	0.90	0.94	0.97	1.00	1.00	1.00	0.97	0.94	0.90	0.90
		Coefficient of I_a	0.15	0.15	0.20	0.25	0.25	0.25	0.25	0.25	0.25	0.20	0.20	0.15
;rassland Ngongoni veld of atal mist belt)	Unimproved grassland	Water use coefficient	0.63	0.63	0.63	0.50	0.35	0.25	0.25	0.25	0.40	0.53	0.63	0.63
		Interception loss	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
		Roots in topsoil	0.90	0.90	0.90	0.94	1.00	1.00	1.00	1.00	1.00	0.94	0.90	0.90
		Coefficient of I_a	0.15	0.15	0.15	0.20	0.25	0.25	0.25	0.25	0.25	0.20	0.2 0	0.15
;rassland Southern tall rassland)	Unimproved grassland	Water use coefficient	0.55	0.55	0.50	0.45	0.40	0.30	0.30	0.30	0.35	0.45	0.50	0.55
		Interception loss	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
		Roots in topsoil	0.80	0.80	0.80	0.80	0.90	0.95	0.95	0.95	0.95	0.80	0.80	0.80
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20

ACRU category	LANDSAT TM Classification	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Grassland (Themeda-festuca alpine veld)	Unimproved grassland	Water use coefficient	0.65	0.55	0.50	0.40	0.30	0.20	0.20	0.20	0.20	0.30	0.50	0.55
		Interception loss	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
		Roots in topsoil	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.94	0.90
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Wetland	Wetland	Water use coefficient	0.80	0.80	0.80	0.70	0.60	0.50	0.40	0.40	0.40	0.50	0.60	0.70
		Interception loss	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Channel	None identified	Water use coefficient	0.78	0.78	0.78	0.72	0.58	0.53	0.55	0.55	0.61	0.71	0.73	0.75
		Interception loss	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60
		Roots in topsoil	0.87	0.87	0.87	0.89	0.91	0.92	0.92	0.92	0.92	0.89	0.87	0.87
		Coefficient of I_a	0.23	0.23	0.23	0.23	0.30	0.30	0.30	0.30	0.30	0.30	0.23	0.23
Channel	None identified	Water use coefficient	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
		Interception loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Dams & Irrigation	Water Bodies	Water use coefficient	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
		Interception loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Dams & Irrigation	Improved Grassland	Water use coefficient	0.80	0.80	0.80	0.70	0.60	0.5 0	0.50	0.50	0.60	0.70	0.80	0.80
		Interception loss	1.40	1.40	1.40	1.40	1.20	1.00	1.00	1.20	1.30	1.40	1.40	1.40
		Roots in topsoil	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
		Coefficient of I_a	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.2 0
Dams & Irrigation (winter cabbages & spring potatoes)	Cultivated: temporary - commercial irrigated	Water use coefficient	0.20	0.20	0.50	0.70	0.70	0.40	0.60	0.80	0.20	0.20	0.20	0.20
		Interception loss	1.00	1.00	1.00	1.00	1.00	1.50	1.50	1.50	1.00	1.00	1.00	1.00
		Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Dams & Irrigation (citrus)	Cultivated: temporary - commercial irrigated	Water use coefficient	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
		Interception loss	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
		Roots in topsoil	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
		Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20

TableA3 Month-by-month factors used for adjustment of daily precipitation values in the "present land use" *ACRU* menus for the Mkomazi study area

