INTEGRATED WATER RESOURCES MANAGEMENT STUDIES IN THE MBULUZI CATCHMENT, SWAZILAND

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ABSTRACT

Problems in the water sector range from degradation and depletion of water resources as a result of the impacts of land based anthropogenic activities, to the impacts of natural hydrological disasters and floods, while inadequate availability of water is at the core of most water related disputes in arid and semi-arid areas at local, regional, national and international levels. In the past, finding practical solutions for these problems fell neatly within the traditional scope of water resources management, which hinged almost entirely on economic viability of engineering oriented endeavors. However, a new set of management challenges has arisen following the high priority nowadays given to equity in water allocation and the protection of the natural environment above other issues. These new challenges have created a need for devising and adopting suitable management approaches, especially that would take social considerations into account. One of the approaches that provides promise relative to the new directions in dealing with contemporary water issues is integrated water resources management (IWRM).

One objective of this study was to critically review the definitions and the fundamental principles of IWRM with the view of determining its applicability in developing countries and highlighting difficulties that may be faced regarding the adoption and implementation of this integrated approach. Swaziland is a typical example of a developing country that is engulfed by the diverse water resources issues highlighted above and is currently engaged in updating water management legislation. Hence, Swaziland's experiences were used to put in perspective the key points and barriers regarding the adoption and implementation of IWRM.

The catchment, the recommended spatial unit of IWRM, poses the first practical barrier, as catchments often cross both political and administrative boundaries, thereby creating the need for many water management problems to be solved across catchments with international security issues, cultural issues, different levels of development and different hydroclimatic regimes. The successful implementation of IWRM depends on effective participation of stakeholders. Lack of information flow between stakeholders of different backgrounds limits informed participation. Therefore, it is necessary to develop tools such as decision support systems (DSSs) that will foster easier multilateral information flow and aid decision making. IWRM requires information which itself should be managed

in an integrated manner and be readily accessible. This is not always the case in developing countries with shortage of funds for data collection, manipulation and storage as well as adequately trained and experienced staff. With the shortage of sufficiently long and reliable hydrological data for water management, the alternative is to synthesize records through hydrological modelling. Another objective of this study was to evaluate and test the suitability of the *ACRU* modelling system, a daily time-step agrohydrological model, to simulate catchment level hydrological processes and land use impacts as part of the assessment studies which form an integral part of integrated water resources management.

ACRU was set up for the Mbuluzi, a 2958 km^2 catchment in Swaziland. The catchment was subdivided into 40 subcatchments, after which the model was used for assessing both the impacts of land use and management changes on runoff yields and available water resources by evaluating present and future sectoral water demands, determining whether river flow from Swaziland into Mozambique meets the quantitative requirements of the international agreement existing between the two countries, and evaluating sediment yield and its spatial and temporal variation as well as its response to potential changes in land management.

The physical-conceptual structure of the model, its multi-level adeptness regarding input information requirements, coupled with in-built decision support systems and generic default values make *ACRU* a suitable modelling tool in developing countries, as it makes it possible to obtain reasonable simulations for a range of levels of input information. Together with the model's multi-purpose nature, the ability of simulating "what if scenarios", which was utilised in this study, makes it useful in the generation of information for IWRM.

Future research needs which were identified include finding means of encouraging effective communication between scientists, water managers and other stakeholders, who may be "lay people". There is a need to conduct research that will lead to equipping *ACRU* with sediment routing and deposition algorithms, as well as routines to account more explicitly for dam operating rules and ecological issues, which would render its output even more useful in IWRM than the model's present structure allows.

I wish to certify that the work reported in this dissertation in my original and unaided work except where specific acknowledgment is made.

Signed: ____________________

D. J. M. Dlamini

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1. INTRODUCTION

Water is one of the world's most valuable natural resources (Heathcote, 1998). Its economic, social, physical and aesthetic value is emphasized by the wide range of problems and conflicts that often arise around issues of water in different climatic and physiographic regions. Unlike temperate regions, where the over-abundance of water may create problems, its shortage is at the core of most water related disputes in arid and semi-arid areas. Arid and semi-arid regions are characterised by a non-homogeneous distribution of rainfall in space and time, as well as annual potential evaporation demands that are much higher than annual rainfall. High intensity convective rain storms of short duration and significant channel water losses through seepage are other characteristics. Arid and semi-arid regions are occupied mainly by developing countries which are generally characterised by poverty, rapid rates of population growth and agriculture-dependent economies, all of which contribute to an ever-increasing demand on a finite water resource.

A wide range of problems and conflicts often arise as a consequence of competition for water resources. Land degradation generally leads to significant reduction of the operational life of hydrological structures and to deteriorating water quality within streams. The negative feedbacks of land degradation, together with occasional droughts, exacerbate the problems of water shortage. An additional dimension to already complex water resources issues are rivers that cross international boundaries between countries. This can be a cause of confrontation when a downstream riparian state feels it is not getting its fair share of the resources, as defined by the Helsinki Rules (International Law Association, 1967), Convention on the Law of the Non-Navigational Uses of International Watercourses (United Nations, 1997) and Protocol on Water and Health to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes (United Nations, 1999), to carry out its own development. Therefore, sound management of the water resource is imperative to ensure equitable sharing of the resource by users. This would minimise water related conflicts and maintain sufficient streamflow to sustain aquatic life forms.

The South African Department of Water Affairs and Forestry (DWAF) defines water resources management as the planning and implementation of actions designed to maintain or restore water systems to a particular agreed status of quantity, quality and distribution of water within an accepted range of variability (DWAF, 1998). These actions are meant to constrain the impacts of land-based activities on water resources to ensure adequate storage, distribution and allocation of water. Rehabilitation of degraded water resources, resolution of conflicts between competing users and the mitigation of impacts of hydrological catastrophes such as floods and droughts also fall within the scope of water resources management.

Water related problems are diverse in nature and involve interactions between the natural and anthropogenic systems. In contrast to the natural organisation of processes and events as interacting systems and subsystems, water managers in the past have often sought structural or civil engineering oriented solutions for isolated and localized problems, frequently ignoring the impacts of the management actions on other parts of the environment. This approach is unsustainable and has not only failed to provide lasting solutions for water-related problems (Heathcote, 1998), but also created additional ones, including disasters.

However, over the past twenty years, water resources management strategies have been shifting gradually towards approaches which are integrative in nature. A review of recent literature reveals a discernible trend of agreement on, and strong advocacy for, these integrated approaches as the appropriate route towards sustainable development and management of water resources (e.g. Johnson, 1993; UNECE, 1993; Young, Dooge and Rodda, 1994; Falkenmark, 1997; Frago, 1998; Heathcote, 1998; Newson, Gardiner and Slater, 2000). The integrated methods are usually referred to as Integrated Catchment Management (ICM). A subset of ICM is Integrated Water Resources Management (IWRM). These approaches promote the idea that water should be managed within a catchment, not as a single entity, but as a component of an integrated system consisting of other natural resources and human systems. In the heart of all the issues highlighted above is striving for better human welfare and social security. In water management, the desire to meet the society's needs manifests in water allocation, referred to by Dent (2001) as a social process. The credibility of this process relies on its embracement and authentication by stakeholders through involvement in making decisions (Dent, 2001). This indicates an apparent paradigm shift from water resources planning and management being a sole government responsibility to a partnership with most initiatives orchestrated by stakeholders. Despite the attractiveness of, and strong recommendations for, such integrated approaches, success in their adoption and implementation has so far been limited, often owing to lack of full understanding and appreciation of the underlying principles by practitioners in the water sector (DWAF, 1998).

Through a review of literature presented in Chapter 2, this study examines the fundamental principles and concepts of ICM and IWRM with the view of determining its applicability in developing countries and highlighting difficulties they face regarding the adoption and implementation of the integrated approaches. Swaziland is used as the example of potentially applying IWRM in a developing country because it is faced with the diverse water resources issues highlighted above and is currently engaged in updating water management legislation.

Modelling systems support reasoning in water allocation, a social process which forms the foundation of IWRM (Dent, 2001). Therefore, this study seeks to evaluate and test a daily agrohydrological model considered suitable for modelling catchment-level hydrological processes and land use impacts for integrated water resources management. A suitable modelling tool is one that is capable, *inter alia*, of estimating the effects of different land and water uses and management as well as their changes. This is important in the light of some debates and controversies surrounding clauses in the new National Water Act (Government of the Republic of South Africa, 1998) relating to special licences and charges for streamflow reduction activities. Classifying activities and estimating the extent of the streamflow reduction they cause, will involve the use of simulation models the choice of which will depend on their capability to perform given tasks. Setting-up of the models should be a product of a consultative process involving stakeholder regarding input data and information.

The Mbuluzi catchment in Swaziland is the test area for this modelling. This catchment is considered to be a microcosm of the hydrological problems of much of the country. Land uses range from dryland subsistence agriculture and livestock grazing to industry, while water uses include domestic and industrial as well as those of large scale intensive irrigation. Over-allocation, inter-catchment transfers and international allocations of water, as well as soil erosion, are important resources management issues in the catchment. The magnitude and extent of these problems, especially of over-allocation and soil erosion, have not been exhaustively investigated in Swaziland. Despite concerns of over-allocation of water resources of the Mbuluzi river in Swaziland by Matola (1999), it has not been established whether sufficient quantities of water flow, and whether of acceptable quality, are released downstream to Mozambique according to the Mozambique-Swaziland Joint Permanent Technical Committe (JPTC) agreement. Mushala (2000) has mapped the extent of soil erosion in the catchment, but the actual soil loss, sediment yield and its spatial and temporal variation as well as reservoir sedimentation have not been studied yet. The modelling tool will subsequently be used for:

a) assessing both the impacts of land use and management changes on runoff yields and available water resources by evaluating present and future sectoral water demands,
b) determining whether river flow into Mozambique meets the quantitative requirements of the JPTC agreement, and
c) evaluating sediment yield and its spatial and temporal variation as well as its response to potential changes in land management.

Reporting on the modelling part of the of the dissertation begins with a description of the test catchment in Chapter 3, followed in Chapter 4 by a general methodology and an appraisal of the Agricultural Catchments Research Unit (*ACRU*) agrohydrological model, which is the modelling tool selected for this study. This chapter also presents a conceptual background to, applications of and input data preparation requirements for the model in a general sense and more specifically to the Mbuluzi catchment. The chapter concludes with a section on the results of, and comments on, the verification of the model output.

The modelling results and their analyses, as well as the descriptions of the modelling scenarios, are presented in Chapters 5 for streamflow and in Chapter 6 for sediment yield. Chapter 7 contains a detailed discussion which covers both the conceptual and application issues of IWRM and the modelling results. An attempt is made for the discussion to be continuous instead of consisting of two discrete sections by starting with specific issues and problems highlighted by modelling and linking them with the IWRM discussions. Recommendations for future research emanating from this study are given in Chapter 8.

2. ASPECTS OF INTEGRATED CATCHMENT MANAGEMENT (ICM) AND INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

2.1 Definitions

There is as yet no universally unified approach to ICM and the discussion which follows, as is the case of virtually all discussions on ICM, therefore is one perspective of a complex issue. Many definitions of Integrated Catchment Management are encountered in the literature, e.g. those by Mitchell (1990), Mitchell and Hollick (1993), DWAF (1998) or Grigg (1999). The majority of these definitions identify as fundamental principles of ICM:

a) the recognition of the catchment as a suitable management unit for water resources,
b) a need for consideration of both the physical and human systems,
c) open and participatory decision making,
d) integrated catchment research and information management, and
e) protection of the environment.

Integrated water management (IWM) may be perceived in at least three ways (Mitchell, 1990). Integration may be viewed simplistically as the consideration of different components of water, e.g. surface and groundwater. This is the first and narrowest level where management is focussed on quantity, quality the spatio-temporal distribution of water for supply, waste treatment and disposal. The second level of integration acknowledges that water is not only a system, but is also a component and in continuous interaction with other components of a larger system. This is a broader perspective of integration which focusses on joint consideration of land and aquatic issues which include erosion control, non-point sources of water pollution, preservation of wetlands and fish habitats, agricultural drainage and the recreational use of water. Bringing social and economic development issues into the management of water resources constitutes a third level of integration which even is broader than the second. At this level, management is concerned with the role and the extent to which water influences economic development, as in production of hydroelectricity, transportation of goods or serving as an input for manufacturing or industrial production.

A review of the international literature does not show a distinctive difference between IWRM and ICM. This initially tends to make the differences between the two concepts appear to be nothing more than semantics. The apparently fuzzy difference could be a result of the fact that, although the water system is a subset of the catchment system, it is often the water fraternity (managers and researchers) which is at the forefront in terms of recommending the integrated approach. Water is also the integrating factor. The management unit, the catchment, is also defined and delineated on the basis of the water system.

In South Africa, however, the DWAF (1998) adopted a concept of IWRM similar to Mitchell's (1990) IWM and further distinguishes ICM as the broadest level of catchment resources management which deals with humanistic matters related to institutional, organisational, political and economic issues from a local catchment scale to international basin scale. Since the focus of this study is on water resources, and IWRM is a subset of ICM, the following sections review IWRM on the basis of the fundamental principles of ICM listed above.

2.2 The Catchment as a Water Resources Management Unit

A catchment refers to the entire area that is drained by a stream or river and includes all the land through, or over, which its waters moves (DWAF, 1998). It is a complex and dynamic system comprising a variety of life-forms and the habitats in which they live. Land, water, the atmosphere and vegetation form the biophysical components of this complex system while humans contribute to the complexity by introducing non-natural activities which impact on the quantity, quality or the distribution of water resources, as shown on **Figure 2.1**.

Experts on integrated water management such as Johnson (1993), Young, Dooge and Rodda (1994), Falkenmark (1997), Frago (1998), Heathcote (1998) and Newson, Gardiner and Slater (2000) agree unanimously that the catchment is the most appropriate spatial unit for water resources management. The organizational and operational advantages of using the catchment as a management unit in water resources management are discussed below.

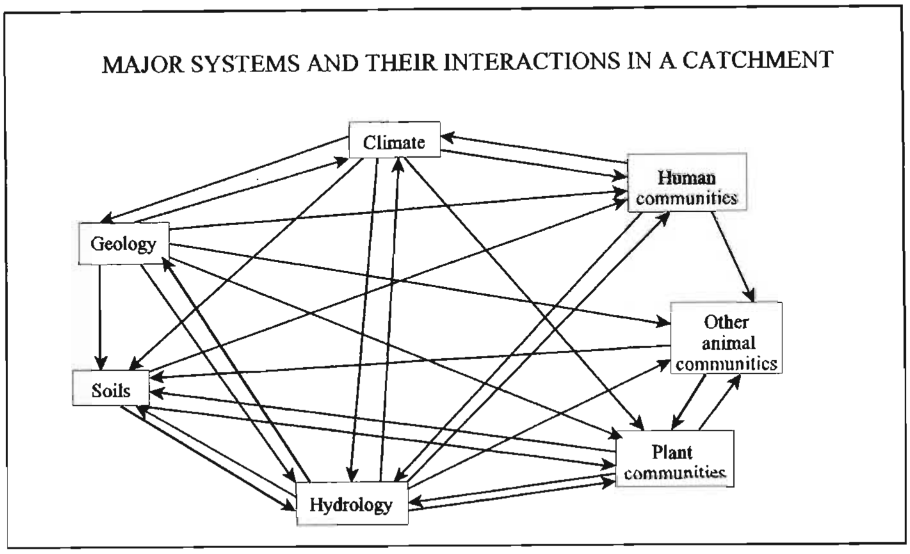


Figure 2.1 Interactions of natural and human processes in a catchment ecosystem (Lang and Armour, 1980)

2.2.1 Benefits of adopting the catchment as a management unit

It is recommended that management of water resources should encompass the study of the entire hydrological cycle, or water budget, for each management unit. Catchments are clearly bounded (Newson *et al.*, 2000), thus are logical units for which the water budget as well as the important hydrological processes within it can be estimated and studied with a degree of confidence. Theoretically, water can be traced from the moment it falls as rain until it leaves the catchment through evaporation, transpiration or through the catchment outlet. In this way catchments can be viewed as distinctive land units. Hence their adoption as management units would mitigate some of the basic problems facing co-ordinated management by spatially matching the supply with the units of jurisdiction (Meckleston, 1990). Catchments may be presented in a hierarchical structure from lower stream order to higher stream order, such as the Quaternary to Tertiary to Secondary to Primary catchment delimitations in southern Africa, with the smaller units nested within the larger ones. This hierarchy is useful for moving up and down the spatial scale depending on the type and scale of the managerial problem to be solved (Water Quality 2000, 1992; Maxwell *et al.,* 1995; Session *et al.*, 1997; Jewitt, 1998). In principle, if the concept of the catchment as a management unit is accepted, then the currently used administrative and political boundaries have to become secondary in importance with respect to water resources management.

However, there are some potential problems and limitations associated with using the catchment as the management unit. Some of the major limitations are discussed in the next section.

2.2.2 Shortcomings of the catchment as a management unit

River basins often cross both political and administrative boundaries. Hence many water management problems may need to be solved across catchments basins with complex international security issues, complex cultural issues, different levels of development and distinctly different hydroclimatic regions (Newson *et al.*, 2000). This increases the number of interested parties involved and invariably increases the complexity of the decision making process. According to Griffin (1999), unless the political and administrative boundaries are re-drawn, thereby re-organising water resources management agencies to correspond better with catchment boundaries, the task of management cannot be simplified. Griffin (1999) also cites Teclaff (1967) and Alder (1995) who argued that some catchment boundaries may be difficult to define. Van der Westhuizen (1996) remarks that groundwater may extend beyond the boundaries of the topographic catchment and the existence of 'sources' and 'sinks' of water may defy the supposition that all rain water that falls in the catchment is confined to it. The use of the catchment as the appropriate spatial unit also has an underlying erroneous assumption that all the biotic and abiotic factors are similarly organised (Griffin, 1999). However, air, wildlife and vegetation are not confined to the catchment boundaries and may therefore not necessarily be served well by using the catchment as a organising domain, especially where the management focus is on ecosystems and not solely on water systems.

2.3 The Concept of Integration in Water Resources Management

In the past decades water resources development and management have focussed largely on either surface or on groundwater for water supply. However, surface and groundwater are integral parts of the hydrological cycle. The availability, status and distribution of water in these forms is influenced by activities within other aspects of the hydrological cycle. Integration therefore implies that planning the development and management of water resources should consider interventions, even in other phases of the hydrological cycle. Technological innovation such as cloud seeding and reduction of industrial emissions or of acid rain-forming gases such as sulphur dioxide are examples of such interventions where management could be implemented beyond the terrestrial or oceanic phase to improve availability, consistency and quality of water. All these interventions should be undertaken within a framework of integrated management.

The already complex natural hydrological system is further complicated by the intervention of humans, which may be constructive or destructive (Falkenmark, 1986). Previously, water resources development and management was focused on water supplies to meet the water demand of humans, with less attention paid to possible environmental degradation. **Figure 2.2** shows some potential negative feedbacks that could occur as a result of the degradation of the environment, and of land and water resources. These feedbacks can inhibit further development of the water resources and certainly involve high costs of rehabilitation.

In the past, the environment was regarded as a user of water that had to compete with other users, ignoring the fact that it is the base from which the resource is derived (DWAF, 1998). This situation is still prevalent in many developing countries because environmental benefits take long to accrue, are difficult to measure and are not obvious to the communities who have to deal with immediate realities of poverty. The harsh reality of this is that ignorance of the need to protect

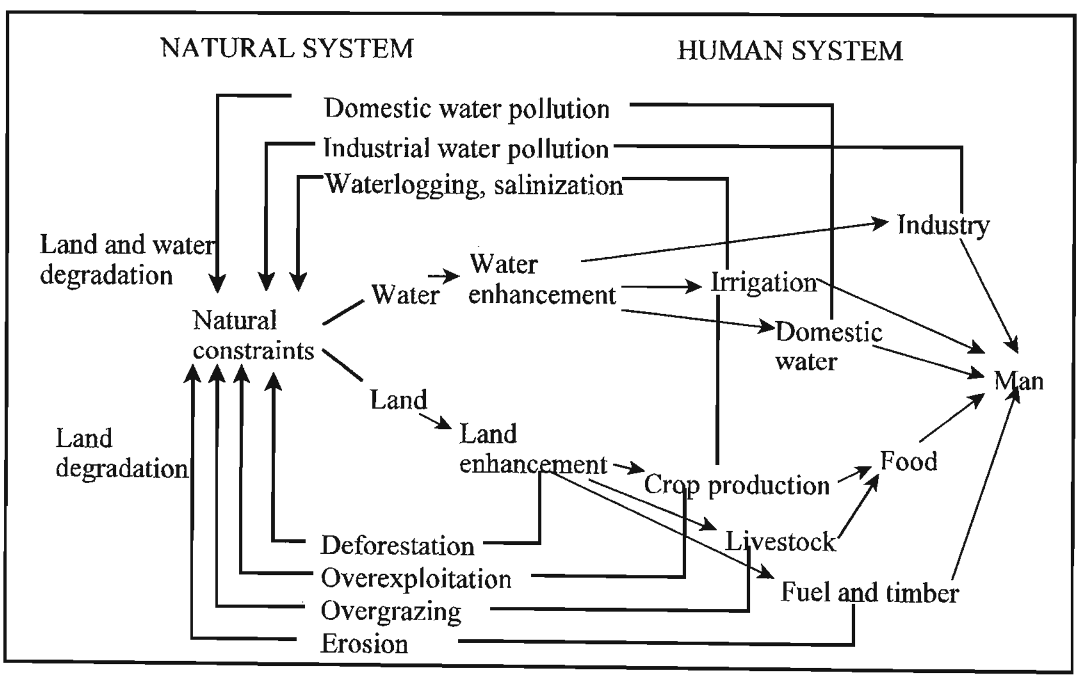


Figure 2.2 Complex interactions and feedbacks between the natural and human systems (after Falkenmark, 1986)

the environment is in no way going to improve the situation, but will rather exacerbate it. This is stressed by Asmal, as cited in DWAF (1998), who states that development that compromises the environment is a threat to human existence. Considerations for the protection of the environment should thus be integrated in management plans to ensure minimum degradation.

2.3.1 Social issues in water resources management

Up until a few years ago, a majority of catchment management initiatives had a strong focus on water resources supply, with the primary concern being on water quality and quantity. Other aspects of the catchment such as welfare of local communities and environmental protection often received limited attention. However, change which is necessary for improved water resources management has to start from the social and economic systems, as they have a profound influence on the entire catchment. Three main ways in which the human system affects the catchment are listed by Heathcote (1998):

a) They influence the attitudes and priorities of catchment residents and decision makers.
b) They affect the value that may be placed on individual catchment features and activities, and thus affect the importance they are given in catchment planning.
c) They constrain the financial resources available to resolve catchment issues.

Pegram *et al.* (1997) state that in South Africa, as in many developing countries, water resources management initiatives have often failed to yield the intended results. This failure may often be attributed to the neglect of the social and economic systems. The manner in which water and other natural resources are perceived and used is a function of the prevailing economic, social, cultural and political climate. Therefore, it would be expedient for scientists representing all these disciplines to engage in interdisciplinary endeavours towards the development of modelling systems and other tools for water resources planning and management.

Many institutions are involved in water resources issues. These could be custodians, users or managers of water and are referred to as stakeholders. Stakeholder participation is crucial when planning the development and management of water resources. It forms another important aspect of integration which will be discussed in greater detail in subsequent sections.

2.3.2 Integrating catchment information management

The concept of integration extends to the management of information for water resources management. According to Mosley (1998), integration of information has the greatest relevance and potential of application in the context of IWRM. There are many different types of data required for IWRM, ranging from rainfall and streamflow time series to population census information. There is a need to integrate the management of all data and derived information to ensure that they are readily available for use. Managing water resources related data and information in an integrated manner has the advantage of improving comparability, increasing economy and efficiency of data collection and enabling access to an expanded data and information bases. In most countries, both lesser and more developed, a variety of information bases are already in existence. In South Africa data capture and storage is undertaken by state and parastatal institutions such as the South African Weather Bureau (SAWB) for climatological data and the Department of Water Affairs and Forestry (DWAF) for hydrological information. Management of these and other hydrologically related data such as those on soils and land cover is not integrated yet. No agency has been assigned the duty of bringing together all these types of catchment data. At this stage, different institutions and individuals with interests in water resources management and research are linked via internet connections and may have access to the databases.

Jewitt (1998) describes the Integrated Catchment Information System (ICIS) for the Kruger National Park Rivers Research Programme (KNPRRP), of which a conceptual model is shown in **Figure 2.3**. The ICIS consists of several subsystems which include an ARCVIEW GIS based Graphical User Interface (GUI), a system manager, GIS functions, predictive tools such as numerical models, a computerised database, routines for performing colour coded animated displays and tools for linking geographically scattered scientists and users to ensure continuous communication and access to remote databases (Jewitt *et al.*, 1997a). The system's development

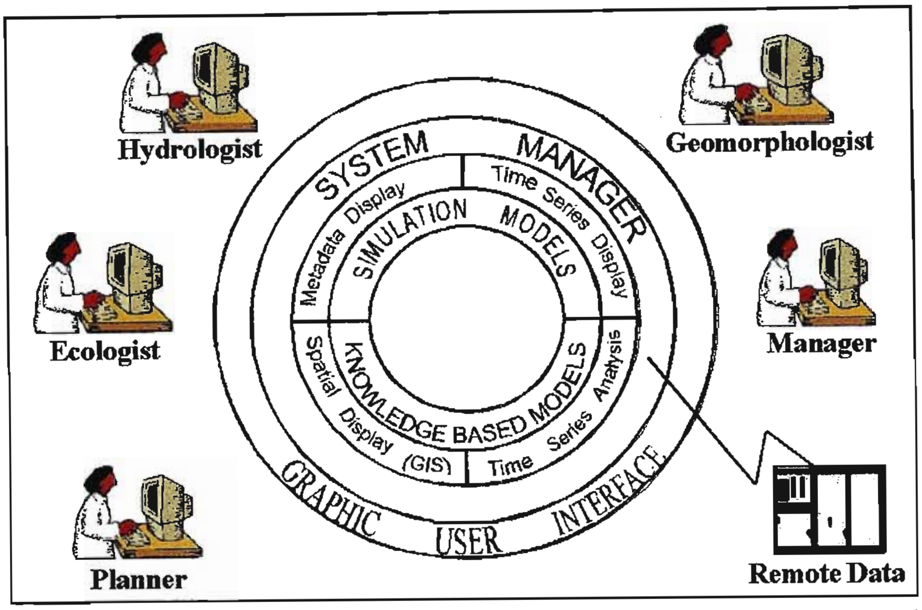


Figure 2.3 A conceptual model of the KNPRRP's integrated catchment information system (after Jewitt, 1998)

was bases on a multi-level approach. The levels of information analysis and presentation range from overview to detailed accounting for both expert and non-expert users (Jewitt, 1998). This is a typical example of a system for managing information in an integrated manner.

A similar information system has recently (beginning of 2001) reached completion with the European Commission-funded Integrated Water Resources Management Systems (*IWRMS*) project. This project covers the Mkomazi, Mupfure and Mbuluzi catchments in South Africa, Zimbabwe and Swaziland respectively. The final product of this project is a GIS based water resources management decision support system for these catchments. The utility of these systems includes aiding catchment managers in making better decisions than before concerning water allocation or the selection of the management options from a series of alternatives.

Mosley (1998) concedes that there exists an automatic, but fallacious, assumption nowadays that a system of managing information has to be computerised. He singles out the Hydrological Atlas of Switzerland as an excellent example of a non-computerised, yet integrated, information source. The South African Atlas of Agrohydrology and -Climatology (Schulze,1997) is a also a good example of an integrated information source which is not electronic.

Despite its attractiveness and potential in IWRM, the achievement of integrated information management nevertheless suffers from some impediments, which are discussed in the following section.

2.3.3 Barriers to integrated information management

Mosley (1998) points out that the core of most impediments to integrated information management includes the involvement of several often unco-ordinated organisations in the water sector. These organisations tend to have individual responsibilities, clients, objectives and supporting programs of data collection. Co-operation with other organisations towards integrated information management can also be inhibited by the costs and need of time for communication and co-ordination. Disruptions associated with any procedural change, potential loss of control over information as well as additional operational costs are identified by Mosley (1998) as other factors which corrode motivation towards co-operation. In the South African situation, Maaren and Dent (1995) observed that lack of human resources, 'rugged individualism with the spirit of pioneering' and 'protectionism through data pricing by the State and parastatals' are crucial barriers to co-operation. Instead of seeing certain users as allies in realising the full economic benefits of primary data collection, they are often viewed as competitors (Maaren and Dent, 1995).

The costs of integrating information management are obvious and felt almost immediately, while the benefits are in the future and therefore less easily demonstrable (Mosley, 1998). This is particularly important in developing countries where education, health care, infrastructural development and poverty relief are usually more pressing issues which take priority over water resources information management and thus command a large percentage of often small budgets. With such considerations, integrated information management and even ICM often seem a "pipedream" in developing countries unless industrialised countries, international organisations and aid agencies transfer management technology, evaluate observation networks and assist in capacity building, as recommended by the Commission for Sustainable Development (United Nations, 1998).

2.4 Sustainability of Water Resources Development and Management

Sustainable development is an old and popular goal that was conceptualized for the management of renewable natural resources to ensure that the rate of their exploitation was less than that of their replenishment. According to the Brundtland Report (WCED, 1987), humanity is obliged to make "development sustainable to ensure that current needs are met without compromising the ability of future generations to meet their own needs." Sustainable development is achievable only if management of resources is integrated. Natural resources development projects should assume a broad and holistic approach which places greater emphasis on system demands and system goals rather than on isolated project demands and goals (Plate, 1993; cited by Burn, 1997). Objectives of different projects undertaken in a catchment should not be in conflict with each other. According to Walker and Johnson (1996), management for sustainable development and use of natural resources is more complex than management exclusively for economic efficiency or environmental conservation because it aims to manage a complex and often poorly understood system of interactions for multiple, rather than single, objectives. Owing to the multi-objective nature of sustainable development, conflicts and disputes are inevitable. Therefore, skills to ensure harmonious conflict resolution are a core requirement for effective water management. Loucks (1997) cites the lack of objective and measurable criteria to assist in decisions regarding when and how much of a preserved resource should be utilised, as issues which make management for sustainable development difficult. A situation like this is often encountered when dealing with non-renewable water resources such as very deep groundwater aquifers that are not naturally replenished (Loucks, 1997).

Another challenge relevant to the concept of sustainability is the need for a yardstick to assess whether there is progress or regression on the sustainability of water resources development. A universally acceptable and applicable technique is not yet available. A number of techniques have been suggested by scholars such as Matheson *et al.* (1997) and Loucks (1997). A review of these techniques is beyond the scope of this review.

However insurmountable these challenges may appear to be, they need not delay the attempts to achieve the goal of sustainable development and management of water resources. Such a goal is reachable only through ICM.

2.5 Stakeholder Participation in Water Resources Management

The word stakeholder refers to all individuals or groups who have interests in water resources within a catchment. The interests may be of a consumptive or non-consumptive nature, on- or off-channel water use or mere aesthetic enjoyment of water (Heathcote, 1998). Besides the understanding of their water uses and needs, perception of water as a resource and a vision of a desired or ideal condition of the catchment, the World Bank (1995) has identified other benefits of broad user participation in management. In that paper the World Bank postulates that, owing to the fact that the ideal representation of stakeholders in planning, operations and management of water resources and services is voluntary, the government could be partially relieved of the financial and management burden in both rural and urban areas. The possibility of having well maintained projects and services is also increased by stakeholder involvement. Stakeholder involvement also has a potential of promoting unity in the community and commitment towards achieving a common goal. Co-operation can spread to other development projects in the catchment and could result in the more efficient operation of the various agencies in the catchment. Broad participation in decision making should be accompanied by a two-way flow of information between water managers and users. Ashton *et al.* (1998) and Savanije and Van Der Zaag (1998) point out that it is equally important that the stakeholders and the general public are informed about the current and future water resources scenarios, as well as the technicalities underpinning water resources development and management. Although seeking broad participation will most likely delay reaching agreements, its benefits by far the disadvantages (World Bank, 1995). Ideally, water users and the public are more likely to identify with the final product and potential conflicts are identified and resolved before they occur. This speeds up the process of implementing management actions.

2.6 Types, Concerns and Roles of Stakeholders Common in Developing Countries

The composition of stakeholders varies from one catchment to another, but often includes governmental agencies, agricultural and industrial water users, public interest groups, indigenous communities and downstream riparian users and states. The following sections examine the types, concerns and roles of stakeholders common in developing countries.

2.6.1 The Government

The levels of government cascade from national to provincial to local. At each level the government is subdivided into ministries or departments which serve as 'long arms' that are directly involved with the water resources management operations. In South Africa, the central government is recognized as the custodian of the national water resources (DWAF, 1998). The government has a statutory and regulatory responsibility to put in place national strategies for long term water resources management (DWAF, 1998; Heathcote, 1998). It is also the responsibility of the government to provide leadership, technical and financial support for the development and management of the water resources. Setting up and enforcing standards for environmental protection, waste minimisation and effluent discharge into stream channels are other duties of the government (Van der Westhuizen, 1996). These standards form a basis on which projects may be monitored and the success of management strategies be measured and thereafter adopted or rejected. Provincial and local governments are expected to adopt the policies of the central government in addressing issues and making appropriate decisions within their individual jurisdictions (Heathcote, 1998).

It should be noted that different ministries within the same government or even divisions within the same ministry, may often have conflicting viewpoints regarding water resources management (Heathcote, 1998). These progress-retarding, yet inevitable, differences are a consequence of the mandates of each ministry, all of which are made in the interests of human welfare. It is in the recognition and need for the resolution of these differences that makes stakeholder involvement become a cornerstone of the ICM concept.

2.6.2 Agricultural water users

Agricultural water refers to all water consumed by deliberately cultivated growing crops. Agricultural water includes commercial forest plantations, but is distinguished from the water used *in situ* by natural plants/forests used for timber and firewood. Sources of water for agricultural use may be rain falling directly on cultivated land, or abstractions from streams, dams or underground water aquifers for supplementary or total irrigation. Agricultural water users are concerned with the quantity, quality and reliability of supply.

According to the World Bank (1995), agriculture is by far the largest water user globally and may consume up to 80% of total allocations in developing countries. The proportion is higher in Africa where it is about 88%. The economies of many developing countries depend largely on irrigated agricultural production. In Swaziland, for example, agricultural production constitutes more than 60% of Gross Domestic Product (GDP). In the past, the importance of agriculture has led to agricultural water users enjoying preferential treatment in the form of subsidised payments for irrigation water. The subsidies, together with lack of other technical understanding, especially of actual crop water requirements, frequency and amounts of irrigation are causes of significant water wastage.

Other problems that are associated with agricultural water usage include salinisation of soil by fertilizer residues or by accumulation of salt precipitates when saline water is used for irrigation, nitrate and/or phosphate loadings in receiving waters which results in eutrophication, pollution of streams with pesticides, contamination of groundwater and soil erosion.

Individual farmers can often be reached through farmer associations which usually have clearly defined objectives. However, large scale farmers and companies owning agricultural plantations (including commercial forests) may dominate stakeholder forums and this may lead to most decisions being in their favour with a bias against small scale farmers and other less influential groups. Means should be developed to ensure that the interests of everyone are considered.

2.6.3 Industrial water users

Industrial water users are the easiest group of stakeholders to identify and characterise because of their usually limited numbers in a catchment (Heathcote, 1998). They are even fewer in developing countries where economic activities are dominated by agricultural production. They are concerned mainly with the quality and quantity of the water resources in meeting the minimum requirements for use as a solvent or coolant. Environmentalists and water resources managers are concerned about the status and effect of the industrial effluent on the quality of receiving waters. Industrial water users are accessible through the sector associations, Chambers of Commerce and regional associations to which they are affiliated (Heathcote,1998). This makes it easier for water resources managers to establish and maintain contacts with them.

2.6.4 Public interest groups

These are Non-Governmental Organizations (NGOs) which purport to represent the interests of the public. Heathcote (1998) cautions that such groups do not necessarily reflect all, or even a majority, of public opinion and concerns. Instead, they are often pushing their own strong and clearly defined agendas which may have a slant towards environmental conservation or preservation. In stakeholder forums, they see an opportunity for publicity, or awareness campaigns, for their cause. In many respects, their cause has good intentions and may be laudable. However, it often leads to clashes between the organisation and the residents of the catchment, especially when the goals of the organisation are in conflict with the needs of the communities (Heathcote,1998).