Sub- and Quaternary Cat. Nos		**Daily Precipitation Adjustment Factors**											
SC	**QC**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	U10B	1.01	0.90	1.11	1.19	1.10	0.79	0.60	0.78	0.84	0.99	0.91	0.91
2	U10B	0.99	0.90	1.10	1.17	1.06	0.76	0.67	0.79	0.83	0.95	0.90	0.90
3	U10B	0.97	0.98	0.97	0.92	0.94	0.81	1.06	0.84	0.91	0.89	0.96	0.98
4	U10B	1.00	0.98	0.98	0.95	0.91	0.70	0.71	1.06	1.04	1.12	1.09	1.01
5	U10A	0.98	0.97	1.11	0.99	1.19	0.83	1.89	1.32	1.09	0.87	1.03	1.03
6	U10A	1.12	0.97	1.02	1.00	1.04	0.99	0.76	0.86	1.09	1.08	1.03	1.06
7	U10A	1.03	1.02	1.01	0.98	0.98	0.88	0.95	0.91	0.97	0.98	1.01	1.03
8	U10D	1.05	1.07	1.07	1.10	0.98	1.30	1.30	1.30	1.10	1.17	1.18	1.08
9	U10D	0.96	0.96	0.96	0.96	0.94	0.91	0.89	0.95	0.95	0.97	0.97	0.96
10	U10D	1.01	1.01	0.98	0.91	1.08	0.70	0.71	0.85	0.96	1.05	0.92	0.98
11	U10C	0.95	0.89	1.05	1.11	1.01	0.74	0.70	0.82	0.81	0.92	0.88	0.88
12	U10C	0.98	0.98	0.98	0.97	0.93	0.73	0.84	0.99	1.01	1.04	1.05	0.99
13	U10C	0.98	1.02	1.00	1.02	1.12	0.78	0.70	1.40	1.24	1.13	1.02	1.04
14	U10D	0.95	0.97	0.99	1.04	0.92	1.30	1.30	1.30	1.05	1.09	1.11	0.98
15	U10E	0.97	0.96	0.96	0.93	0.99	0.70	1.11	0.98	1.02	1.01	0.95	0.95
16	U10E	1.00	1.00	1.00	0.96	1.05	0.70	1.00	0.92	1.01	1.03	0.97	0.98
17	U10E	0.99	1.00	1.03	1.03	1.04	0.72	1.01	0.86	1.02	0.95	1.00	0.98
18	U10E	0.96	0.94	0.93	0.92	0.92	0.70	0.83	0.90	0.88	0.92	0.89	0.93
19	U10F	1.02	1.03	1.03	1.03	1.14	0.7	1.30	1.02	1.11	1.08	1.02	0.99
20	U10F	0.96	0.96	0.95	0.94	0.93	0.87	0.83	0.88	0.92	0.92	0.94	0.96
21	U10F	0.99	0.98	1.01	1.04	1.01	1.22	1.14	1.08	1.09	1.04	1.10	0.98
22	U10F	0.97	0.96	0.96	0.96	0.94	0.85	0.93	0.95	0.95	0.96	0.96	0.96
23	U10F	1.11	1.05	1.03	1.06	0.96	0.76	0.81	0.94	0.90	0.96	1.02	1.08
24	U10F	1.05	1.01	0.99	1.01	0.92	0.72	0.83	0.93	0.90	0.95	0.99	1.02
25	U10G	0.99	1.01	1.00	0.99	1.21	0.74	1.30	1.06	1.21	1.16	1.02	1.05
26	U10G	0.98	0.85	0.99	0.81	0.71	0.78	0.76	1.06	0.79	0.83	0.92	0.98
27	U10G	0.98	0.89	1.02	0.81	0.73	0.79	0.76	1.03	0.83	0.85	0.93	0.97
28	U10H	0.96	0.88	1.04	0.80	0.68	0.93	0.71	1.13	0.88	0.86	0.95	0.97
29	U10H	1.08	1.05	1.05	1.04	0.97	0.81	0.87	0.98	1.02	1.05	1.05	1.08
30	U10H	1.00	0.98	0.98	0.97	0.97	0.76	0.89	0.96	1.03	1.00	0.95	0.98
31	U10H	1.05	1.08	0.95	1.04	1.08	0.65	0.97	0.88	0.93	0.86	0.98	0.95
32	U10J	1.07	1.02	1.01	0.86	0.82	0.70	0.96	0.75	0.81	0.90	0.97	0.98
33	U10J	0.94	0.98	0.92	0.94	1.01	0.76	0.79	0.95	1.01	1.02	0.92	1.00
34	U10J	1.10	1.15	1.08	1.02	0.83	1.06	1.13	1.22	1.09	1.01	1.04	0.92
35	U10J	0.99	0.91	0.98	0.95	1.28	1.30	1.09	1.12	1.11	1.04	0.99	1.09
36	U10J	1.13	1.01	1.03	0.98	1.08	1.30	1.30	1.21	1.12	1.12	1.06	1.06
37	U10J	1.13	1.03	1.10	0.97	0.95	0.83	0.91	0.84	0.93	0.99	1.04	1.01
38	U10L	1.03	1.01	1.01	0.99	0.99	1.30	1.30	1.30	1.11	1.30	1.02	1.03
39	U10L	1.02	0.98	0.97	1.04	1.16	1.30	1.30	1.30	1.16	1.20	0.99	0.99
40	U10K	0.99	0.98	1.07	0.95	1.20	0.70	0.70	0.94	0.80	1.02	0.92	1.05
41	U10K	1.03	1.05	1.02	1.02	0.88	1.00	1.09	1.07	1.05	0.97	1.01	0.94
42	U10K	1.04	1.07	1.02	1.04	0.89	1.02	1.11	1.11	1.09	0.98	1.03	0.94
43	U10K	0.96	0.99	0.95	0.99	0.80	1.26	1.24	1.14	1.06	0.91	0.94	0.86
44	U10K	1.07	0.94	0.95	0.86	1.06	1.30	1.30	1.21	1.05	1.07	1.01	1.03
45	U10L	1.04	0.86	0.88	0.92	1.10	1.30	1.30	1.30	1.15	1.09	0.97	0.94
46	U10M	1.02	1.00	0.99	0.94	0.75	0.89	0.93	1.13	0.89	0.90	0.99	0.80
47	U10M	0.90	0.96	0.90	1.09	1.14	0.89	1.01	0.95	1.05	0.90	0.90	0.89
48	U10M	0.93	1.01	0.85	0.84	1.04	0.97	0.86	1.14	0.98	0.93	1.02	0.90
49	U10M	1.00	1.00	1.01	0.89	0.76	0.71	0.77	0.90	0.87	1.01	0.94	1.08
50	U10M	1.01	0.99	1.01	0.95	0.86	0.81	0.87	0.91	0.93	0.99	0.96	1.05
51	U10M	0.99	1.07	0.95	0.94	1.23	1.12	1.03	1.24	1.10	1.01	1.09	0.97
52	U10M	1.03	1.01	1.04	0.98	0.90	0.89	0.89	0.94	0.95	1.01	0.99	1.06

Table A4 Land Types identified in the Mkomazi study area

A	**RED-YELLOW APEDAL, FREELY DRAINED SOILS**										
	Aa	Humic soils > 40%									
		14	19	20							
	Ab	Red, dystrophic and / or mesotrophic									
		137	138	139	140	141	148	149	150	161	162
		163	164	165	166	171	172				
	Ac	Red and yellow dystrophic and / or mesotrophic									
		215	224	227	228	229	234	237	238	239	240
		241	242	243	244	245	246	247	248	250	254
		255	256	257	258	260	267	295	297	298	302
		306	307	309	312	313	314	315	316	317	318
		319	320	321	322	323	324	325	326	327	328
		329	330	331	332	333	334	335	336	337	338
		339	340	341	342	343	344	345	348	349	350
		351	352	353	354	355	356	357	358	395	396
	Ad	Yellow, dystrophic and / or mesotrophic									
		27	31								
B	**PLINTHIC CATENA: RARE UPLAND DUPLEX AND MARGALITIC SOILS**										
	Bb	Upland duplex / margalitic soils > 10%									
		114	118								
C	**PLINTHIC CATENA: COMMON UPLAND DUPLEX AND MARGALITIC SOILS**										
	Ca	Upland duplex / margalitic > 10%									
		101									
E	**ONE OR MORE OF VERTIC, MELANIC, OR RED STRUCTURED SOILS**										
	Ea	Vertic, melanic or red structured > 50%									
		195	196	203							
F	**GLENROSA AND / OR MISPAH SOILS**										
	Fa	Lime not encountered regularly									
		473	474	481	482	483	484	485	486	487	488
		524	541	542	543	544	545	546	547	548	550
		551	553	554	555	556	557	558	561	585	586
		587	591	640	692	694	695	696	697	698	699
		700	701	702	703	704	705	706	707	708	709
		710	711	712	713	714	715	716	717	718	719
		720	721	722	723	724	725	726	738	746	879
H	**GREY REGIC SANDS**										
	Hb	Deep grey sands > 20% , < 80%									
		92									
I	**MISCELLANEOUS SOILS**										
	Ic	Exposed country rock, stones or boulders > 80%									
		171									