There are some advantages to having the so-called public interest groups in the stakeholder forums. Even though at times they raise issues without sufficient background research, they highlight sensitive and controversial issues which would otherwise be neglected. Some organizations have members who are experts in different disciplines and hence have access to impressive research resources and can produce comprehensive reports on fundamental themes with regards to planning and management of water resources (Heathcote, 1998).

2.6.5 Indigenous communities

Indigenous communities generally refer to tribes, ethnic and often minority groups of people who lead simple and unsophisticated lives. Their livelihood depends almost entirely on raw or un-enhanced natural resources such as soils, water, animals and plants. In addition to the basic water needs, they tend to have special cultural bonds with, and respect of the landscape and the resources. These perceptions are borne out of their cultural heritage and history. The World Bank (1995) suggests that their social and economic status restricts their capacity to assert their interests and rights in land and other productive resources. This makes them vulnerable to being disadvantaged in development projects. These communities are not present in all catchments, but considerations of their interests in water resources development and management become extremely important where they are found.

Instead of benefiting from the development of large scale water resources projects, indigenous communities often become victims. The most common form of victimisation is their forced dislocation from their ancestral homes and traditional life styles and being relocated to areas which are unfamiliar to them and marginal for their survival. Jordan *et al.* (1993) cites as an example the 75000 Tonga tribesmen who were relocated by the construction of the Kariba Dam on the Zambezi River.

The World Bank (1995) has made it a precondition for projects they will fund, or invest in, that provisions be made at the early planning stages of projects to ensure that adverse effects such as involuntary resettlement be avoided or minimised. In cases where these side effects are inevitable, especially resettlement, incomes and living standards have to be restored or improved through compensations. These people must also be involved during the planning and implementation of the settlements.

Heathcote (1998) notes that in some countries indigenous communities, such as the Indians of North America, may be subject to different laws and agreements to those that apply to non-indigenous groups. In some cases these groups, for example the San of the northwestern parts of South Africa, have their own semi-autonomous or self-governance structures and may have interests in, and jurisdiction over, their lands. They may raise questions about jurisdiction and harmonisation of standards which may be contentious and divisive at times in catchment management (Heathcote, 1998). This should not be taken to imply that they have to be left out, but rather that their participation be promoted and hence guarantee acceptance of, and compliance with, the final product by everyone who is affected after its implementation.

2.6.6 Downstream international obligations

According to the Helsinki Rules (International Law Association, 1967) a river system which has components that are situated in different states is an international river. These states, also known as riparian states, have the right to utilise the river's water in an equitable and reasonable manner. Such countries are duty-bound to co-operate in the protection and development thereof (International Law Association, 1967; United Nations, 1997; United Nations, 1999). Upstream states must ensure that water in sufficient quantities and of acceptable quality is released to downstream countries. Failure to adhere to that can lead to serious conflicts.

In most instances, the largest part of the river system's yield originates from the upper riparian states and the quality and quantity of water that reaches downstream states is a function of the activities of upstream states. Meanwhile, the downstream riparian states which often depend most on it, do not have control over these activities. Other than lack of consideration by upstream states, absence of objective criteria to describe what is meant by reasonable utilisation and what constitutes fair sharing of water could be the cause of disputes among countries sharing common resources. Such disputes can be overcome by negotiations and co-operation between riparian states.

Inasmuch as rivers shared by different states have a potential for causing conflict, they can be binding factors between nations . It transpired from a conference on the management of shared river basins held in Maseru in 1998, that through regional organisations such as Southern African Development Community (SADC), international or joint commissions or development projects may be established to engage states sharing common rivers (Savenije and Van Der Zaag, 1998). The Lesotho Highlands Water Project and the Komati Basin Water Authority are examples of initiatives involving South Africa and Lesotho and South Africa and Swaziland, respectively.

2.7 A Review of Water Resources Management in Swaziland

Swaziland is a typical example of a developing country according to the World Bank's (1999) classification criteria. The country is among the lower-middle income economies. It is faced with an increasing demand of water resources as a response to the pressure exerted by the high population growth rate, which to date has been more than 3% per annum (Meigh *et al.*, 1998). Agricultural production, most of which is supported by irrigation and related industries, are the mainstay of the economy, with sugarcane and related manufacturing industries contributing about 60% of the country's GDP (Knight Piesold Consulting Engineers, 1997). This could explain the reason why irrigation is Swaziland's largest single water user. Despite observations by Engelman and LeRoy (1993) that Swaziland has, and will have, enough water until 2015, water shortage problems and other water related concerns are surfacing already. For example, the Water

Apportionment Board has declared all water in the Mbuluzi River to be fully committed, implying that there is no longer any water available for further development. Besides intra-national competition for the limited resources by different users, downstream states' considerations are also emerging, especially from Mozambique which shares the Mbuluzi river with Swaziland. The observation by the Engelman and LeRoy (1993) only focused on the national water yield on an annual basis, without accounting for the high spatial and seasonal variation of the country's hydrological regime, large tracts of which can be classed as semi-arid. Water shortage is critical during the dry season, especially in the drier Lowveld (**Figure 3.2**). The scarcity of water is exacerbated by insufficient storage facilities, inefficient water usage and degradation of the quality of water resources and environment. In the light of the above issues, the Government of Swaziland realised the critical need for a firm, sensible and implementable water policy to foster good management of water resources. In 1996 a new Water Act was drafted with the aim of replacing the outdated Water Act of 1968 currently in use (Government of Swaziland, 1996). Once a few further adjustments have been made, and suggestions by Knight Piesold Consulting Engineers (1997) have been incorporated, the Draft Water Act has the potential of addressing current and future water issues which the existing Water Act fails to address.

2.7.1 Existing institutional framework

The existing institutional set-up for water resources development and management is founded on the Water Act of 1968. Planning, development, operation and management of water resources schemes is presently undertaken by up to ten organisations consisting of different bodies from five government departments and one parastatal organisation. A simplified organisational structure of the set-up is shown on **Figure 2.4**

Management of water resources in Swaziland falls primarily under the Ministry of Natural Resources and Energy (MNRE), which has two operational arms. The Water Resources Branch has the responsibility of making available technical information necessary for allocating and revoking water permits, planning development and controlling pollution of water resources. This information is acquired through capturing, storing and analysing streamflow data. Providing water and sanitation in rural communities is the responsibility of the Rural Water Supply Branch with the assistance of the Groundwater Research Unit. Groundwater is an important source of

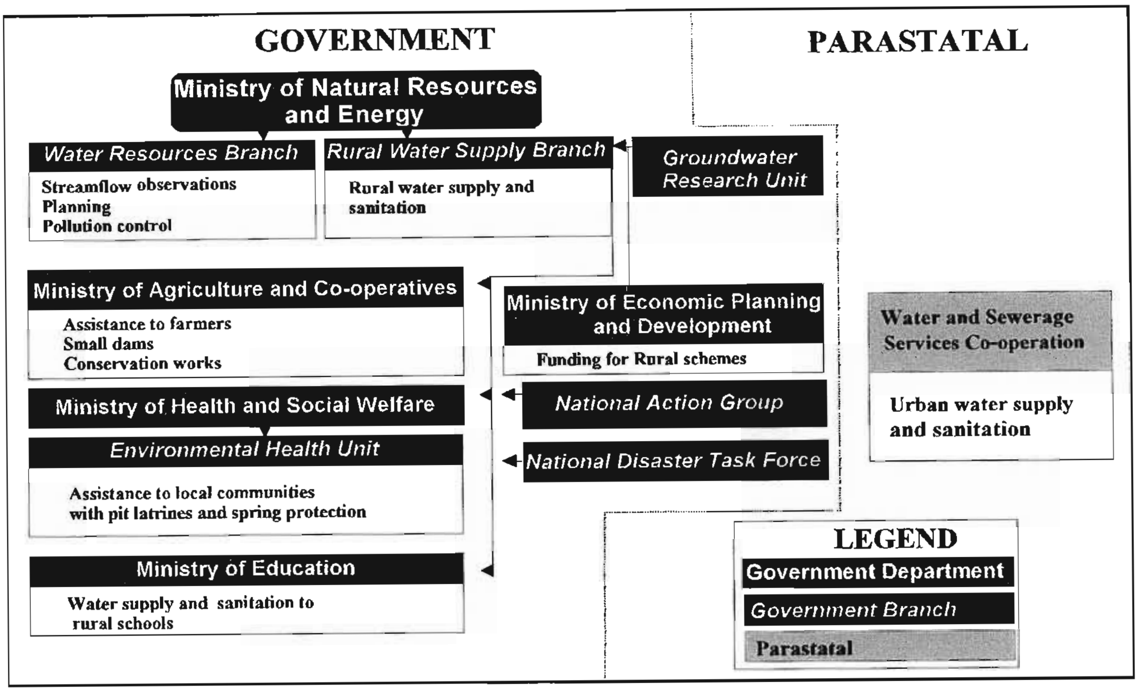


Figure 2.4 Existing institutional set-up for water resources development and management in Swaziland (after Knight Piesold Consulting Engineers, 1997)

water in drier parts of the country. In urban areas water and sanitation services are provided by the Swaziland Water and Sewerage Services Corporation, which is a parastatal organisation.

Besides the MNRE other government departments are involved and make important contributions in water resources development and management. These are The Ministry of Agriculture and Co-operatives, The Ministry of Health and Social Welfare, The Ministry of Education and The Ministry of Economic Planning and Development.

The Ministry of Agriculture and Co-operatives assists farmers with design work for small dams, conservation works and small scale irrigation schemes. The Environmental Health Unit, a section within The Ministry of Health and Social Welfare, helps rural communities in the construction of pit latrines and minor spring protection schemes. The Ministry of Education and The Ministry of Economic Planning and Development are, respectively, responsible for contracting out projects for water supply and sanitation to rural schools and assisting in soliciting external funding for rural water supply schemes.

Operations involving different ministries are undertaken by inter-departmental organisations such as the National Action Program and the National Disaster Task Force. The latter was established to mitigate the impacts of the devastating drought of the early 1990s. Within this body, there is a water committee which has the duty of purchasing and erecting water tanks, which was an emergency relief operation. After the drought the board was retained and it is presently pushing the on-going pro-active programme of installing boreholes and hand pumps in drought risk areas. Water resources works also involve many NGOs. The NGOs are also active in rural areas where they help solicit funds for water schemes. They also work with the government in disaster stricken areas.

2.7.2 Proposed institutional structure

The Draft Water Act of 1996 seeks to launch major reforms in the institutional set-up within the water resources sector. It makes a provision for the establishment of a National Water Authority (NWA) and a Department of Water Affairs (DWA). The Director-General of the DWA will provide technical advice to the NWA and help to promote co-operation among the different government departments, boards and task forces involved in water resources management, as well as with international water commissions. The primary objective of the NWA will be to prepare, adopt and update a Water Resources Master Plan (WRMP). The plan will enable the NWA to carry out its functions and give directions towards sound development and management of water resources. A proposed institutional structure based on the bodies instituted by the draft Water Law of 1996 is shown in **Figure 2.5.**

2.7.3 The Water Resources Master Plan

The Master Plan will contain an inventory of the total water resources of Swaziland and outline the guidelines for equitable sharing, optimum usage and preservation of water resources. In line with the current trend in the management of water resources, the plan will include principles of catchment, or river basin based, management which will formulate the groundwork for the establishment of River Basin Authorities (RBAs). The RBAs will have the responsibility of implementing water resources development and management recommended actions under the auspices of the WRMP, in the specific basin areas. A Basin Authority will consist of

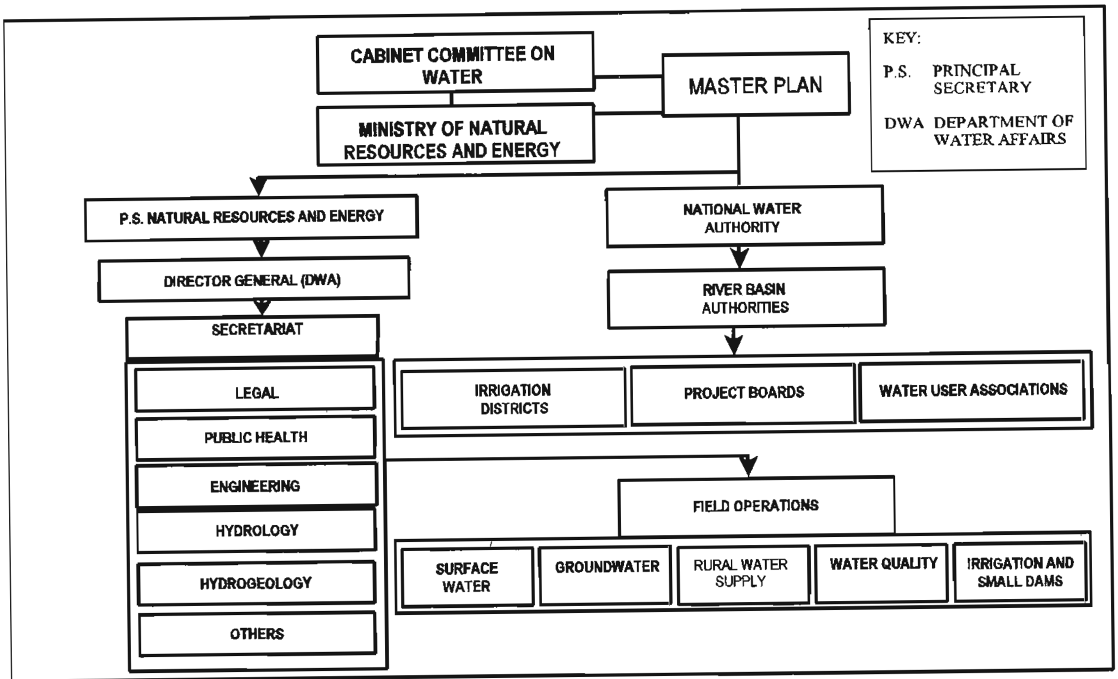


Figure 2.5 Proposed institutional structure of the water sector in Swaziland (after Knight Piesold Consulting Engineers, 1997)

representatives of all relevant water use sectors in each basin. The water use sectors include domestic, agriculture, forestry, conservation, mining and industry.

The plan will also take into consideration potential developments and co-operation with the Republics of South Africa and Mozambique with respect to the shared river systems. The Joint Water Commission established by the Government of Swaziland and the Republic of South Africa, the Komati River Basin Authority and similar commissions, committees or authorities which have been or may be established between Swaziland, South Africa and Mozambique, will continue to be recognised and ratified (Government of Swaziland, 1996).

Another objective of the plan will be to set down provisions for integrating water resources management with those of other resources such as land. Despite the commitment in Swaziland to improve water management, there is lack of suitably qualified and experienced staff at the MNRE presently to develop an IWRM plan. Knight Piesold Consulting Engineers (1997) suggest that Swaziland should take advantage of the existing ties between Swaziland and South Africa. It is suggested that Swaziland can learn or even adopt integrated planning and management techniques similar to those employed in South Africa. These techniques could be modified to suit the conditions and unique management issues of Swaziland. Another major limitation to development of the IWRM plan is a lack of funding, as there is no budget set aside at this stage in the ministry for such an exercise.

2.8 Hydrological Modelling for Integrated Water Resources Management

Many conceptualisations of hydrological models are encountered in literature (e.g. Fleming, 1975; Branson *et al.*, 1981; Schulze, 1987; Schulze, 1998). In broad and simple terms, hydrological models can be defined as simplified representations of the rather complex terrestrial hydrological system. The advent of high speed computers with huge storage capacities has seen an increase in the use of the models as tools for both research and finding solutions for water resources management problems since the early 1970s (Shaw, 1994). Uses of hydrological models range from replacing missing records and making efficient and cost effective quantitative estimates of water related variables at ungauged locations to generating reliable information to aid in decision making for sustainable development, utilisation and management of water resources (Schulze, 1998). Models reflect, *inter alia*, the philosophy around hydrological problem solving during the era of their development, e.g. specificity to individual research approaches or locations. The paradigm shift in the management of water resources from solving isolated or locational problems to integrated approaches will require suitable and integrated modelling tools (Dent, 1996).

The hydrological modelling fraternity has a legacy of having developed "multitudes of monolithic models" with limited flexibility and utility (Argent, Vertessy and Watson, 2000). These models were designed for different purposes and in the context of integration may have to be linked with other models from scientific and socio-economic disciplines involved in water management. Argent *et al.* (2000) warn though that an exercise of "simply plugging models together" does not constitute integrated catchment modelling. They propose that catchment modelling tools suitable for integrated management should be designed such that major catchment hydrological processes and activities are represented as modules. Models need to be constructed such that they can incorporate socio-economic tools and methodologies (Calder, 1999). It should be possible to select and combine modules to form new applications to suit different problems (Ng and Yeh, 1990; Calder, 1999; Pressman, 2000 cited by Argent *et al.*, 2000). The practicality of such a modelling approach coupled with user-friendly decision support systems is that it allows a number of "what if"questions to be asked and answered which, according to Ewing, Grayson and Argent (2000), enable users to "explore the effect of potential management decisions without having to deal with the consequences".

Active and effective stakeholder participation is a cornerstone of integrated management. This implies that communities have to make decisions regarding the management of catchments. Some of these communities might have little, if any, scientific understanding of the complex catchment processes. Integrated simulation modelling has more to offer than just providing mechanisms for giving answers to decision makers. It has to include support for the process of empowering the stakeholders by illuminating the management issues (Dent, 1996). Mindful of these consideration, Ewing *et al.* (2000) recommend decision support system (DSS) types of tools that do not only integrate catchment information, but also present it in forms that are easy for catchment decision makers to understand.

Key to the usefulness of DSS tools is the capability of their structure to truly represent the problem at hand, while the involvement of stakeholders in their development enhances their chances of being accepted and adopted by instilling a sense of ownership (Ewing, Grayson and Argent, 1997) and creates a feeling that their needs have been accommodated (Jewitt, 1998). In this context involvement implies effective participation by making contributions than using the presence of stakeholders as stamps of approval, a practice warned against by Calder (1999). Therefore a major challenge is creating platforms where scientists are able to communicate with all stakeholders. Calder (1999) reviews a set of new methods such as problem structuring methods, or PSMs (Rosehead, 1996), soft system methods (Omerod, 1996), collaborative planning-support systems (CPSS) and cognitive planning, together referred to as "soft system tools", which are stated facilitate communication between system developers and users, regardless of their backgrounds. This implies that scientists have to sit side-by-side with resources managers, or even "lay citizens", during model development. Only a few years ago such a prospect would have been considered not only novel, but also absurd. Collaboration of scientists and end-users has been shown to be practical by Ewing *et al.* (2000) in the Blackwood River catchment in Australia, where they were exploring the potential contribution of adaptive environmental assessment and management (AEAM) to ICM.