Table A5 Mkomazi Catchment: Subcatchment soils related information

SC and QC Numbers		**Thickness of A horizon (m)**	**Thickness of B horizon (m)**	**Permanent Wilting Point (m.m^{-1})**		**Drained upper limit (m.m^{-1})**		**Porosity (m.m^{-1})**		**Saturated Redistribution (fraction.day^{-1})**		**Adjunct Impervious Area (fraction)**	**Disjunct Impervious Area (fraction)**
				A	**B**	**A**	**B**	**A**	**B**	**A - B**	**B - GW**		
1	U10B	0.22	0.22	0.138	0.147	0.229	0.244	0.438	0.420	0.34	0.34	0.015	0.198
2	U10B	0.23	0.26	0.135	0.149	0.227	0.246	0.441	0.422	0.37	0.37	0.012	0.128
3	U10B	0.26	0.41	0.143	0.174	0.236	0.266	0.432	0.417	0.39	0.39	0.018	0.076
4	U10B	0.23	0.27	0.146	0.167	0.238	0.259	0.433	0.417	0.35	0.35	0.036	0.107
5	U10A	0.22	0.25	0.142	0.158	0.233	0.253	0.435	0.417	0.34	0.34	0.016	0.214
6	U10A	0.23	0.30	0.144	0.164	0.239	0.263	0.433	0.422	0.37	0.37	0.023	0.175
7	U10A	0.24	0.34	0.141	0.170	0.232	0.259	0.437	0.418	0.37	0.37	0.020	0.104
8	U10D	0.25	0.36	0.152	0.186	0.242	0.275	0.426	0.413	0.36	0.36	0.038	0.086
9	U10D	0.23	0.29	0.147	0.166	0.236	0.254	0.425	0.404	0.34	0.34	0.017	0.126
10	U10D	0.26	0.42	0.139	0.178	0.222	0.255	0.408	0.387	0.37	0.37	0.024	0.080
11	U10C	0.22	0.24	0.138	0.148	0.228	0.242	0.441	0.420	0.34	0.34	0.013	0.166
12	U10C	0.26	0.38	0.137	0.171	0.225	0.256	0.432	0.413	0.39	0.39	0.028	0.045
13	U10C	0.27	0.41	0.138	0.175	0.229	0.261	0.435	0.414	0.40	0.40	0.026	0.070
14	U10D	0.28	0.47	0.144	0.192	0.231	0.270	0.431	0.410	0.40	0.40	0.035	0.048
15	U10E	0.28	0.49	0.151	0.189	0.245	0.282	0.425	0.413	0.38	0.38	0.017	0.138
16	U10E	0.28	0.47	0.145	0.190	0.234	0.272	0.429	0.410	0.40	0.40	0.027	0.104
17	U10E	0.27	0.44	0.156	0.177	0.254	0.282	0.418	0.415	0.38	0.38	0.016	0.064
18	U10E	0.29	0.51	0.158	0.196	0.251	0.290	0.423	0.417	0.37	0.37	0.017	0.073
19	U10F	0.29	0.51	0.148	0.189	0.241	0.279	0.426	0.412	0.38	0.38	0.015	0.068
20	U10F	0.30	0.55	0.162	0.200	0.262	0.310	0.409	0.419	0.38	0.38	0.019	0.044
21	U10F	0.31	0.55	0.163	0.207	0.259	0.309	0.413	0.419	0.38	0.38	0.024	0.032
22	U10F	0.30	0.52	0.165	0.194	0.267	0.309	0.408	0.421	0.37	0.37	0.018	0.067
23	U10F	0.27	0.45	0.173	0.205	0.260	0.294	0.429	0.426	0.34	0.34	0.020	0.068
24	U10F	0.28	0.49	0.181	0.217	0.264	0.298	0.437	0.430	0.33	0.33	0.022	0.043
25	U10G	0.29	0.50	0.143	0.190	0.232	0.271	0.430	0.408	0.40	0.40	0.013	0.092
26	U10G	0.28	0.49	0.146	0.190	0.235	0.273	0.427	0.409	0.39	0.39	0.014	0.041