Success, or even applicability, of such approaches in developing countries is not guaranteed. The next section therefore discusses obstacles in modelling for integrated water resources management in developing countries.

2.9 Modelling Problems in Developing Countries

There is limited application of hydrological models in developing countries. Several reasons for this were identified during the Nanyuki Modelling Workshop (1994) in Kenya (Schulze, 1998). Most of the reasons relate to hydrological model in general. This sections deals with those particular impediments affecting modelling for IWRM.

The core of most problems in developing countries is lack of funds for purchasing hardware, training personnel and supporting programmes of data collection and management for use in modelling. To alleviate that problem, Chapter 18 of Agenda 21 of the 1992 UNCED Earth Summit meeting (Johnson, 1993) encourages developed countries and donor organisations to assist developing countries through funding capacity building around integrated water resources management. In response to that call, several research projects have been conducted and some are still on-going in developing countries. However, for some reasons, these efforts do not appear to produce the desired effects. In many instances, the organisations do not only provide funding, but they also use their own models and staff (Nanyuki Modelling Workshop,1994). Impressive reports and recommendations which are rarely implemented are often left behind with no real capacity building and empowerment of the locals. Ewing *et al.* (2000) document a stakeholders' opinion that, just like ICM/IWRM, catchment modelling should be a "continually evolving process" which undergoes continuous refinement. Who is then going to modify and refine the models when more data become available, if no local capacity is developed? Should this be viewed as a deliberate ploy by the donors to create a market for their models and opportunities for their scientists at the expense of those from the developing countries? If so, this is not only unethical and dishonest, but also "flies in the face" of the principles and objectives of sustainable development.

Disintegrated scientific practice is a major limitation in the technical aspect of IWRM (Calder, 1999). Science is supposed to provide the means and tools such as models and DSSs for integrating information from different disciplines. Hydrologists, hydrogeologists and water chemists are all involved in water research and data collection, but do not have a tradition of working closely together (Calder, 1999). Calder (1999) contends that if a tradition of integration does not exist even amongst the closely related water resources disciplines, co-operation amongst wider disciplines (some of which have divergent characteristics like operating at different spatio-temporal scales to those of hydrologists), which could include environmental sciences, ecology, socio-economics and health, poses an even bigger challenge. The problem of disintegrated sciences prevails in all countries, but is expected to be worse in developing countries which, according to the outcomes of the Nanyuki Modelling Workshop (1994), have few engineers and scientists with intimate hydrological modelling experience.

The importance of stakeholder participation not only in IWRM, but also in catchment modelling and DSS development has been alluded to in the previous section. The promise and practicability of this approach, though not without problems, is evident in relatively developed countries such as Australia (Argent *et al.,* 2000). The same cannot be said of developing countries with low levels of literacy and numeracy. Most of developing countries also have fledging democracies and making important decisions, including hydrological ones, remains the privilege of the politically and economically powerful and influential individuals.

Beginning with making a distinction between the often confused IWRM concepts by revisiting popular definitions, this chapter has made an attempt to address the issue of lack of understanding of the integrated water resources and catchment management approaches through a review of literature. The principles of IWRM and integration oriented management were evaluated by establishing their applicability in developing countries. Most of the problems with respect to adopting and implementation of IWRM in developing countries centre around unavailability of funding.

Ensuing chapters cover modelling aspects of this study. Chapter 3, which follows, presents a description of the test or study area, *viz.* Mbuluzi catchment.

3. DESCRIPTION OF THE STUDY AREA

3.1 Geographical Location

The Mbuluzi river is the only major river which originates within Swaziland. Its source is in the northwestern part of the country near Ngwenya close to the border with South Africa. It drains a 2958.9 km^2 area before crossing into Mozambique in the east. The Swaziland part of catchment area stretches latitudinally from 25°54' to 26°30' S and longitudinally from 31°02' to 32°06' E, as shown in **Figure 3.1**. The Mbuluzi catchment is bordered by the Komati and the Usuthu catchments in the north and south respectively.

3.2 Physiography, Geology and Relief

Swaziland has four altitude and physiographic (**Figure 3.2**), geological (**Figure3.3**), as well as slope (**Figure 3.4**) related regions of which all are found within the Mbuluzi catchment. The western part of the catchment is mostly highveld with altitude ranging from 800 to 1800 m above mean sea level (a.m.s.l) (cf. **Figure 3.2**). This region is generally mountainous and the rock formation is chiefly granitic with Locheal and Mswati being the dominant groups. The Mswati granites (**Figure3.3**) occur in the eastern part of Mbabane as steep sloped monolithic outcrops. The Lochiel Granites form the catchment divide between Mbuluzi and Komati rivers, stretching from the highveld to the lower parts of the middleveld (**Figure 3.2**). The middleveld consists of undulating topography with an altitude that ranges from 400 to 1000 m a.m.s.l. The average slope is about 12% (**Figure 3.2**). Extensive areas are underlain by Ngwane Gneiss rock types. The geology of the upper middleveld comprises of Usuthu Intrusive rocks, which are weathered to saprolitic regolith. The lowveld is largely flat land with fluviatile sedimentary rocks of the Ecca Group, Nkondolo Group sandstones and conglomerates and Sabie River basalts, forming almost parallel geological strips running in a north-south direction. The average slope of the lowveld is often not more than 3% (**Figure 3.4**) while the altitude is seldom more than 400 m (**Figure 3.2**). The eastern end of the catchment is a plateau on top of the Lubombo range of mountains. The main geological formation is the Lubombo Rhyolite.

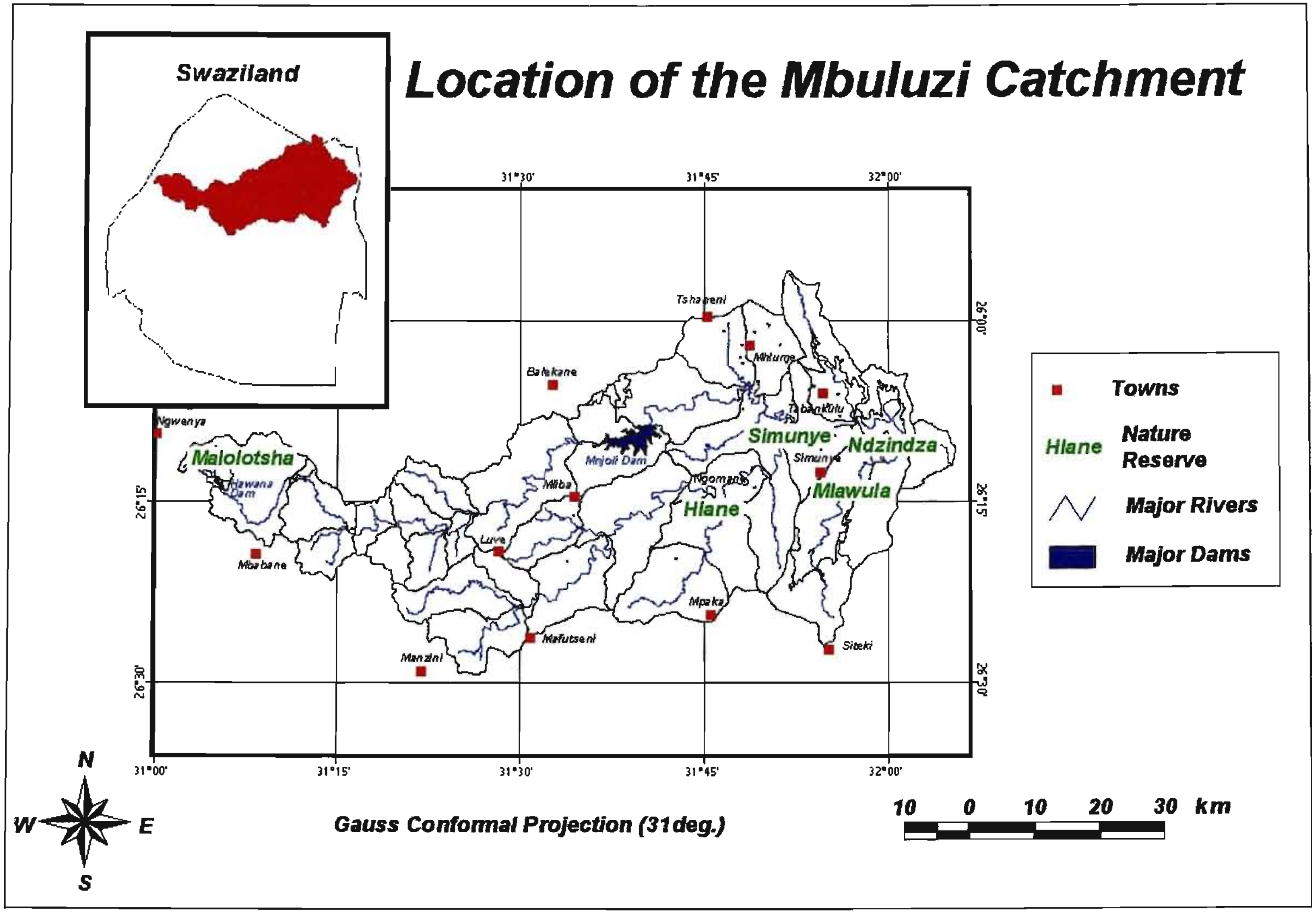


Figure 3.1 Location of the Mbuluzi catchment

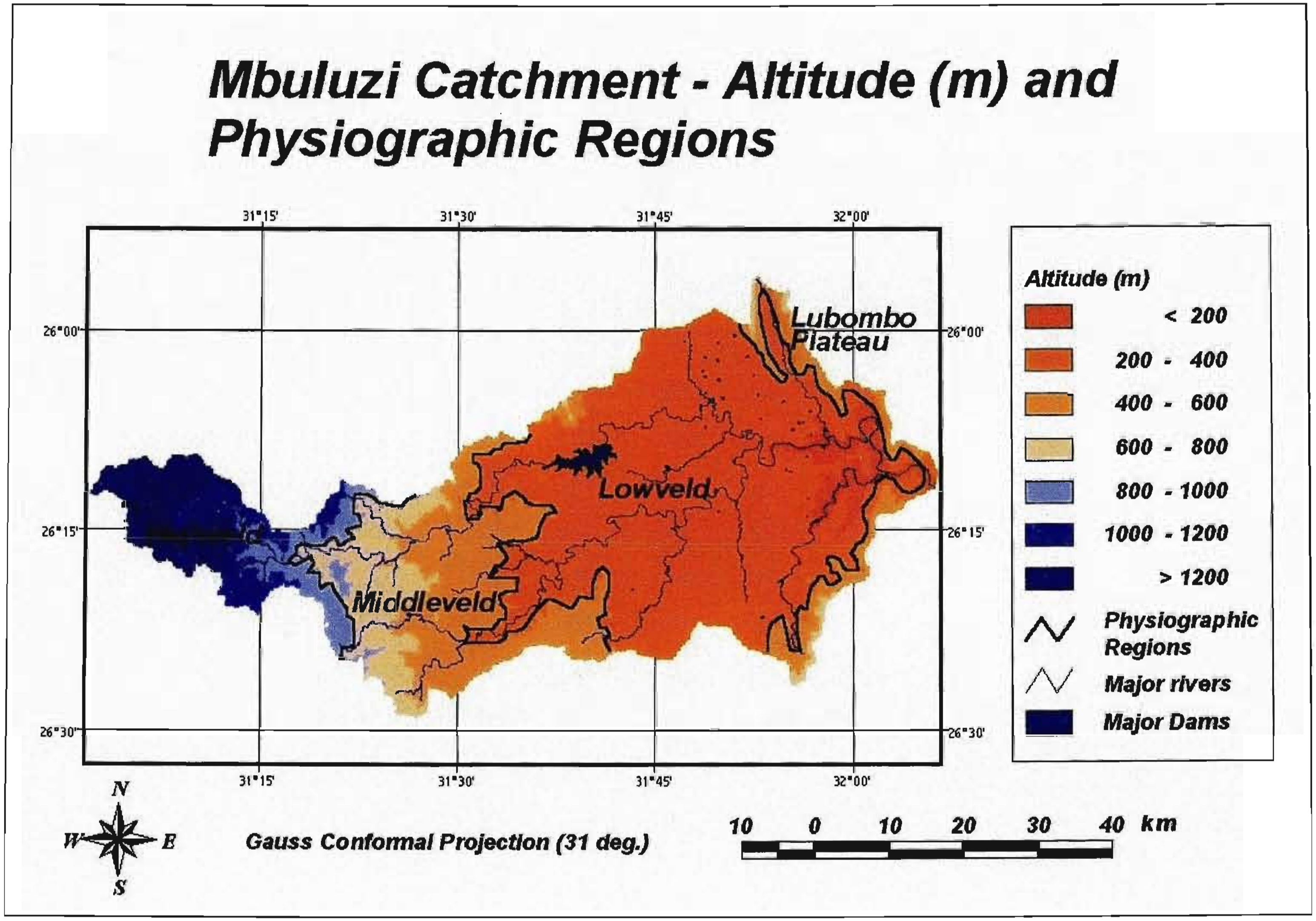


Figure 3.2 Physiographic regions and altitude of the Mbuluzi catchment

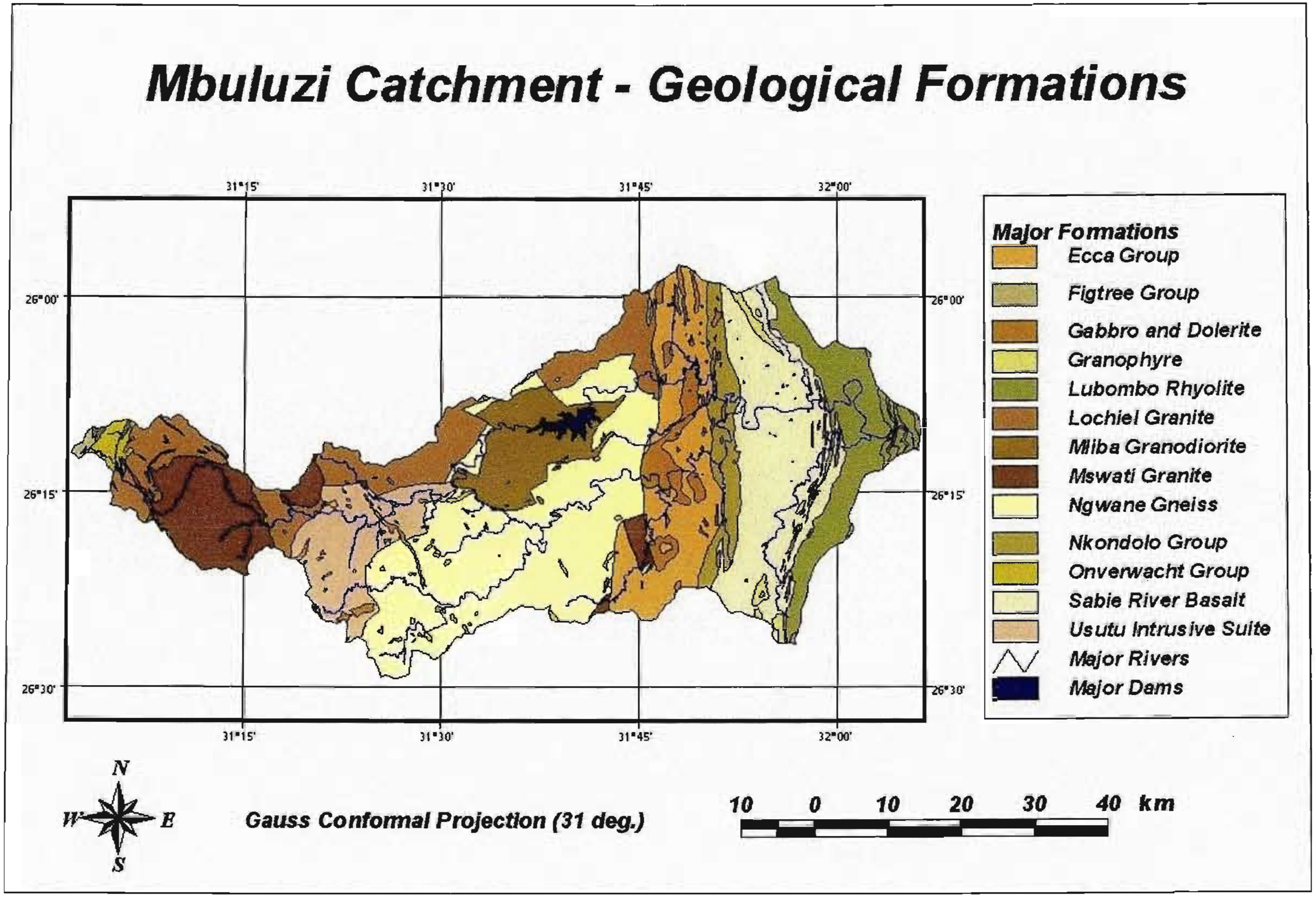


Figure 3.3 Major geological formations in the Mbuluzi catchment (after Murdoch, 1968)