SC and QC Numbers		Thickness of A horizon (m)	Thickness of B horizon (m)	Permanent Wilting Point (m.m^{-1})		Drained upper limit (m.m^{-1})		Porosity (m.m^{-1})		Saturated Redistribution (fraction.day^{-1})		Adjunct Impervious Area (fraction)	Disjunct Impervious Area (fraction)
				A	B	A	B	A	B	A - B	B - GW		
27	U10G	0.25	0.39	0.159	0.188	0.249	0.278	0.431	0.419	0.33	0.33	0.017	0.032
28	U10H	0.26	0.43	0.151	0.179	0.247	0.282	0.425	0.422	0.39	0.39	0.021	0.048
29	U10H	0.30	0.54	0.166	0.199	0.266	0.311	0.412	0.426	0.38	0.38	0.026	0.030
30	U10H	0.25	0.41	0.163	0.190	0.259	0.292	0.418	0.420	0.34	0.34	0.020	0.036
31	U10H	0.28	0.46	0.152	0.179	0.250	0.284	0.420	0.416	0.38	0.38	0.014	0.036
32	U10J	0.27	0.40	0.157	0.178	0.253	0.282	0.419	0.417	0.35	0.35	0.014	0.045
33	U10J	0.27	0.46	0.144	0.186	0.232	0.270	0.407	0.396	0.35	0.35	0.019	0.035
34	U10J	0.27	0.46	0.145	0.172	0.238	0.268	0.434	0.424	0.41	0.41	0.050	0.039
35	U10J	0.26	0.37	0.149	0.166	0.243	0.266	0.432	0.423	0.35	0.35	0.026	0.030
36	U10J	0.21	0.11	0.144	0.138	0.228	0.231	0.447	0.425	0.27	0.27	0.025	0.047
37	U10J	0.29	0.47	0.158	0.189	0.254	0.293	0.420	0.421	0.35	0.35	0.019	0.028
38	U10L	0.25	0.36	0.167	0.179	0.247	0.258	0.437	0.413	0.28	0.28	0.023	0.000
39	U10L	0.27	0.45	0.141	0.142	0.232	0.239	0.454	0.438	0.41	0.41	0.029	0.014
40	U10K	0.33	0.62	0.159	0.211	0.256	0.309	0.415	0.419	0.40	0.40	0.017	0.015
41	U10K	0.32	0.60	0.165	0.212	0.259	0.307	0.419	0.421	0.39	0.39	0.028	0.017
42	U10K	0.32	0.57	0.223	0.257	0.294	0.327	0.428	0.439	0.30	0.30	0.032	0.038
43	U10K	0.27	0.39	0.177	0.95	0.261	0.281	0.432	0.426	0.30	0.30	0.028	0.024
44	U10K	0.24	0.26	0.152	0.156	0.240	0.250	0.437	0.420	0.29	0.29	0.020	0.026
45	U10L	0.27	0.41	0.133	0.138	0.226	0.237	0.450	0.434	0.41	0.41	0.025	0.033
46	U10M	0.23	0.27	0.131	0.118	0.229	0.224	0.447	0.428	0.40	0.40	0.013	0.077
47	U10M	0.24	0.31	0.136	0.131	0.230	0.232	0.445	0.427	0.39	0.39	0.018	0.108
48	U10M	0.21	0.19	0.128	0.119	0.220	0.216	0.453	0.429	0.35	0.35	0.019	0.010
49	U10M	0.21	0.19	0.128	0.126	0.216	0.219	0.455	0.432	0.33	0.33	0.011	0.005
50	U10M	0.22	0.26	0.134	0.140	0.216	0.225	0.441	0.422	0.35	0.35	0.016	0.000
51	U10M	0.26	0.43	0.122	0.135	0.198	0.215	0.421	0.408	0.40	0.40	0.031	0.000
52	U10M	0.24	0.36	0.133	0.143	0.213	0.226	0.430	0.414	0.41	0.41	0.023	0.001

Table A6 Input information on dams in the Mkomazi study area

SC and QC Numbers		Number of Dams	Total Capacity - all Dams (m^3)	Total Surface Area - all Dams (ha)	Total Seepage** - Each, for all Dams ($m^3.day^{-1}$)	Normal Flow ($m^3.day^{-1}$)	Inter-Basin Transfer ($10^6m^3.month^{-1}$)
3	U10B	1	55 123	3.22	30.20	0	0
7	U10A	1	771 139	3.92	38.98	0	0
9	U10D	6	2 265 793	80.15	1241.53	0	0
10	U10D	2	155 673	8.29	85.30	0	0
12	U10C	2	422 266	17.97	231.38	0	0
13	U10C	1	48 184	2.91	26.40	0	0
17	U10E	6	959 639	41.12	525.83	0	0
19	U10F	7	1 818 672	71.16	996.53	0	0
21	U10F	3	89 337	5.96	48.95	0	0
* 23	U10F	1	137 000 000	583	0.00	91333	18.14
25	U10G	10	2 509 852	91.86	1375.26	0	0
26	U10G	11	730 529	39.47	400.29	0	0
27	U10G	2	42 319	2.69	23.19	0	0
28	U10H	3	72 371	5.07	39.66	0	0
29	U10H	4	3 249 871	80.05	1780.75	0	0
30	U10H	19	282 110	125.23	1549.65	0	0
31	U10H	1	58 283	3.36	31.94	0	0
33	U10J	2	117 955	6.75	64.63	0	0
39	U10L	1	4 323	0.45	2.39	0	0
40	U10K	4	441 646	20.05	242.00	0	0
41	U10K	10	1 508 845	55.50	826.76	0	0
42	U10K	6	1 924 595	56.15	1054.57	0	0
43	U10K	11	239 749	15.80	131.37	0	0
44	U10K	2	29 055	2.11	15.92	0	0

*proposed Smithfield Dam (phase 1)

**seepage from earth wall dams estimated at 0.0006 x full supply capacity per day, *i.e.* dam would empty in approximately 5 years

Table A7 Acocks' (1988) Veld Types in the Mkomazi Catchment and areal extents applied in baseline land cover simulations

Sub- and Quaternary Cat. Nos		Veld Types and Areal Extents (km^2)						
SC	QC	Coastal Forest and Thornveld	Ngongoni Veld	Valley Bushveld	Highland Sourveld and Döhne Sourveld	Ngongoni Veld of Natal Mist Belt	Southern Tall Grassland	Themeda-Festuca Alpine Veld
1	U10B	0	0	0	123.060	0	0	39.853
2	U10B	0	0	0	45.203	0	0	18.119
3	U10B	0	0	0	131.324	0	10.363	0
4	U10B	0	0	0	12.756	0	16.461	0
5	U10A	0	0	0	67.214	0	0	75.754
6	U10A	0	0	0	54.102	0	0	3.655
7	U10A	0	0	0	182.877	0	25.129	0
8	U10D	0	0	0	20.278	0	26.812	0
9	U10D	0	0	0	164.377	0	24.849	0
10	U10D	0	0	0	63.299	0	14.145	0
11	U10C	0	0	0	63.093	0	0	30.297
12	U10C	0	0	0	32.865	0	0	0
13	U10C	0	0	0	121.301	0	26.846	0
14	U10D	0	0	0	11.859	0	18.111	0
15	U10E	0	0	0	18.867	0	0	0
16	U10E	0	0	0	37.015	0	33.924	0
17	U10E	0	0	0	62.171	0	7.484	0
18	U10E	0	0	0	80.954	5.914	71.677	0
19	U10F	0	0	0	55.421	0	22.269	0
20	U10F	0	0	0	55.130	0	0	0
21	U10F	0	0	0	24.082	0.0416	0	0
22	U10F	0	0	0	7.624	1.436	0	0
23	U10F	0	0	0	31.685	44.496	69.636	0
24	U10F	0	0	0.772	0	28.011	36.545	0
25	U10G	0	0	0	128.472	7.523	0	0
26	U10G	0	0	0	50.684	53.058	2.738	0
27	U10G	0	0	9.789	2.774	52.77	50.840	0
28	U10H	0	0	31.930	10.696	64.126	30.790	0
29	U10H	0	0	4.684	42.255	365.997	34.497	0
30	U10H	0	0	2.008	59.801	35.937	24.915	0
31	U10H	0	0	30.284	0	31.331	14.931	0
32	U10J	0	0	4.133	0	0.735	2.411	0
33	U10J	0	0	0	27.087	48.977	0	0
34	U10J	0	47.771	23.530	0.055	29.741	0	0
35	U10J	0	50.037	82.091	18.089	53.266	7.958	0
36	U10J	0	6.454	5.489	0	0	0	0
37	U10J	0	65.452	27.126	0	5.251	0	0
38	U10L	0	23.282	0.456	0	0	0	0
39	U10L	0	44.039	12.002	0	0	0	0
40	U10K	0	0	0	11.946	36.416	0	0
41	U10K	0	0	0	1.456	28.286	0	0
42	U10K	0	0	0.747	0	29.319	0	0
43	U10K	0	16.782	50.182	0	76.660	0	0
44	U10K	0	30.717	68.202	0	10.935	0	0
45	U10L	9.853	117.435	98.932	0	0	0	0
46	U10M	16.002	0	0.758	0	0	0	0
47	U10M	76.013	35.149	88.605	0	0	0	0
48	U10M	25.703	0	0	0	0	0	0
49	U10M	26.233	0	0	0	0	0	0
50	U10M	0.785	0	0	0	0	0	0
51	U10M	2.297	0	0	0	0	0	0
52	U10M	5.716	0	0	0	0	0	0

Table A8 Month-by-month factors used for adjustment of A-pan equivalent values in the climate change menus for the *ACRU* model applied to the Mkomazi study area

Sub- and Quaternary Cat. Nos		**A-pan Equivalent Adjustment Factors**											
SC	**QC**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	U10B	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
2	U10B	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
3	U10B	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
4	U10B	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
5	U10A	1.09	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
6	U10A	1.09	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
7	U10A	1.09	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
8	U10D	1.10	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
9	U10D	1.10	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
10	U10D	1.10	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
11	U10C	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
12	U10C	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
13	U10C	1.09	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
14	U10D	1.10	1.10	1.07	1.10	1.10	1.07	1.08	1.08	1.08	1.05	1.07	1.06
15	U10E	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.06	1.06
16	U10E	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.06	1.06
17	U10E	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.06	1.06
18	U10E	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.06	1.06
19	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
20	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
21	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
22	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
23	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
24	U10F	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
25	U10G	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
26	U10G	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
27	U10G	1.10	1.10	1.07	1.10	1.10	1.08	1.08	1.08	1.08	1.05	1.07	1.06
28	U10H	1.10	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.09
29	U10H	1.10	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.09
30	U10H	1.10	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.09
31	U10H	1.10	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.09
32	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
33	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
34	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
35	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
36	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
37	U10J	1.09	1.10	1.07	1.10	1.10	1.02	1.08	1.08	1.08	1.05	1.06	1.06
38	U10L	1.09	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.06
39	U10L	1.09	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.06
40	U10K	1.09	1.10	1.07	1.09	1.10	1.08	1.08	1.08	1.08	1.08	1.05	1.06
41	U10K	1.09	1.10	1.07	1.09	1.10	1.08	1.08	1.08	1.08	1.08	1.05	1.06
42	U10K	1.09	1.10	1.07	1.09	1.10	1.08	1.08	1.08	1.08	1.08	1.05	1.06
43	U10K	1.09	1.10	1.07	1.09	1.10	1.08	1.08	1.08	1.08	1.08	1.05	1.06
44	U10K	1.09	1.10	1.07	1.09	1.10	1.08	1.08	1.08	1.08	1.08	1.05	1.06
45	U10L	1.09	1.10	1.07	1.10	1.09	1.08	1.08	1.08	1.08	1.05	1.07	1.06
46	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
47	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
48	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
49	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
50	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
51	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04
52	U10M	1.08	1.09	1.07	1.09	1.09	1.07	1.08	1.08	1.08	1.05	1.06	1.04

Table A9 Month-by-month factors used for adjustment of daily precipitation values in the climate change menus for the *ACRU* model applied to the Mkomazi study area