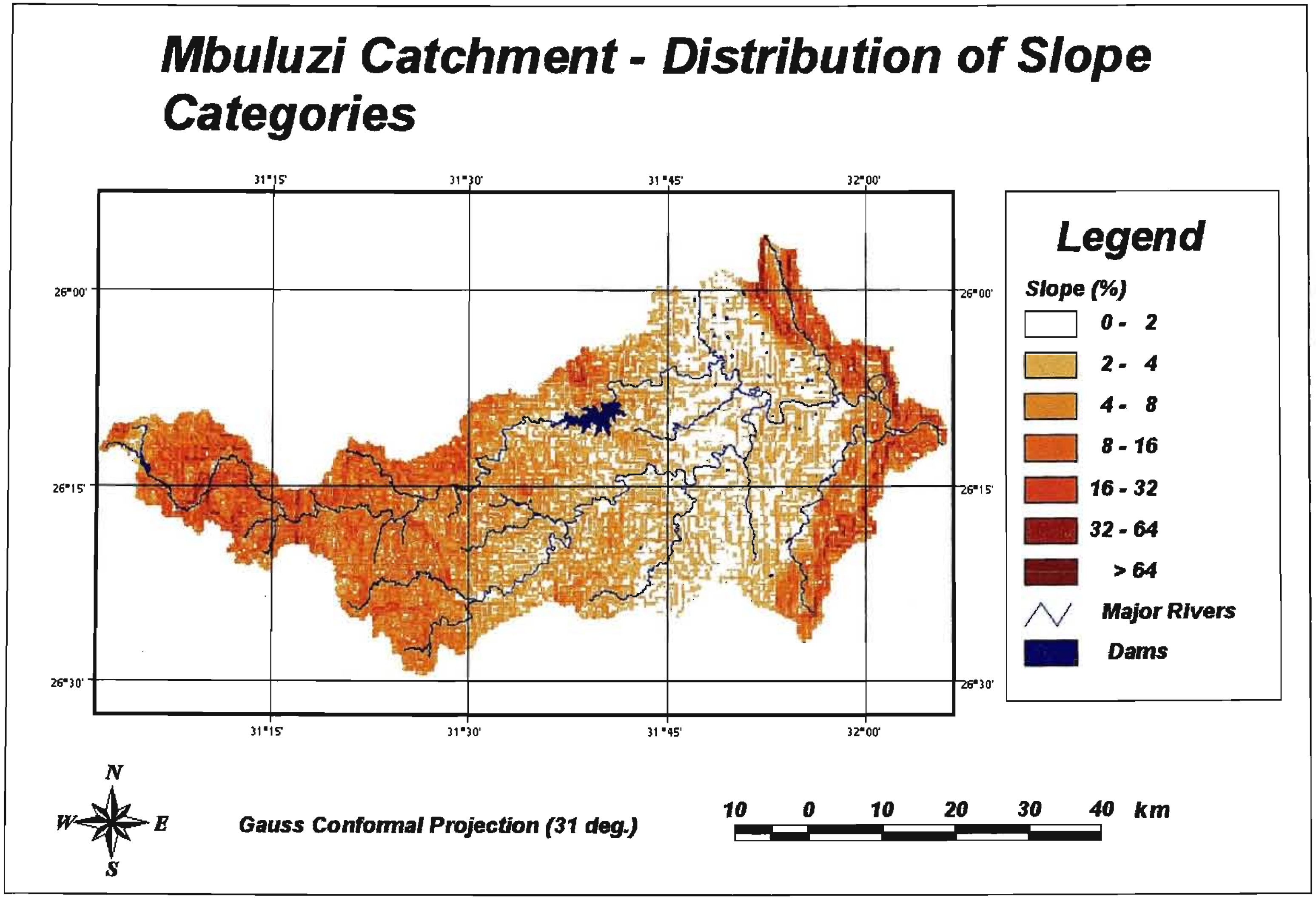


Figure 3.4 Distribution of different slope (%) catergories in the Mbuluzi catchment, calculated using GIS from a 200 m x 200 m Digital Elevation Model modified by Hughes (1997) from a DEM produced by the Chief Directorate of Surveys and Mapping (1997)

3.3 Climate

Except for the lowveld which is semi-arid, most of the catchment has a subhumid temperate climate. The catchment receives most of its rainfall during the wet summer season which begins in October and ends in March. These rains are mainly from convective storms in the higher altitudes of the highveld and from more maritime air mass regimes in the east. Mean Annual Precipitation (MAP) rarely exceeds 700mm in the lowveld while it may be in the excess of 1200mm in some parts of the highveld. Temperatures appear to vary according to altitude. The lowveld is the hottest region in the catchment with minimum and maximum temperatures respectively exceeding 11 °C and 26 °C in winter (July) and 22 °C and 33 °C in summer (Jannuary). With mean temperatures ranging between 16 °C and 23 °C in summer and 6 °C and 20 °C in winter, the highveld is the coldest part of the catchment. Owing to the high temperatures, especially in summer, the lowveld tends to have the highest A-pan equivalent potential evaporative demand values, in excess of 200 mm, while the values in the cooler highveld barely exceed 180 mm in January (Schulze, 1997). Potential evaporation is at its lowest in June, when the mean monthly A-pan values are less than 100 mm throughout the catchment (Schulze, 1997).

3.4 Soils

Soils in Swaziland were classified by Murdoch (1968) using an approach similar to Dudal's (1968) FAO discretisation criteria. A visual assessment of the soil map (**Figure 3.5**) suggests an association between the physiography and the distribution of some of the soils sets in the Mbuluzi catchment. The highveld is overlain by young, mineral soils. The rock outcrops and stony gravels are occasionally broken by grey sands on orange gravelly loam, deep yellow sands on red loam and patches of peat or organic soils. The middleveld has a variety of soils ranging from different variants of sands to those of clays though lithosolic shallow grey sands and sandy loams on hard rock are dominating in this region. Most of the soils are underlain by materials of lower hydraulic conductivities such as clay pans and hard rocks, which would suggest a strong interflow contribution to runoff. The distribution of soils in the upper middleveld, an interface zone between the high- and middleveld is similar to that of the middleveld except that the most common soils are very acidic deep red loams underlain by saprolite.

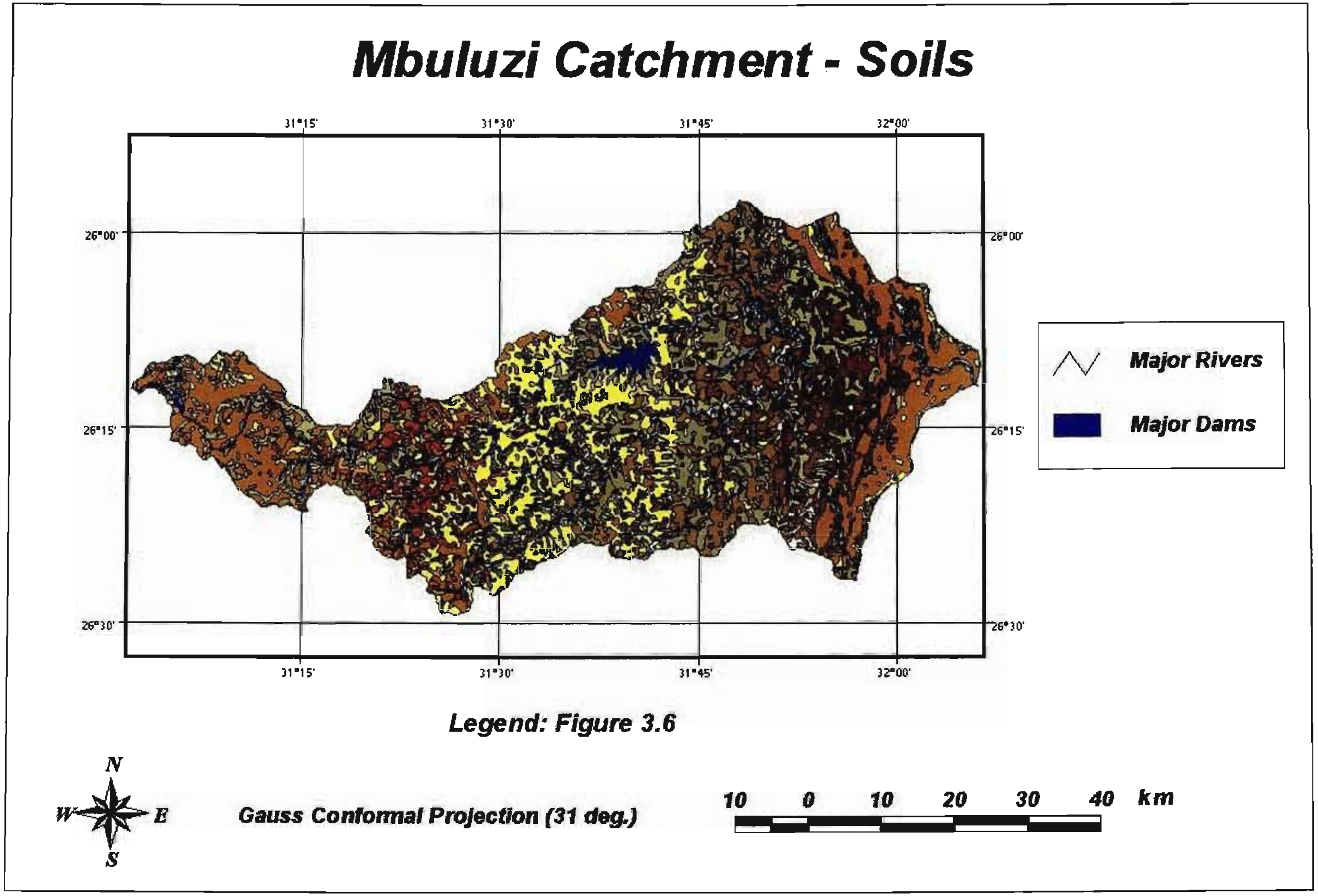


Figure 3.5 Distribution of soils in the Mbuluzi catchment (after Murdoch, 1968)

Figure 3.6 Legend of the soils map shown in **Figure 3.5**

According to Scholten, Felix-Henningsen and Mushala (1995), saprolite is highly susceptible to erosion, hence severely eroded areas in the form of deep gullies are found in this region. Grey and dark grey sandy loams respectively on top of mottled clay and clay pans are the predominant soils in the lowveld. The colours of the soils indicate the poor drainage properties of the subsoil. Flecks of shallow brown or black loam to clay soils also occur and together with red clays become common features in the eastwards direction. Streaks of brown sandy old alluvium are found in the floodplains. The steep slope faces ascending to the Lubombo Plateau are covered mostly by rock outcrops and raw mineral soils. Like the middleveld, the Lubombo Plateau has a heterogeneous distribution of soils ranging from clays to coarse sands.

3.5 Natural Vegetation

The type and nature of indigenous vegetation in a host area are a function of the physical characteristics such as soils, altitude, slope and aspect as well as the macro- and microclimate. Major natural vegetation types in the Mbuluzi catchment are associated with physiographic regions. From Acocks' (1988) map (**Figure 3.7**), four major Veld Types prevail in the catchment and each physiographic region is dominated by one Veld Type. The Veld Types constitute the baseline land cover in this study. The natural vegetation in the highveld consists of the Northeastern Sourveld with some patches of montane forests along river valleys and interfluves.

A mixture of tall grasses, bushes and savanna type vegetation described by Acock's (1988) as Lowveld Sour Bushveld is found in the middleveld. In the eastwards direction towards the lowveld, the grassland savanna is replaced by woodlands comprising of thorn bushes and the broadleafed trees. Vegetation in the Lubombo Plateau resembles that of the middleveld.

3.6 Present Land and Water Use in the Catchment

The land and water resources in the Mbuluzi catchment have undergone a considerable amount of development and utilization since Swaziland attained independence in 1968. From the 1996 LANDSAT TM image (**Figure 3.8**), more than 10% of the 2958.9 km^2 catchment area is under

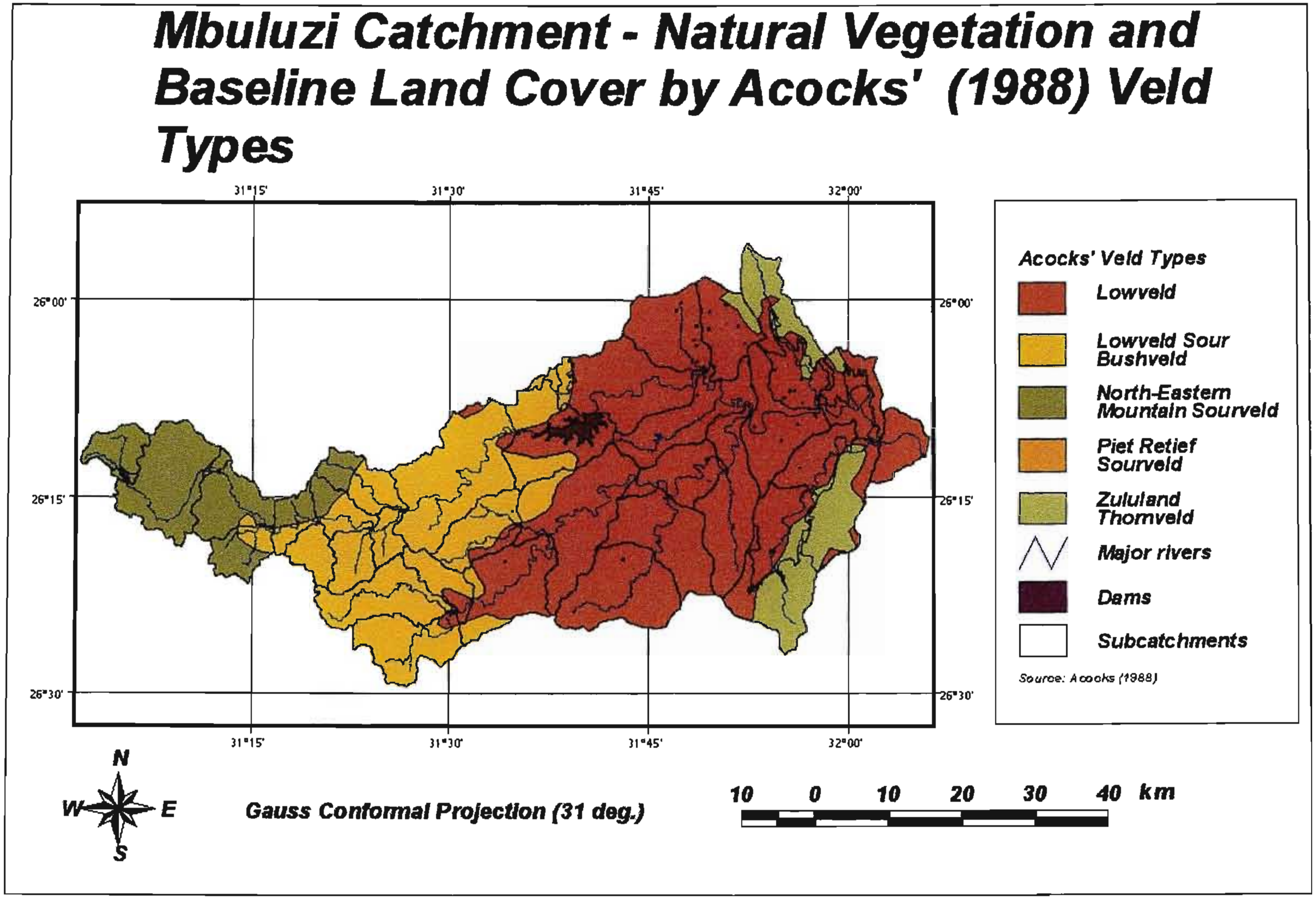


Figure 3.7 Natural vegetation and baseline land cover in the Mbuluzi catchment as represented by Acocks' (1988) Veld Types

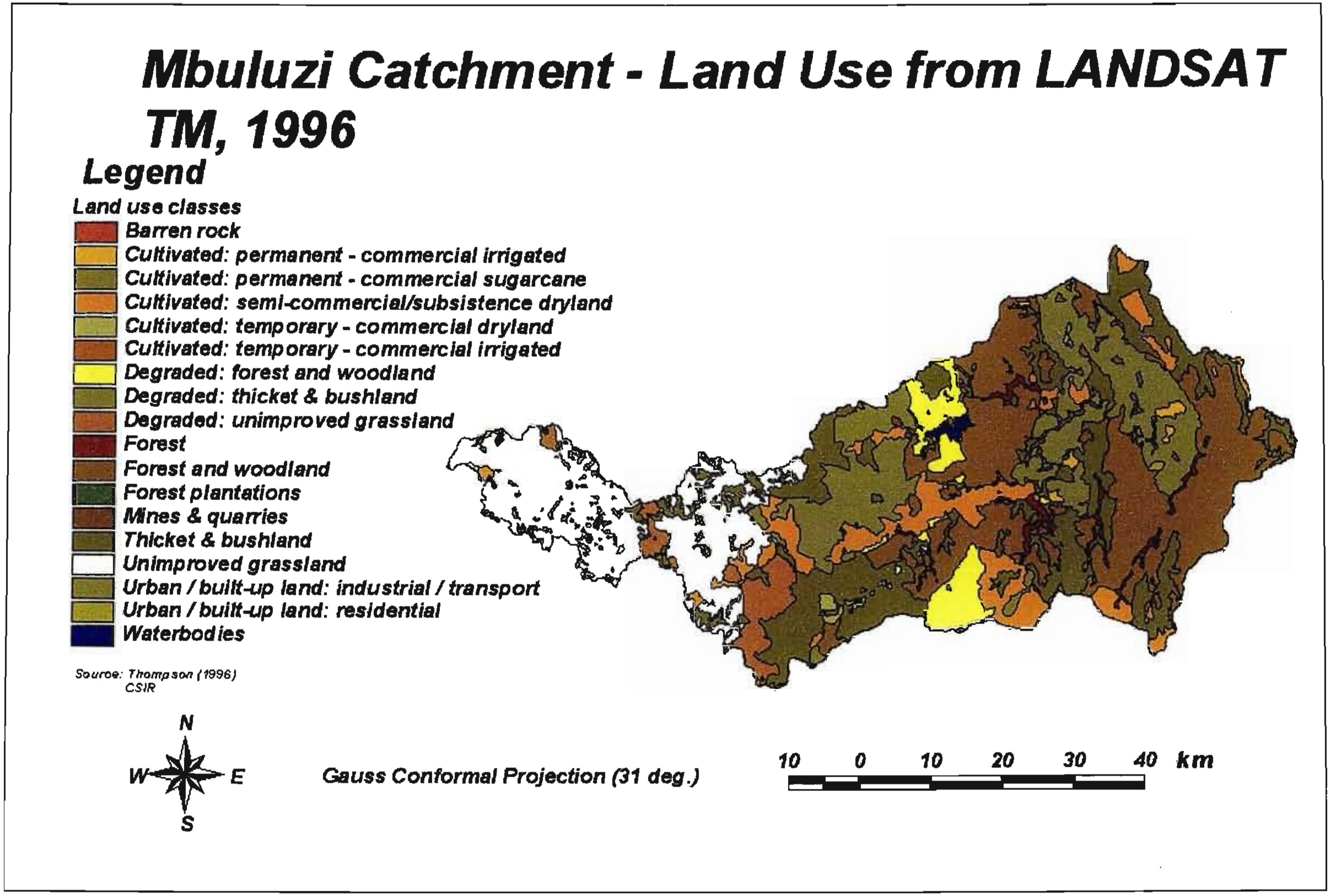


Figure 3.8 Mbuluzi catchment land cover from the 1996 National LANDSAT TM image (CSIR, 1996)

intensive large scale irrigated agriculture and a further 2000 ha of land in Hlane nature and game reserve (**Figure 3.1**) are being developed, also for irrigated agriculture. Most of the irrigation takes place in the eastern part of the catchment around Simunye and Mhlume (**Figure 3.1**), a region aptly called the "sugar belt". Sugarcane is not only grown within the Mbuluzi catchment, but in large parts elsewhere in the east and lowveld regions of Swaziland. The second important irrigated cash crop also grown in the lowveld region is citrus fruit in Tabankulu (**Figure 3.1**). Water for irrigation, domestic and industrial use in Simunye and a portion for Tabankulu is drawn from the Mnjoli Dam, while Mhlume and surrounding areas, including the Tabankulu, obtain water as inter-catchment transfers from the Sand River Dam in the adjacent Komati Basin to the north.

Dryland agriculture is prevalent in the middle and some areas in the upper reaches of the catchment. These areas being mostly inhabited by rural communities, the agricultural activity consists mainly of maize production, the staple food crop, for subsistence and cash generation with the surplus if there is any. The production of cotton in the same region, also under dryland conditions, is not uncommon.

Another important land use in the catchment is livestock rearing. Grazing takes place in communal pastures around the rural communities and in privately owned ranches. Contrary to the communal grazing areas which are often overgrazed as a result of overstocking, the grasslands in most of the privately owned ranches appear to be maintained in good condition. Livestock watering often occurs at the water sources such as streams and wells, although in some instances water diversions are made for watering, especially at the ranches.

Large tracts of land in the catchment are reserved for nature conservation. Hlane, Ndzindza, Mlawula and Simunye (**Figure 3.1**) are four of the five nature and game reserves in the catchment and all are found in the lowveld, bordering the sugarcane plantations. A portion of Malolotsha Nature Reserve makes up the fifth one.

Although most of the land in the catchment is occupied by rural communities and is under agricultural use, some pockets of land have undergone urban development with industrial activity and concentrations of human populations. Mbabane, the capital city of Swaziland falls within the Usuthu Basin, but parts of it overlap into the Mbuluzi catchment. Its water supplies are augmented by the Hawana Dam, which also provides water for Ngwenya (**Figure 3.1**). A similar situation exists in Manzini City, which also extends into the catchment. The difference is that Manzini receives all its water from the Usuthu river, but some return flows contribute to the flow in Mbuluzi River. Mafutseni and Mpaka railway station (**Figure 3.1**) are smaller municipalities with water allocations from Mbuluzane, a tributary of the Mbuluzi river. Sugarcane production has been followed by processing industries and the growth of small towns such as Simunye and Mhlume, as well as nucleated residential villages.

This overview has illustrated the importance of the Mbuluzi river, not only to the catchment residents, but also to the socio-economic well-being of the whole country. Claims by the Water Resources Branch that water in the Mbuluzi system has been fully allocated raise concerns, as they effectively curtail further development if sound water management strategies are not implemented. Besides the water shortage claims, other concerns include soil erosion and the effects of the effluent (from the sugar industry) discharged into the river, on the water quality. The water quality issue may not be directly affecting Swaziland as yet, with only a few dependants downstream of the industry. However, the Mbuluzi river is an international system shared with Mozambique. Therefore, it is essential that sufficient water of acceptable quality be passed on to Mozambique.

4. METHODOLOGY

4.1 Introduction

Evaluating and testing a model suitable for modelling catchment-level hydrological processes and land use impacts for integrated water resources management is one of the objectives of this study. Nowadays, there is a wide range of models available and some of them have similar outputs, hence selecting a suitable one can be a difficult task. In this study, it was desired that the modelling tool be deterministic in nature and capable of simulating hydrological processes in sub-humid to semi-arid climates. The *ACRU* agrohydrological modelling system (Schulze, 1995; Smithers and Schulze, 1995), although without reviewing other modelling systems, was found to satisfy these criteria. Therefore, this chapter reviews the conceptual framework, input data requirements, applications and thus the potential of the *ACRU* model in IWRM, particularly in developing countries. The review is followed by a detailed description of the configuration of the catchment and data preparation for the setting up of an *ACRU* model input menu for the Mbuluzi catchment. Finally, results from, and comments on, the verification studies of the model output in the Mbuluzi catchment are presented.

4.2 The *ACRU* Agrohydrological Modelling System

The *ACRU* modelling system is a daily time step, physical-conceptual and multi-purpose model (**Figure 4.1**) with options to output, *inter alia,* daily values of streamflow, peak discharge, reservoir status, recharge to groundwater, sediment yield, irrigation water supply and demand as well as the facility to output seasonal yields of selected crops at any location within the catchment (Schulze, 1995).

The model revolves around multi-layer soil water budgeting (**Figure 4.2**). It is structured to be hydrologically sensitive to catchment land uses and changes thereof, including the impacts of reservoirs, irrigation practices, urbanisation, afforestation and of greenhouse effect induced climate change on catchment streamflow and sediment generation (Schulze, 1995; Schulze and Perks, 2000).

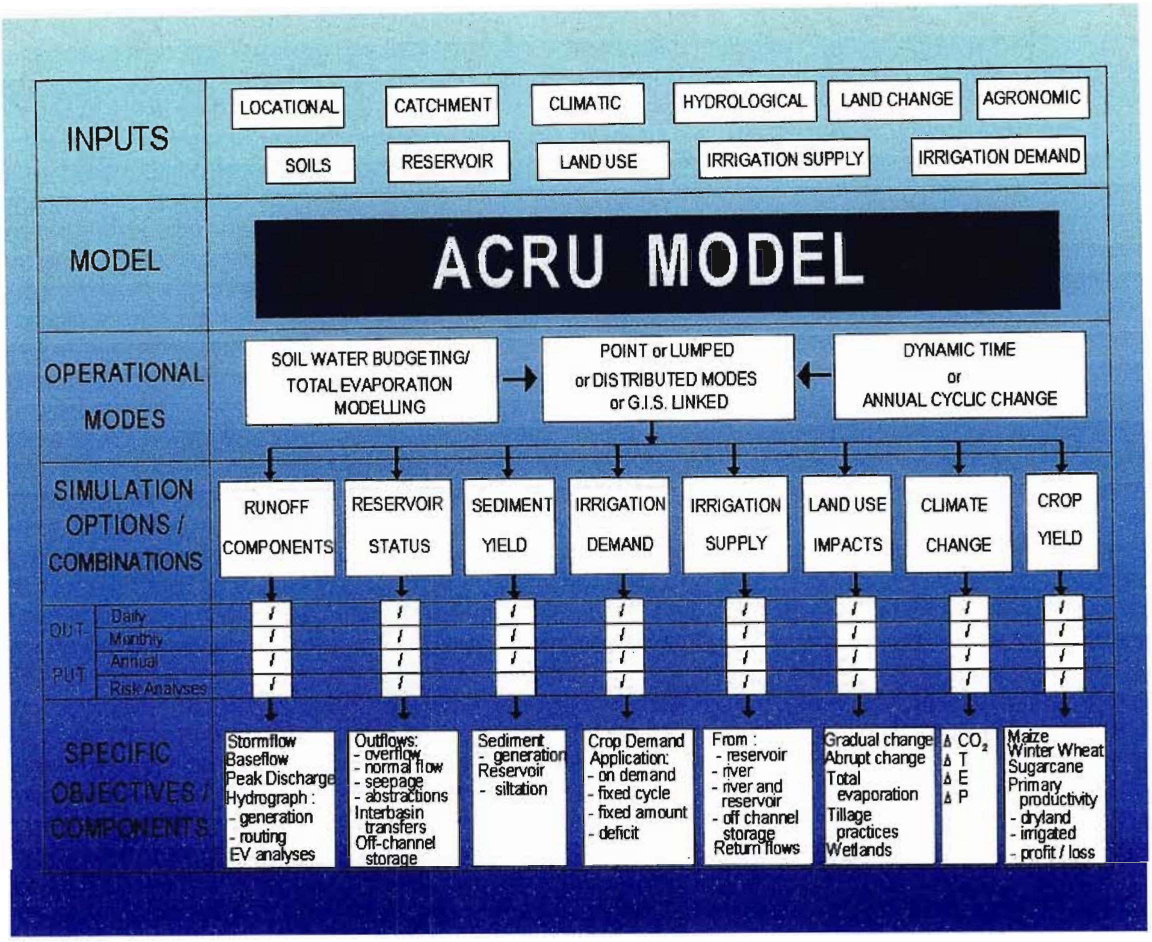


Figure 4.1 The *ACRU* agrohydrological modelling system: Concepts (Schulze, 1995)

ACRU can operate at a point or as a lumped catchment model. However, for large catchments or in areas of complex land uses and hydrological variability of soils, or where streamflows in the channel have been modified by reservoirs/ abstractions, the model can operate as a hydrologically cascading distributed cell-type model.

The model requires input of known and measurable spatially and temporally variable factors characterising the catchment. Catchment information may be classified by :

a) climate (daily rainfall, temperature, potential evaporation),
b) physical characteristics (size, soils, and altitude),
c) bio-physical (baseline land cover and present land use) and
d) land use/management practices (irrigation demand and supply as well as domestic, industrial and livestock water abstractions).

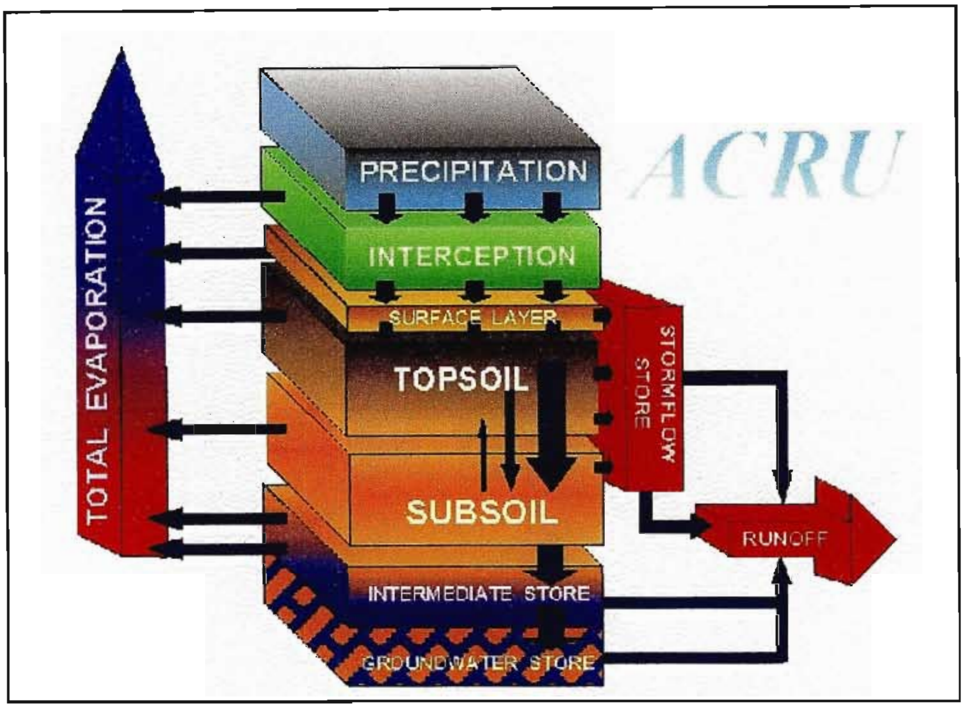


Figure 4.2 The *ACRU* agrohydrological modelling system: Structure

Within the model the information undergoes transformation to produce the eventual catchment responses through routines representing the processes within each sub-system and the manner in which they interact and are linked. The model also calculates thresholds at which catchment responses occur and response rates change.

The model then produces output of the unmeasured, or simulated, variables that can be analysed within the modelling system or by using other post-processing software such as spreadsheets and statistical packages. Examples of the output include:

a) streamflow on a daily basis, separated into stormflow and baseflow and
b) sediment yield (on an event-by-event basis)

Certain statistical analysis routines are embedded within the modelling; thus frequency analysis and comparative statistical calculations can be performed and output as post-simulation results. The simulated variables as well as simulated vs observed values can also be viewed graphically as time series or scatter plots using the model's graphics output utility.

4.3 Applications of the *ACRU* Model

ACRU model output has been successfully verified and the model has been used extensively to provide solutions to a wide range of water resources related problems in different climatic and physiographic conditions. Many studies have been undertaken using this model since the mid 1980s. From recent literature, a few selected references are cited as examples of its use in the different categories of water resources related research. These include

a) water resources assessments (Kienzle, Lorentz and Schulze, 1994)
b) design flood estimation (Schulze *et al.*, 1993)
c) irrigation water demand and supply (Dent *et al.*, 1988)
d) assessments of impacts of land use change on water resources (Jewitt and Schulze, 1991; Schulze *et al.*, 1996; Schulze *et al.*, 1998)
e) assessments of hydrological impacts of wetlands (Smithers and Schulze, 1993)
f) assessments of potential impacts of global climate change on water resources (Schulze and Perks, 2000) and
g) sediment yield studies (Kienzle, Lorentz and Schulze, 1997).

It is against this background that the *ACRU* model was chosen for modelling hydrological responses from the Mbuluzi catchment. A strength of this model is that it is physically-conceptual in structure. This implies that even though it was developed predominantly under southern African conditions, the major physical processes are represented explicitly. *ACRU* can be, and has been, used with some confidence in a wide range of climatic and physiographic locations without extensive external calibration. This has a particular relevance in this study which has a focus on developing countries which usually have poor gauging networks and unreliable and incomplete records of data. The multi-level nature of the input information requirements, coupled with in-built decision support systems and generic default values make it possible to obtain reasonable simulations for a range of levels of input information that is available.

With the many modules embedded in the model, it can be used as an integrated hydrological modelling tool to assess the individual and interrelated effects of a combination of different land

and water uses as well as management systems in different spatial locations within a catchment. This is congruent with the recommended systems, or integrated, approach for the management of catchment resources. The possible effects of several alternative management systems can be assessed and a suitable one be adopted.

4.4 Modelling the Hydrology of the Mbuluzi Catchment

The *ACRU* hydrological modelling system was configured for the Mbuluzi catchment upstream of border with Mozambique to simulate streamflows for 40 subcatchments over the 46-year period from 1 January 1950 to 31 December 1995. Simulated time series were compared against observed time series where these are available. Maps, tables and graphs were produced to quantify the following hydrological components, on a subcatchment (i.e Sub-Quaternary Catchment) basis:

a) streamflows under baseline land cover condition,
b) streamflow production under present land use condition,
c) the impact of present land uses and water demands on streamflow production, and
d) the impact of possible future land uses and water demands on streamflow production,
e) sediment yields under present land use condition, and
f) the potential impacts of land use and management changes.

The above list of investigated hydrological components of the catchment study does not address all information requirements for IWRM. Cognisant of the apparent restrictions by the modelling system, such as inability to simulate water quality, river channel geomorphological dynamics and ecological regimes, the research was not designed to be a mega-exercise to model all aspects of IWRM. The modelling provides some information regarding availability (quantity) of the water resources which is necessary for water allocation, which is at the core of IWRM.

4.4.1 Layout and configuration of the Mbuluzi catchment simulation system

The first step in setting up the *ACRU* model for distributed modelling was the delimitation of the entire catchment within the borders of Swaziland into subcatchments. These subcatchments had to be relatively homogeneous, in a hydrological sense. The following list of requirements formed criteria for delineating the Mbuluzi catchment into subcatchments:

a) ideally for the runoff generating process representation in *ACRU* , the subcatchments should not be larger than 50 km^2, except where a high level of homogeneity existed or where the rainfall station network was sparse,

b) each subcatchment had to be relatively homogeneous in terms of climate, soils and land cover,

c) currently operational gauging weirs with sufficiently long records, operated by the Water Resources Branch (WRB) in the Ministry of Natural Resources and Energy (MNRE) were designated as outlets of subcatchments,

d) confluences of major tributaries of the Mbuluzi river were located at the outlet of a particular subcatchment,

e) individual subcatchments were delineated at outflows of major dams, and

f) each subcatchment had to be a subset of a Quaternary Subcatchment.

Following the above criteria, the catchment was delineated into 40 subcatchments (**Figure 4.3**). Each of these subcatchments was further subdivided into seven sub-subcatchments, or cells, by making use of the national LANDSAT TM 1996 coverage provided by the Council for Scientific and Industrial Research (CSIR). This was done by defining seven broad land cover /land use/land management categories for modelling with *ACRU*. Each of the 18 land use classes from the LANDSAT TM coverage (**Figure 3.8**) was appropriately allocated to one of the seven broad categories (**Table 4.1**). If one or more categories were not present in a subcatchment, those categories did not feature as subsets of that subcatchment. This resulted in a modelling system with a total of 175 linked hydrological response units. This approach allows hydrological responses of different land uses to be modelled explicitly as separate units and land use impact scenarios to be undertaken with ease. The order in which simulated runoff generated in one cell had to be routed to another cell and subsequently from upstream subcatchment to downstream subcatchment was determined by procedures outlined in Schulze *et al.* (1998). The configuration and flow cascade from subcatchment to subcatchment and from cell to cell are shown **Figure 4.4** and **Figure 4.5** respectively.