Sub- and Quaternary Cat. Nos		**Daily Precipitation Adjustment Factors**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	U10B	0.81	0.81	1.00	0.96	0.78	0.95	0.72	1.02	0.94	1.19	0.93	0.75
2	U10B	0.79	0.81	1.00	0.95	0.75	0.91	0.72	1.03	0.93	1.14	0.92	0.74
3	U10B	0.78	0.89	0.88	0.75	0.70	0.97	1.09	1.10	1.02	1.07	0.98	0.80
4	U10B	0.80	0.89	0.89	0.77	0.70	0.84	0.73	1.30	1.16	1.30	1.11	0.83
5	U10A	0.78	0.88	0.99	0.80	0.83	1.00	1.30	1.30	1.21	1.04	1.05	0.84
6	U10A	0.89	0.88	0.91	0.81	0.73	1.19	0.78	1.12	1.21	1.29	1.05	0.86
7	U10A	0.82	0.92	0.90	0.79	0.70	1.18	0.98	1.18	1.07	1.17	1.03	0.84
8	U10D	0.84	0.97	0.96	0.88	0.70	1.30	1.31	1.30	1.22	1.30	1.19	0.86
9	U10D	0.77	0.87	0.86	0.77	0.70	1.09	0.90	1.23	1.05	1.16	0.98	0.77
10	U10D	0.81	0.91	0.88	0.73	0.75	0.84	0.72	1.10	1.06	1.26	0.93	0.78
11	U10C	0.76	0.80	0.94	1.00	0.72	0.89	0.71	1.07	0.90	1.11	0.90	0.72
12	U10C	0.78	0.88	0.88	0.88	0.70	0.88	0.86	1.29	1.13	1.25	1.07	0.81
13	U10C	0.78	0.92	0.89	0.92	0.79	0.94	0.71	1.30	1.38	1.36	1.04	0.85
14	U10D	0.70	0.76	0.85	0.70	0.70	1.09	1.20	1.30	1.27	1.21	1.03	0.70
15	U10E	0.78	0.87	0.87	0.75	0.70	0.85	1.12	1.28	1.13	1.22	0.96	0.76
16	U10E	0.80	0.91	0.91	0.77	0.73	0.85	1.01	1.20	1.11	1.24	0.98	0.79
17	U10E	0.79	0.91	0.93	0.83	0.73	0.87	1.02	1.12	1.13	1.15	1.01	0.79
18	U10E	0.77	0.85	0.84	0.74	0.70	0.85	0.84	1.17	0.97	1.11	0.90	0.75
19	U10F	0.82	0.92	0.92	0.83	0.80	0.84	1.30	1.30	1.22	1.30	1.02	0.80
20	U10F	0.77	0.86	0.85	0.76	0.70	1.05	0.83	1.15	1.01	1.11	0.94	0.77
21	U10F	0.80	0.88	0.91	0.84	0.71	1.47	1.14	1.30	1.20	1.25	0.10	0.79
22	U10F	0.78	0.86	0.86	0.77	0.70	1.02	0.93	1.24	1.05	1.16	0.96	0.77
23	U10F	0.89	0.94	0.92	0.85	0.70	0.92	0.81	1.23	0.99	1.16	1.02	0.87
24	U10F	0.85	0.91	0.89	0.81	0.70	0.87	0.83	1.21	0.99	1.14	0.99	0.82
25	U10G	0.79	0.91	0.90	0.79	0.84	0.89	1.30	1.30	1.30	1.30	1.02	0.84
26	U10G	0.78	0.76	0.89	0.70	0.70	0.94	0.76	1.30	0.87	1.00	0.92	0.78
27	U10G	0.78	0.80	0.92	0.70	0.70	0.95	0.76	1.30	0.91	1.02	0.93	0.77
28	U10H	0.77	0.80	0.93	0.70	0.70	1.12	0.71	1.30	0.97	1.03	0.96	0.79
29	U10H	0.86	0.95	0.94	0.83	0.70	0.97	0.87	1.28	1.13	1.26	1.06	0.87
30	U10H	0.80	0.89	0.88	0.78	0.70	0.91	0.89	1.25	1.14	1.20	0.96	0.79
31	U10H	0.84	0.98	0.85	0.83	0.76	0.78	0.97	1.15	1.03	1.03	0.99	0.77
32	U10J	0.85	0.91	0.90	0.70	0.70	0.83	0.96	0.97	0.89	1.08	0.97	0.78
33	U10J	0.75	0.86	0.82	0.75	0.71	0.91	0.79	1.23	1.11	1.23	0.92	0.80
34	U10J	0.88	1.03	0.97	0.81	0.70	1.26	1.13	1.30	1.19	1.21	1.04	0.73
35	U10J	0.79	0.81	0.88	0.76	0.90	1.30	1.09	1.30	1.22	1.25	0.99	0.87
36	U10J	0.90	0.90	0.92	0.78	0.76	1.30	1.30	1.30	1.23	1.30	1.06	0.85
37	U10J	0.90	0.92	0.98	0.77	0.70	0.99	0.91	1.09	1.02	1.19	1.04	0.81
38	U10L	0.82	0.91	0.90	0.80	0.70	1.56	1.30	1.30	1.23	1.30	1.03	0.83
39	U10L	0.81	0.89	0.87	0.84	0.81	1.56	1.30	1.30	1.28	1.30	1.00	0.80
40	U10K	0.80	0.89	0.96	0.77	0.84	0.84	0.70	1.23	0.89	1.24	0.94	0.86
41	U10K	0.83	0.95	0.92	0.82	0.70	1.20	1.09	1.30	1.17	1.18	1.03	0.77
42	U10K	0.84	0.97	0.92	0.84	0.70	1.23	1.11	1.30	1.21	1.19	1.05	0.77
43	U10K	0.77	0.90	0.85	0.80	0.70	1.30	1.24	1.30	1.18	1.11	0.96	0.70
44	U10K	0.86	0.85	0.85	0.70	0.75	1.30	1.30	1.30	1.17	1.30	1.03	0.84
45	U10L	0.83	0.78	0.79	0.74	0.77	1.30	1.30	1.30	1.27	1.30	0.98	0.76
46	U10M	0.82	0.92	0.87	0.77	0.70	1.07	0.93	1.30	1.00	1.10	1.05	0.70
47	U10M	0.73	0.88	0.79	0.89	0.79	1.07	1.01	1.25	1.18	1.10	0.96	0.74
48	U10M	0.75	0.93	0.75	0.70	0.72	1.17	0.86	1.50	1.10	1.14	1.08	0.75
49	U10M	0.81	0.92	0.89	0.73	0.70	0.85	0.77	1.18	0.98	1.24	1.00	0.90
50	U10M	0.81	0.91	0.89	0.78	0.70	0.98	0.87	1.20	1.04	1.21	1.02	0.88
51	U10M	0.80	0.98	0.83	0.77	0.85	1.35	1.03	1.63	1.23	1.24	1.16	0.81
52	U10M	0.83	0.93	0.91	0.80	0.70	1.07	0.89	1.24	1.07	1.24	1.05	0.89