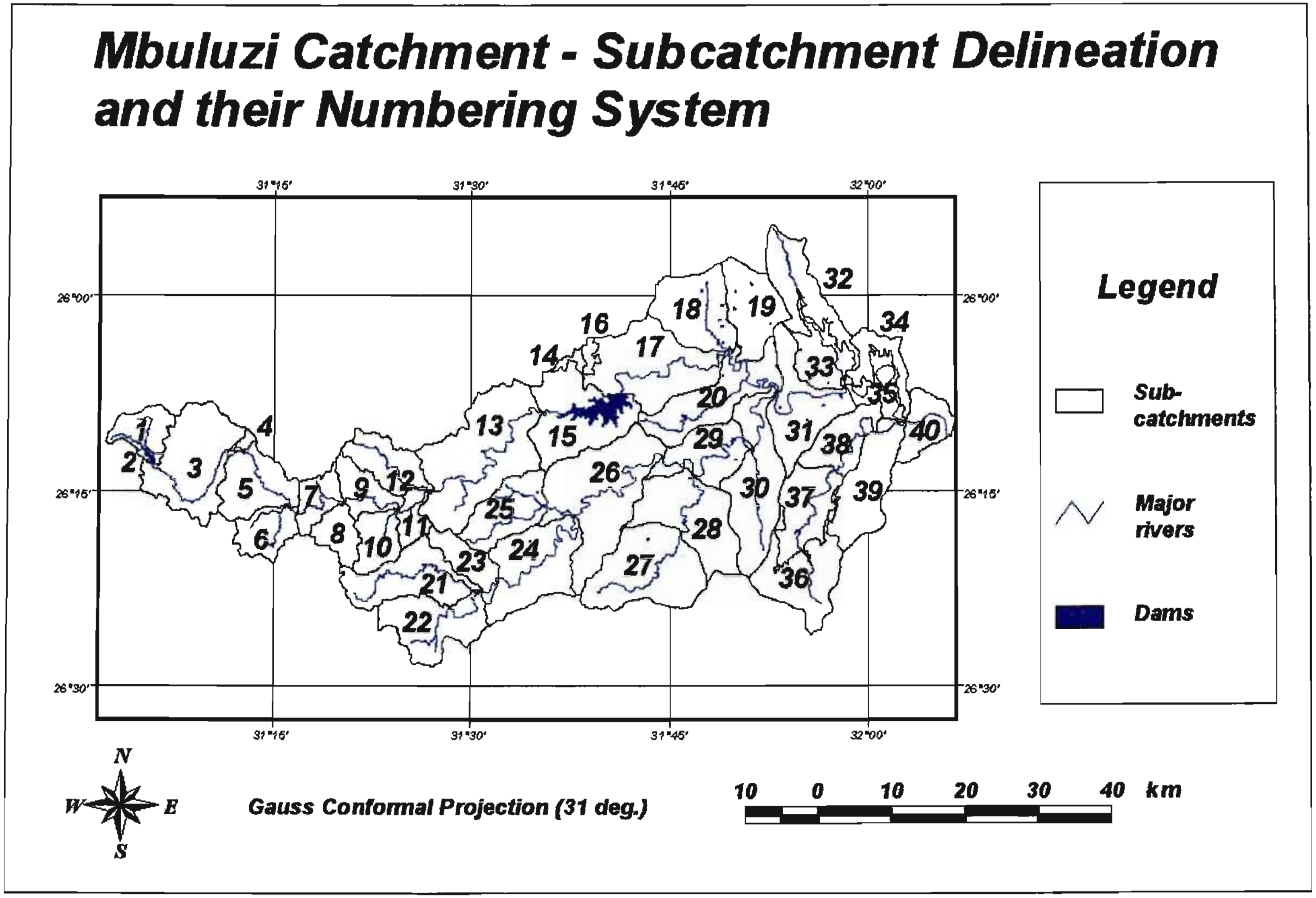


Figure 4.3 Forty subcatchments delineated within the Mbuluzi catchment and their numbering system

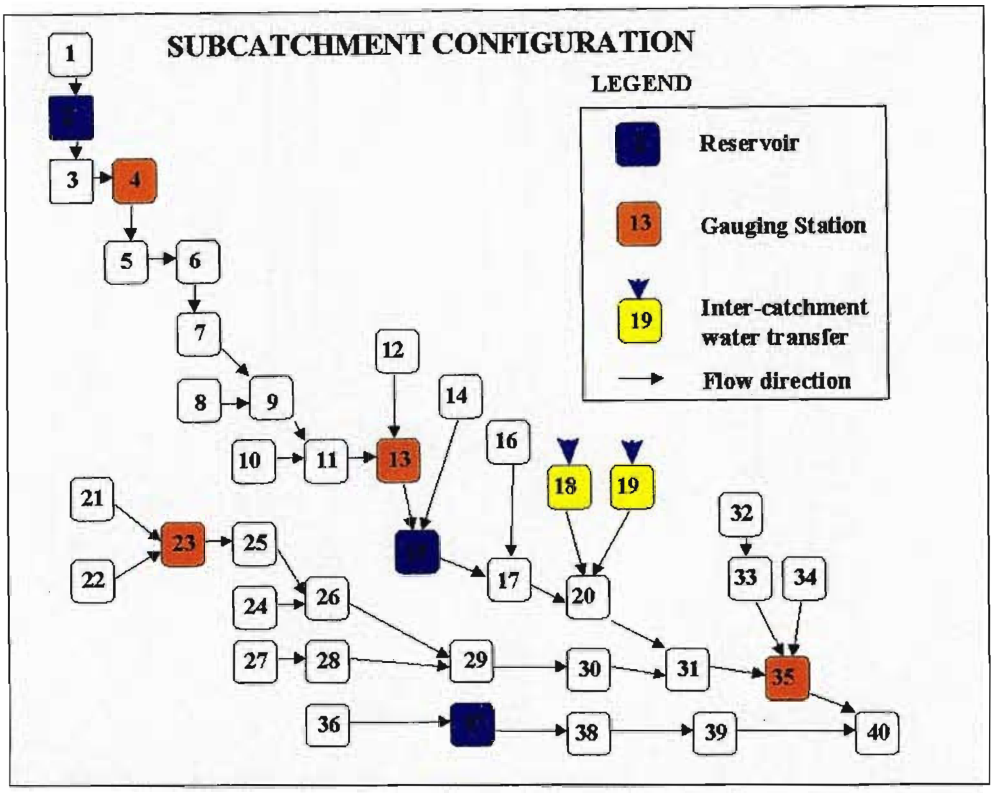


Figure 4.4 Subcatchment configuration and flow routing

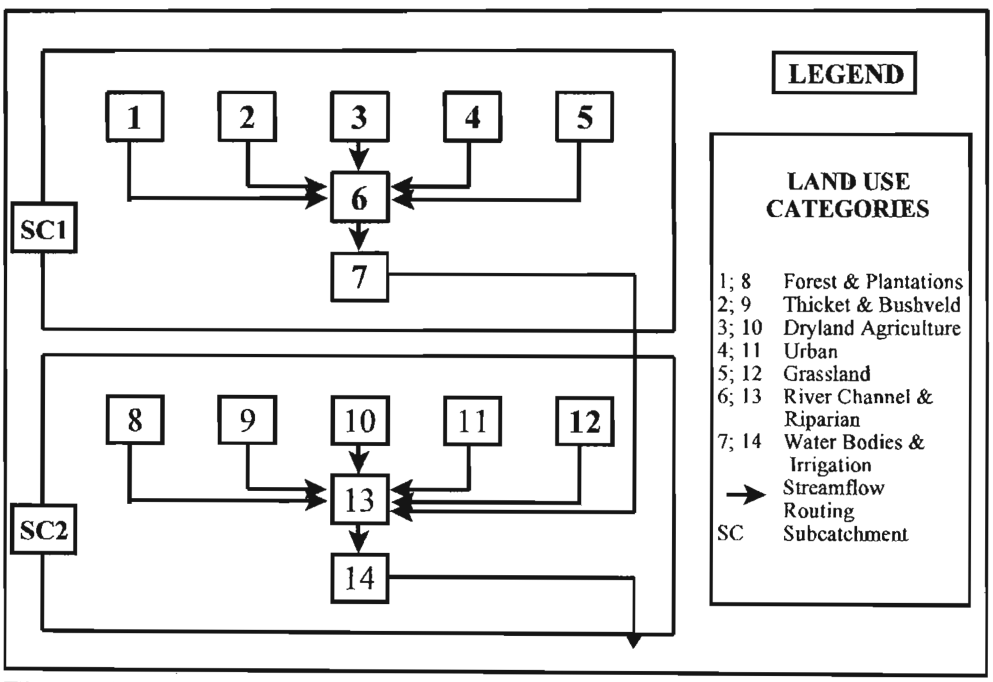


Figure 4.5 Cell to cell flow routing, using Subcatchments 1 and 2 as examples

Table 4.1 Mbuluzi Catchment: Land cover and land use categorisation

ACRU CATEGORIES	LANDSAT TM CLASSIFICATION
Forest & Plantations	Forest Forest plantations Forest & woodland Degraded forest & woodland
Thicket & Bushland	Thicket & bushland Degraded: thicket & bushland
Dryland Agriculture	Cultivated: semi-commercial/subsistence dryland Cultivated: temporary commercial dryland
Urban	Barren Urban/built-up land: industrial/transport Urban/built-up land: residential Mines & quarries
Grassland	Unimproved grassland Degraded: unimproved grassland
River Channel and Riparian	Not identified in LANDSAT TM, 1996
Water Bodies & Irrigation	Water bodies Cultivated: permanent-commercial irrigated Cultivated: permanent-commercial sugarcane Cultivated: temporary-commercial irrigated

4.4.2 Preparation of the model input

A general overview of the input information and data requirements of the *ACRU* model has been presented in **Figure 4.1**. Modelling inputs for the Mbuluzi catchments were obtained from different sources and included primary data (from observed time series and personal interviews) and secondary data (from published and unpublished reports). The following sections describe the sources of essential data and information, as well as the procedures of converting them into hydrological variables for the *ACRU* model.

The Mbuluzi catchment and its subcatchments were delimited on a 1:50 000 topographical maps and digitized. The resultant coverage was overlaid on a 200 m resolution digital elevation model (DEM). Subcatchment information such as area, geographical location (**Figure 3.1**), mean elevation and average slope (**Figure 3.3**) were calculated using algorithms developed by Hughes (1997) and GIS, *viz.* ARC/INFO 6.1 (ESRI,1996) provided by the Computing Centre for Water Research (CCWR). This information was exported and written to the *ACRU* data input menu.

4.4.2.1 Rainfall information

Rainfall "drives" most hydrological processes (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995) and is one variable to which catchment responses are generally highly sensitive to. Therefore a considerable amount of effort was expended into achieving reliable representations of daily point and areal rainfall for hydrological modelling for each subcatchment.

Information on all operational and no longer operational rainfall stations with daily records within and bordering the Mbuluzi catchment was extracted from the database of the CCWR. A station had to be assigned to "drive" the hydrological processes for each subcatchment. Ideally, the station should be within the subcatchment. However, owing to the uneven and sparse distribution of stations within the catchment, some subcatchments did not have stations in them. In such cases, the closest appropriate station to the subcatchment of interest was selected, conditional upon the subcatchment's displaying similar characteristics to the one in which the station was located. A total of 20 rainfall stations (listed in **Table 4.2** and their locations shown in **Figure 4.6**) was selected, and some assigned to more than one subcatchment.

All the stations had either incomplete or short daily rainfall records, or both. An inverse distance weighting program (Meier, 1997) was used to fill-in missing data and to extend the records of all the stations from 1 January 1950 to 31 December 1995.

Monthly adjustment factors (**Table 4.3**) were determined to render the each station's point rainfall areally representative of the whole subcatchment. This factor was calculated using median monthly rainfall values from Dent *et al.* (1989) on a one minute latitude by one minute longitude grid. The factors and the values of mean annual precipitation (MAP) for each subcatchment were written on the input menu. In **Figure 4.7** the values of MAP in each subcatchment are shown.

Table 4.2 Mbuluzi Catchment : Rainfall stations used in the hydrological modelling, for each subcatchment (SC)

Subcatchment	Quartenary Catchment	SAWB Number	Station Name	Latitude (°, ′)	Longitude (°, ′)	Altitude (m)	MAP (mm)
1	W60A	0481848W	Steysdorp	26 09	30 59	954	676.9
2	W60A	0481848W	Steysdorp	26 09	30 59	954	676.9
3	W60A	0482229	Mbabane	26 19	31 08	1219	1201.0
4	W60A	0482344	Mbu. Dem. Fm	26 14	31 11	1082	1179.4
5	W60B	0482229	Mbabane	26 19	31 08	1219	1201.0
6	W60B	0482229	Mbabane	26 19	31 08	1219	1201.0
7	W60C	0482581W	Herman's Hoop	26 11	31 20	936	1534.8
8	W60C	0482229	Mbabane	26 19	31 08	1219	1201.0
9	W60C	0482581W	Herman's Hoop	26 11	31 20	936	1534.8
10	W60C	0482689	Kwaluseni	26 29	31 23	609	905.4
11	W60C	0482581W	Herman's Hoop	26 11	31 20	936	1534.8
12	W60C	0482581W	Herman's Hoop	26 11	31 20	936	1534.8
13	W60D	0483064W	Balegane	26 04	31 33	335	758.9
14	W60E	0483064W	Balegane	26 04	31 33	335	758.9
15	W60E	0483193	Mliba Ranch	26 13	31 37	392	779.4
16	W60F	0483064W	Balegane	26 04	31 33	335	758.9
17	W60F	0483426W	Homestead	26 06	31 45	250	684.1
18	W60F	0483512S	Mhlume Mill	26 02	31 48	280	838.9
19	W60F	0483512S	Mhlume Mill	26 02	31 48	280	838.9
20	W60F	0483522S	Ngomane	26 12	31 48	244	842.4
21	W60G	0482867	St. Josephs	26 27	31 29	572	790.0
22	W60G	0483082	Dinedor	26 22	31 33	403	682.3
23	W60G	0483082	Dinedor	26 22	31 33	403	682.3
24	W60H	0483042W	Croydon	26 12	31 34	381	788.2
25	W60H	0483260	Triangle	26 20	31 39	405	562.4
26	W60H	0483260	Triangle	26 20	31 39	405	562.4
27	W60J	0483504	Mpaka	26 24	31 47	304	792.1
28	W60J	0483504	Mpaka	26 24	31 47	304	792.1
29	W60J	0483522S	Ngomane	26 12	31 48	244	842.4
30	W60J	0483522S	Ngomane	26 12	31 48	244	842.4
31	W60K	0483702S	Simunye	26 12	31 54	233	746.6
32	W60K	0483695W	Vuvulane	26 05	31 54	256	792.4
33	W60K	0483695W	Vuvulane	26 05	31 54	256	792.4
34	W60K	0483695W	Vuvulane	26 05	31 54	256	792.4
35	W60K	0483695W	Vuvulane	26 05	31 54	256	792.4
36	W60K	0483807	Siteki	26 29	31 57	725	835.4
37	W60K	0483702S	Simunye	26 12	31 54	233	746.6
38	W60K	0483702S	Simunye	26 12	31 54	233	746.6
39	W60K	0484135	Mhlumeni	26 15	32 05	427	799.7
40	W60K	0484135	Mhlumeni	26 15	32 05	427	799.7

Source: CCWR

Key:

W60A to W60K	Numbers of the Quaternary Catchment in which a subcatchment is located
Mbu. Dem. Fm	Mbuluzi Demonstration Farm
0xxxxxxW	South African Weather Bureau (SAWB) rainfall station
0xxxxxxS	South African Sugar Association rainfall station
0xxxxxx	Other rainfall stations

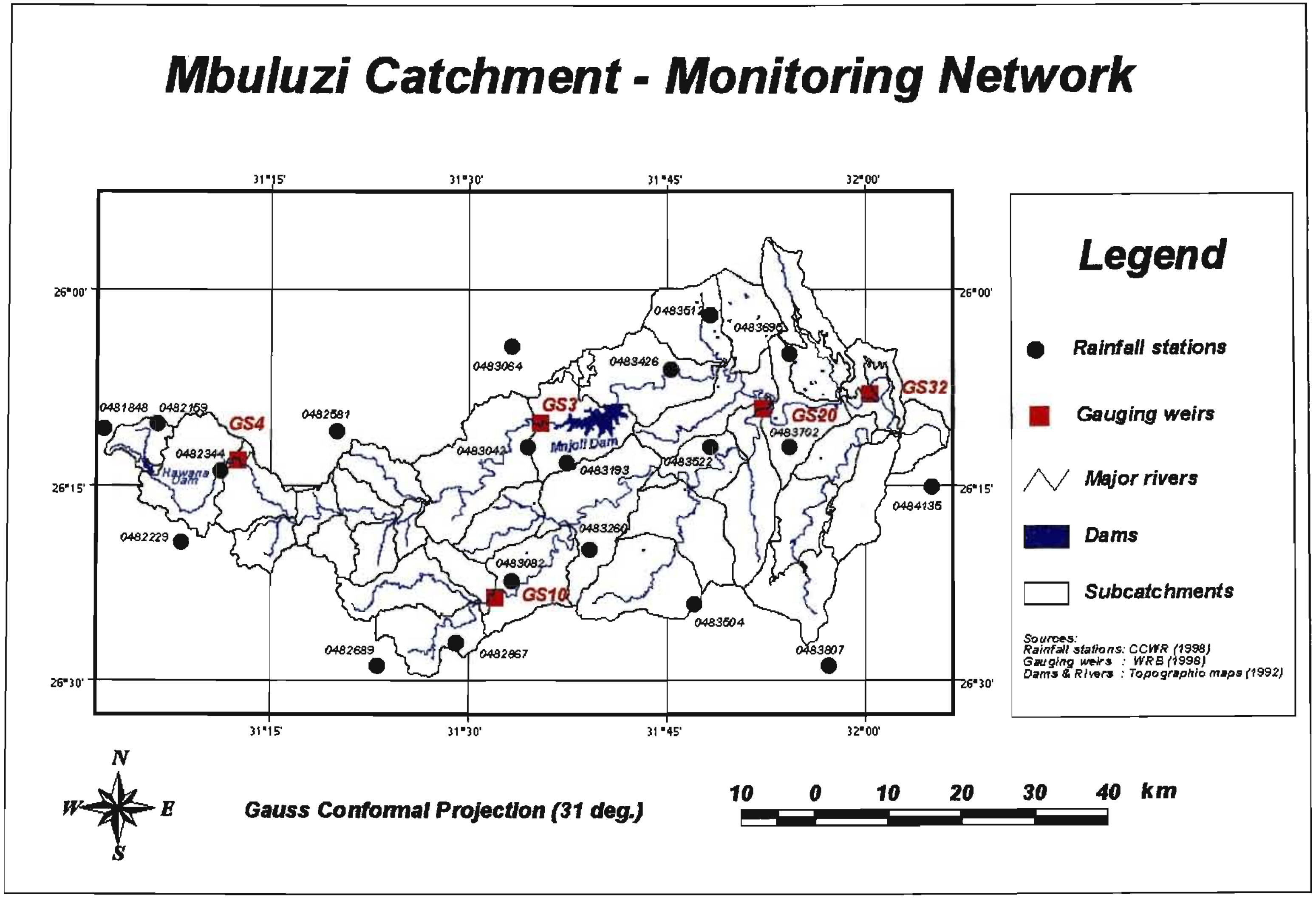


Figure 4.6 Rainfall and streamflow gauging stations used in modelling the hydrological responses of the Mbuluzi catchment

Table 4.3 Mbuluzi catchment: Monthly adjustment factors for daily rainfall (mm) values per subcatchment (SC)