APPENDIX B

Table B1 Population and livestock distribution and density by subcatchment in the Mkomazi Catchment

SC No	QC No	Area (km^2)	Population				Livestock Units			
			Rural	Urban	Total	Density (per km^2)	Large	Small	Total	Density (per km^2)
1	U10B	162.91	127	377	504	3	3516	1863	5379	1739
2	U10B	63.32	182	584	766	12	126	632	758	63
3	U10B	141.69	95	409	504	4	1392	1133	2525	710
4	U10B	29.22	80	402	482	16	10	51	61	4
5	U10A	142.97	84	215	299	2	5410	1851	7261	3472
6	U10A	57.76	77	224	301	5	2192	750	2942	565
7	U10A	208.01	82	330	412	2	6204	2122	8326	4204
8	U10D	47.09	81	347	428	9	499	216	715	79
9	U10D	189.23	61	243	304	2	7165	2451	9616	5986
10	U10D	77.44	120	525	645	8	1142	391	1533	184
11	U10C	93.12	138	460	598	6	186	928	1114	173
12	U10C	32.87	115	417	532	16	66	329	395	24
13	U10C	148.15	81	362	443	3	2757	2738	5495	1838
14	U10D	29.97	126	585	711	24	617	442	1059	45
15	U10E	18.87	84	414	498	26	58	20	78	3
16	U10E	70.94	122	605	727	10	0	0	0	0
17	U10E	69.99	45	281	326	5	6537	4685	11222	2409
18	U10E	158.55	56	294	350	2	5869	4201	10070	4562
19	U10F	77.69	37	218	255	3	996	341	1337	407
20	U10F	55.13	66	396	462	8	5235	3747	8982	1072
21	U10F	24.12	135	681	816	34	1476	1056	2532	75
22	U10F	9.06	88	354	442	49	850	609	1459	30
23	U10F	145.82	107	490	597	4	337	241	578	141
24	U10F	65.33	90	393	483	7	521	373	894	121
25	U10G	136.00	103	462	565	4	4981	1704	6685	1609
26	U10G	106.48	70	360	430	4	2739	937	3676	910
27	U10G	116.18	25	135	160	1	313	170	483	351
28	U10H	137.54	46	204	250	2	2114	625	2739	1507
29	U10H	117.43	136	554	690	6	6221	3657	9878	1681
30	U10H	122.67	150	483	633	5	5711	1124	6835	1325
31	U10H	76.55	60	112	172	2	2197	405	2602	1158
32	U10J	7.28	28	37	65	9	224	42	266	30
33	U10J	76.07	102	166	268	4	3499	609	4108	1166
34	U10J	101.10	227	858	1085	11	1886	328	2214	206
35	U10J	211.44	134	306	440	2	7834	1403	9237	4439
36	U10J	11.94	96	261	357	30	310	60	370	12
37	U10J	97.83	124	272	396	4	1689	321	2010	497
38	U10L	23.74	154	583	737	31	662	115	777	25
39	U10L	56.04	128	576	704	13	425	74	499	40
40	U10K	48.36	393	687	1080	22	2222	386	2608	117
41	U10K	29.74	482	986	1468	49	1353	235	1588	32
42	U10K	30.07	364	1010	1374	46	1383	241	1624	36
43	U10K	143.62	479	748	1227	9	6608	1149	7757	908
44	U10K	109.86	485	1073	1558	14	5029	875	5904	416
45	U10L	226.22	194	676	870	4	4970	1073	6043	1571
46	U10M	16.76	166	888	1054	63	0	0	0	0
47	U10M	199.77	141	611	752	4	1844	615	2459	653
48	U10M	25.70	139	856	995	39	229	76	305	8
49	U10M	26.23	167	754	921	35	684	185	869	25
50	U10M	0.79	176	165	341	432	29	8	37	0
51	U10M	2.30	261	964	1225	533	80	21	101	0
52	U10M	5.72	115	140	255	45	278	66	344	8
Totals		4383	7424	24533	31957	1683	118675	47674	166349	46633

Table B2 Building Block Methodology IFR Table for IFR Site 1 on the Mkomazi River (after Umgeni Water, 1999)

IFR SITE NUMBER 1	RIVER: MKOMAZI			PRESENT STATE: C/B			DFS: B							
IFR MAINTENANCE LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x $10^6 m^3$	% of VIRGIN MAR 690 x $10^6 m^3$
Flow ($m^3.s^{-1}$)	2.3	6.1	6.8	7.2	7.6	7.6	5.7	4.2	3	2.4	2.1	1.75		
FDC % (virgin)	71	71	84	90	93	95	88	77	74	68	63	77		
Volume (x $10^6 m^3$)	6.16	15.81	18.2	19.3	18.4	20.3	14.8	11.2	7.8	6.4	5.5	4.5	148.37	21.5
IFR MAINTENANCE HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)	4.6	11.4 19	38 15.2	22.8 38	286 45.6 15.2	38 15.2								
Duration (Days)	2	3	3	3	5 3	3 3								
FDC % (virgin)	47	42 22	24 58	57 37		37 78								
Volume (x $10^6 m^3$)	0.26	2.8	6.2	7.2	45.6	7.1							69.2	10

IFR DROUGHT LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x $10^6 m^3$	% of VIRGIN MAR 690 x $10^6 m^3$
Flow ($m^3.s^{-1}$)	1.1	1.5	2.3	3	4.2	4.2	3	1.9	1.5	1.4	1.1	0.76		
FDC % (virgin)	92	98	96	96	98	100	98	96	92	88	92	94		
Volume (x $10^6 m^3$)	2.9	3.9	6.2	8	10.2	11.2	7.8	5.1	3.9	3.7	2.9	2	67.8	9.8
IFR DROUGHT HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)		4.6	15.2	9.1 9.1	45.6 9.1	9.1								
Duration (Days)		2	3	3	5 3	3								
FDC % (virgin)		80	58	84 84	38 92	93								
Volume (x $10^6 m^3$)		0.37	2	1.9	9.1	0.76							14.13	2

Table B3 Building Block Methodology IFR Table for IFR Site 2 on the Mkomazi River (after Umgeni Water, 1999)

IFR SITE NUMBER 2	RIVER: MKOMAZI			PRESENT STATE: C/B			DFS: B							
IFR MAINTENANCE LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 909 x 10^6m^3
Flow ($m^3.s^{-1}$) FDC % (virgin) Volume (x 10^6m^3)	3 72 8.03	5 84 12.96	9 83 24.1	9.5 88 25.4	10 94 24.2	10 96 26.8	7.5 87 19.4	5.5 75 14.7	4 74 10.4	3.2 67 8.6	2.7 63 7.2	2.3 76 6	187.79	20.67
IFR MAINTENANCE HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$) Duration (Days) FDC % (virgin) Volume (x 10^6m^3)	6 2 46 0.36	15 25 3 42 23 3.7	20 50 3 56 24 8.1	30 50 3 56 36 9.6	350 60 20 5 3 6.7 83 82 49.7 9.3	20 50 3 3 77 36 7.8							88.56	9.74
IFR DROUGHT LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 909 x 10^6m^3
Flow ($m^3.s^{-1}$) FDC % (virgin) Volume (x 10^6m^3)	1.5 92 4.02	2 98 5.2	3 96 8.04	4 97 10.7	5.5 98 13.3	5.5 100 14.73	4 98 10.37	2.5 95 6.7	2 92 5.2	1.8 90 4.8	1.5 91 3.9	1 96 2.7	89.66	9.9
IFR DROUGHT HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$) Duration (Days) FDC % (virgin) Volume (x 10^6m^3)		6 2 79 0.48	20 3 57 2.64	12 12 3 84 2.49	60 12 20 3 3 38 92 82 9.5	12 3 93 1.01							16.12	1.77

Table B4 Building Block Methodology IFR Table for IFR Site 3 on the Mkomazi River (after Umgeni Water, 1999)

IFR SITE NUMBER 3 RIVER: MKOMAZI PRESENT STATE: D/C DFS: B

IFR MAINTENANCE LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 1004 x 10^6m^3
Flow ($m^3.s^{-1}$)	3.5	5.8	10.3	11.1	11.8	11.8	8.7	6.4	4.7	3.7	3.3	3.3		
FDC % (virgin)	70	82	81	87	93	95	86	72	71	65	58	63		
Volume (x 10^6m^3)	9.4	15	27.6	29.7	28.5	31.6	22.5	17.1	12.2	9.9	8.8	8.5	220.8	22
IFR MAINTENANCE HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)	9	14 24	26 48	26 71	19 57 377	28 86								
Duration (Days)	2	3 3	3 3	3 3	3 3 5	3 3								
FDC % (virgin)	32	50 27	52 27	65 27	85 42 4	70 21								
Volume (x 10^6m^3)	0.56	1.27 2.83	2.44 5.86	2.32 9.32	1.12 7.03 51.2	2.21 11.5							97.66	10

IFR DROUGHT LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 1004 x 10^6m^3
Flow ($m^3.s^{-1}$)	1.7	2.2	3.3	4.4	6.1	5.1	4.4	2.8	2.2	2	1.7	1.5		
FDC % (virgin)	91	96	95	97	98	100	98	95	92	87	89	91		
Volume (x 10^6m^3)	4.5	5.7	8.8	11.8	14.8	16.3	11.4	7.5	5.7	5.4	4.6	3.9	100.4	9.8
IFR DROUGHT HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)		6	19	11 11	71 11	11								
Duration (Days)		3	3	3 3	5 3	3								
FDC % (virgin)		81	63	87 87	34 93	96								
Volume (x 10^6m^3)		0.46	0.86	1.03 1.03	8.85 0.76	0.76							13.75	1.37

Table B5 Building Block Methodology IFR Table for IFR Site 4 on the Mkomazi River (after Umgeni Water, 1999)

IFR SITE NUMBER 4	RIVER: MKOMAZI			PRESENT STATE: C			DFS: B							
IFR MAINTENANCE LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 1064 x 10^6m^3
Flow ($m^3.s^{-1}$)	3.7	6.2	11	11.8	12.5	12.5	9.3	6.8	3	4	3.5	3.5		
FDC % (virgin)	83	89	86	90	93	88	80	80	80	78	75	85		
Volume (x 10^6m^3)	9.9	16.1	29.5	31.6	30.2	33.5	24.1	18.2	13	10.7	9.4	9.1	235.3	22.1
IFR MAINTENANCE HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)	10	15 25	60 28	75 28	400 60 20	90 28								
Duration (Days)	2	3	3	3	5 3	3 3								
FDC % (virgin)	40	59 33	28 58	36 68	2 52 85	26 78								
Volume (x 10^6m^3)	0.76	4.29	10.26	12.35	62.8	14.5							104.96	10
IFR DROUGHT LOW FLOWS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL x 10^6m^3	% of VIRGIN MAR 1064 x 10^6m^3
Flow ($m^3.s^{-1}$)	1.8	2.4	3.5	4.7	6.5	6.5	4.7	3	2.4	2.1	1.8	1.6		
FDC % (virgin)	98	100	99	98	97	99	99	96	97	98	96	96		
Volume (x 10^6m^3)	4.8	6.2	9.4	12.6	15.7	17.4	12.2	8	6.2	5.6	4.8	4.1	107	10.1
IFR DROUGHT HIGH FLOWS														
Flow (instantaneous peak $m^3.s^{-1}$)		6	20	12 12	75 60 12	12								
Duration (Days)		2	3	3	5 3	3								
FDC % (virgin)		90	69	90 90	52 93	95								
Volume (x 10^6m^3)		0.44	2.57	2.27	11.7	0.85							17.83	1.7