SC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.21	1.07	1.21	1.02	0.96	0.70	0.96	0.73	1.30	0.97	1.15	1.05
2	1.25	1.12	1.25	1.06	0.94	0.70	1.06	0.82	1.30	0.99	1.17	1.08
3	0.94	0.94	0.94	0.94	0.94	0.70	0.93	0.97	1.30	0.95	0.94	0.94
4	1.24	1.02	1.17	1.19	0.99	0.83	1.20	1.06	1.30	1.08	1.23	1.15
5	0.93	0.93	0.95	1.16	0.93	0.81	1.02	1.05	1.30	0.95	0.95	0.94
6	0.85	0.70	0.82	0.81	0.76	0.70	0.70	0.70	1.30	0.72	0.91	0.82
7	1.16	1.00	0.94	1.04	0.82	0.70	0.70	0.70	1.12	1.01	1.07	0.95
8	0.81	0.70	0.77	0.79	0.71	0.70	0.70	0.70	0.88	0.72	0.85	0.77
9	1.10	0.94	0.88	1.00	0.78	0.70	0.70	0.70	1.05	0.97	1.01	0.90
10	1.30	1.09	1.26	1.10	1.04	0.88	0.96	0.70	1.30	1.03	1.23	1.23
11	0.90	0.76	0.71	0.83	0.70	0.70	0.70	0.70	0.86	0.81	0.82	0.73
12	1.17	0.99	0.93	1.07	0.82	0.75	0.70	0.70	1.09	1.02	1.07	0.95
13	1.16	1.10	1.25	0.96	0.92	0.73	1.22	0.70	1.30	1.12	1.15	1.07
14	1.19	1.16	1.30	1.03	0.94	0.77	1.20	0.70	1.30	1.09	1.17	1.09
15	1.13	0.89	1.04	0.90	0.98	0.82	1.19	0.70	1.30	1.09	1.20	1.10
16	1.20	1.19	1.30	1.04	0.92	0.89	1.11	0.70	1.30	1.09	1.20	1.10
17	1.05	0.91	1.30	1.27	1.02	1.30	1.30	0.70	1.30	1.06	1.15	1.09
18	0.88	0.95	1.20	1.00	0.83	0.70	0.97	0.70	1.25	1.02	1.09	1.10
19	0.95	1.02	1.30	1.14	1.03	0.91	1.24	0.70	1.30	1.10	1.18	1.18
20	1.02	1.00	1.28	1.20	1.30	0.92	0.85	0.70	1.30	1.16	1.29	1.09
21	0.95	0.95	0.95	1.11	1.20	0.99	1.19	0.72	1.30	0.96	0.95	0.95
22	1.13	1.19	1.19	1.06	1.06	1.13	1.02	0.73	1.30	1.10	1.12	1.10
23	1.30	1.28	1.28	1.29	1.28	0.70	1.30	0.72	1.30	1.20	1.30	1.14
24	1.17	1.02	1.23	1.13	1.15	1.18	1.24	0.72	1.30	1.06	1.19	0.99
25	1.15	0.99	1.21	1.07	1.02	0.81	0.99	0.70	1.30	1.13	1.30	1.09
26	1.02	0.90	1.11	0.98	0.96	0.76	0.88	0.70	1.30	0.98	1.18	0.94
27	1.04	1.10	1.20	1.13	1.24	0.78	0.70	0.70	1.30	1.14	1.30	0.97
28	0.99	1.06	1.16	1.09	1.23	0.86	0.70	0.70	1.30	1.06	1.28	0.93
29	1.00	0.99	1.25	1.16	1.30	0.79	0.75	0.70	1.30	1.17	1.29	1.06
30	0.98	0.98	1.27	1.21	1.30	0.89	0.76	0.70	1.30	1.16	1.28	1.04
31	1.06	0.94	1.06	1.08	1.19	0.88	0.96	0.70	1.22	1.09	1.03	0.87
32	1.18	1.11	1.30	1.18	1.08	0.97	1.30	0.70	1.30	1.16	1.28	1.18
33	1.05	0.95	1.17	1.10	1.06	1.01	1.30	0.70	1.22	1.03	1.09	0.96
34	1.05	0.99	1.19	1.10	1.06	0.92	1.30	0.70	1.28	1.04	1.13	0.99
35	0.94	0.89	1.08	1.00	1.05	0.83	1.30	0.70	1.17	0.96	1.03	0.89
36	1.19	0.87	1.13	1.27	1.01	1.01	0.70	0.70	1.08	1.21	1.28	1.13
37	1.03	0.92	1.02	1.02	1.24	1.30	0.81	0.70	1.26	1.09	1.02	0.86
38	1.05	0.95	1.06	1.08	1.20	0.83	0.85	0.70	1.26	1.10	1.04	0.88
39	1.00	0.95	0.88	1.11	1.00	0.99	0.96	0.70	1.29	0.96	1.11	0.97
40	0.99	0.95	0.87	1.11	0.98	1.04	0.97	0.70	1.24	0.921	1.09	0.96

NB : Upper and lower limits of 1.30 and 0.70 were set according to recommendations by Smithers and Schulze (1995)

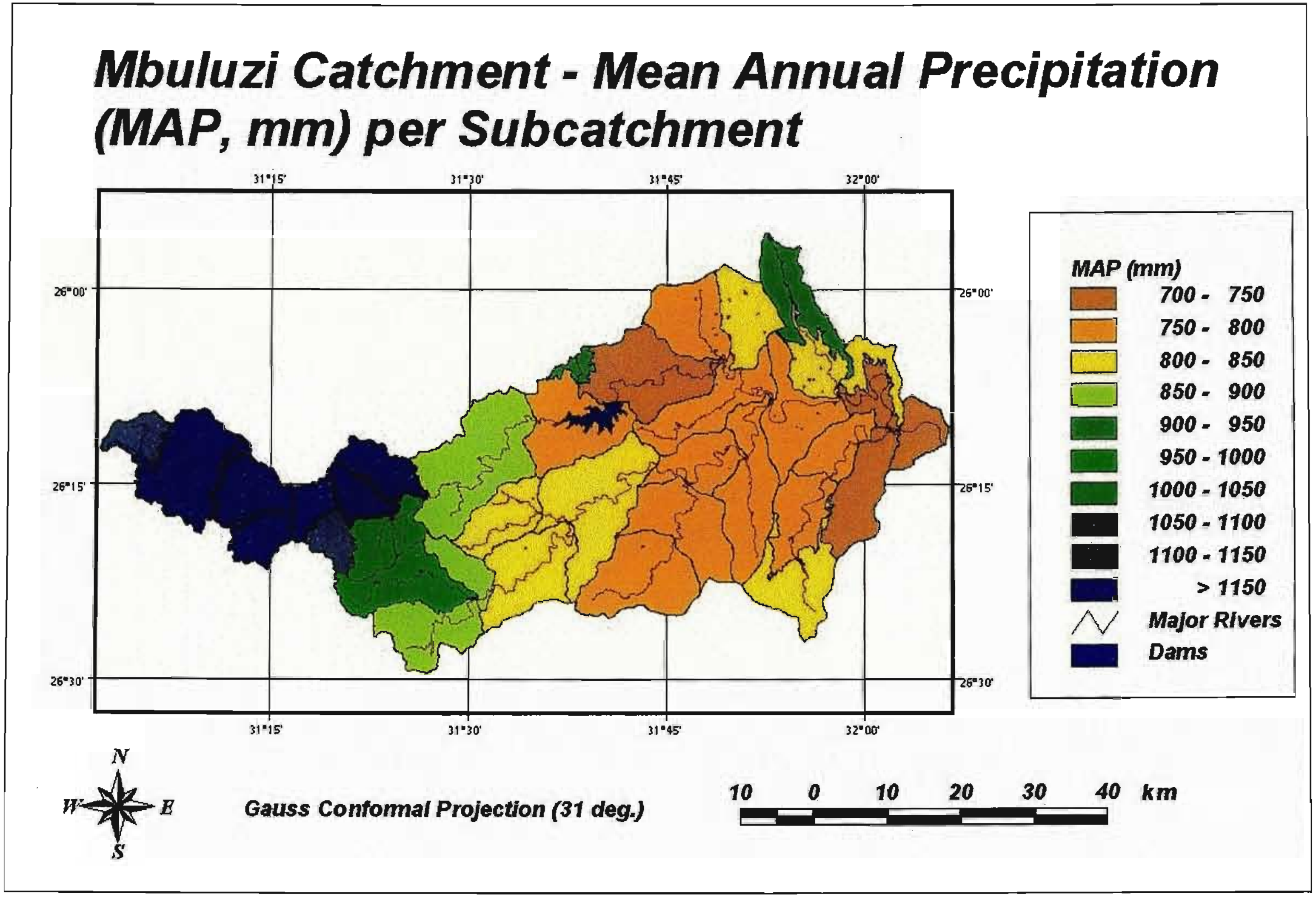


Figure 4.7 Mean annual precipitation (mm) per subcatchment in the Mbuluzi catchment

4.4.2.2 Potential evaporation and temperature information

Values of mean monthly A-pan equivalent reference potential evaporation were extracted from a one minute latitude by one minute longitude gridded surface that was developed by Schulze (1997) for each subcatchment. Using Fourier Analysis, the *ACRU* model disaggragates initially the monthly values internally into mean daily values, thereafter making potential evaporation adjustments down for rainy and up for rainless days that occurred on the subcatchment on a given day. The mean monthly values of reference potential evaporation for each subcatchment are presented in **Table 4.4**. Monthly means of daily maximum and minimum temperature for each subcatchment were extracted from a southern African one minute latitude by one minute longitude gridded surface also developed by Schulze (1997) and are shown in **Tables 4.5** and **4.6** respectively.

4.4.2.3 Soils information

Soils play an important role in influencing the hydrological responses of catchments. Soils facilitate the infiltration of precipitation. Depending on its type, antecedent moisture content and the surface conditions, soils largely determine how much and at what rate precipitation water crosses the air- soil interface, is contributing to runoff and how much is retained within the soil profile. Soils also act as media which store and further distribute water, both within and out of it through lateral and vertical drainage as well as through evaporation and transpiration. It is a consequence of the above roles that information about the hydrological characteristics of soils in each subcatchment are important and compulsory inputs for the *ACRU* model.

Information about the soils in the Mbuluzi catchment was provided by the Department of Geography, Environmental Science and Planning (GEP) at the University of Swaziland, in the form of a GIS coverage. The coverage had been obtained by digitizing the published (Murdoch,1968) national soil map. The map was a product of a project whose primary objective was to classify the soils for agronomic purposes. Therefore the classification criteria had focussed on fertility-related soil characteristics such as texture, acidity, organic matter content and concentration of nutrients. Hydrological soil parameters such as thickness of top- and subsoil horizons, their soil water contents at saturation, drained upper limit and permanent wilting point

Table 4.4 Mbuluzi catchment: Mean monthly values of A-pan equivalent reference potential evaporation (mm) per subcatchment (SC)

S C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	158.5	138.5	141.1	127.5	115.6	91.8	108.4	147.2	153.1	159.3	152.8	174.7
2	160.1	141.1	142.6	127.9	115.5	92.3	108.6	147.4	154.5	162.2	154.9	176.5
3	166.0	147.6	145.5	129.0	115.5	93.2	109.0	147.6	155.7	167.1	158.1	180.3
4	173.6	156.9	150.2	130.8	116.1	94.4	109.8	147.9	157.8	173.6	163.2	185.9
5	176.1	157.4	151.2	130.8	116.1	94.4	109.8	147.7	158.2	174.0	164.4	187.4
6	180.6	160.6	153.8	131.3	116.1	95.0	110.0	147.6	159.3	175.9	167.2	190.7
7	187.6	167.9	157.8	132.9	117.1	95.9	110.8	147.8	161.5	182.6	171.4	195.5
8	189.9	168.0	159.3	133.3	117.5	96.1	110.8	147.7	161.7	181.7	173.5	197.4
9	188.1	168.0	158.7	133.3	117.8	96.0	110.9	147.7	161.1	182.0	171.9	195.8
10	197.6	173.5	163.8	134.8	118.7	97.0	111.4	147.9	164.1	186.1	179.2	203.4
11	200.5	175.9	165.9	135.7	119.6	97.4	111.7	148.0	164.7	187.5	181.5	205.5
12	187.1	168.2	158.5	133.4	118.0	96.0	110.9	147.7	160.9	182.6	170.9	194.9
13	206.6	181.2	170.3	137.6	121.2	98.0	112.3	148.2	166.4	191.5	185.8	209.7
14	200.1	178.3	167.6	135.3	120.3	97.1	111.0	145.2	161.1	184.5	179.4	202.8
15	210.8	183.8	173.1	137.9	121.7	98.3	112.0	146.7	165.5	190.3	188.1	212.3
16	199.6	177.6	167.1	125.2	120.4	97.0	111.1	145.1	160.5	184.1	178.8	202.2
17	209.1	183.1	172.0	136.5	121.0	97.6	111.5	145.1	163.1	187.0	186.0	209.7
18	208.2	182.9	170.8	134.3	119.2	96.8	110.2	142.4	160.8	183.4	184.2	207.6
19	204.0	180.8	168.7	133.0	118.2	96.2	109.5	141.1	158.3	180.1	180.4	203.6
20	207.6	182.4	171.2	135.7	120.3	97.1	111.1	144.1	161.5	185.5	184.3	208.2
21	203.0	176.6	166.7	135.6	119.1	97.6	111.6	147.8	165.6	188.4	183.2	207.4
22	207.0	178.9	168.8	136.1	119.2	98.0	111.8	147.7	166.7	190.4	186.1	210.3
23	209.2	181.7	170.8	137.1	120.7	98.5	112.3	148.0	167.3	191.9	188.3	212.4
24	213.1	184.1	173.5	138.2	121.7	98.9	112.6	147.8	167.8	193.0	191.4	215.6
25	209.8	182.5	171.9	138.0	121.5	98.5	112.4	148.1	167.1	192.2	188.6	212.6
26	210.5	182.8	172.8	138.4	122.2	98.5	112.5	147.4	166.0	190.6	188.7	212.8
27	208.8	181.4	171.8	138.0	121.7	98.3	112.4	147.2	165.4	190.0	187.3	211.7
28	208.8	181.7	172.4	138.5	122.4	98.3	112.6	147.1	164.8	189.5	187.2	211.2
29	209.3	183.0	172.0	136.1	120.4	97.5	111.3	144.5	162.4	187.0	185.7	210.0
30	207.1	181.0	171.1	136.5	120.8	97.3	111.5	144.9	161.8	185.8	184.3	208.4
31	206.1	181.0	170.1	134.5	119.3	96.5	110.4	142.6	159.1	182.2	182.4	206.5
32	191.6	171.7	162.7	131.7	118.2	96.0	109.4	140.6	153.8	172.9	171.5	192.7
33	204.0	180.6	168.7	132.4	117.4	95.7	109.2	140.2	156.8	178.9	179.8	203.9
34	197.8	175.5	165.4	131.5	117.6	95.4	109.0	139.9	154.0	174.5	175.1	198.1
35	205.2	180.7	169.2	132.7	117.8	95.8	109.4	140.3	156.4	178.6	180.3	204.5
36	197.2	172.3	166.5	136.5	121.2	96.7	111.7	145.9	159.5	180.3	178.4	201.7
37	205.9	179.6	170.8	136.6	121.1	97.3	111.6	144.8	161.0	184.4	183.6	207.4
38	205.7	180.3	170.4	135.9	120.7	96.9	111.2	143.9	159.6	183.2	182.5	206.3
39	200.2	174.4	167.5	135.1	120.6	96.5	110.9	143.7	157.4	178.5	179.0	201.7
40	199.2	174.3	166.8	133.9	120.0	96.0	110.3	142.3	155.5	175.9	177.5	199.8

Table 4.5 Mbuluzi catchment: Mean monthly values of daily maximum temperatures (°C) per subcatchment (SC)

SC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	23.2	23.0	22.5	20.9	19.4	17.2	17.5	19.6	21.6	21.8	21.9	23.0
2	23.5	23.5	22.9	21.4	19.9	17.7	18.0	20.1	22.1	22.3	22.3	23.4
3	24.6	24.6	24.0	22.4	20.8	18.6	18.9	20.9	22.8	23.1	23.2	24.4
4	25.9	26.1	25.3	23.7	22.1	19.9	20.1	21.9	23.7	24.2	24.5	25.7
5	26.1	26.2	25.4	23.7	22.1	19.9	20.2	22.0	23.8	24.3	24.6	25.9
6	26.5	26.6	25.9	24.1	22.5	20.2	20.5	22.3	24.0	24.6	25.0	26.3
7	27.9	27.9	27.0	25.2	23.6	21.4	21.6	23.3	25.0	25.7	26.1	27.5
8	27.8	27.9	27.0	25.2	23.6	21.4	21.6	23.3	25.0	25.7	26.1	27.5
9	28.0	28.0	27.1	25.3	23.7	21.5	21.7	23.4	25.1	25.8	26.1	27.6
10	28.8	28.7	27.9	26.1	24.4	22.2	22.4	24.0	25.8	26.5	26.9	28.4
11	29.2	29.2	28.3	26.4	24.8	22.6	22.8	24.4	26.1	26.8	27.3	28.8
12	28.0	28.1	27.2	25.5	23.8	21.7	21.9	23.5	25.2	25.9	26.2	27.7
13	30.2	30.1	29.2	27.3	25.7	23.5	23.6	25.2	26.9	27.7	28.1	29.7
14	29.8	29.8	29.0	27.2	25.6	23.5	23.6	25.1	26.6	27.4	27.8	29.3
15	30.8	30.7	29.7	28.0	26.3	24.2	24.3	25.8	27.4	28.2	28.6	30.2
16	29.9	29.8	28.9	27.2	25.6	23.5	23.6	25.1	26.6	27.4	27.8	29.3
17	30.9	30.8	29.9	28.1	26.5	24.4	24.5	26.0	27.5	28.2	28.7	30.3
18	30.9	30.8	29.9	28.1	26.6	24.5	24.6	26.1	27.5	28.3	28.8	30.4
19	30.6	30.6	29.7	28.0	26.4	24.4	24.4	25.9	27.3	28.0	28.5	30.1
20	30.9	30.8	29.9	28.1	26.6	24.5	24.5	26.0	27.5	28.3	28.7	30.3
21	29.3	29.2	28.3	26.5	24.8	22.6	22.8	24.4	26.1	26.9	27.4	28.9
22	29.8	29.5	28.7	26.6	25.1	22.9	23.1	24.7	26.5	27.3	27.8	29.3
23	30.2	30.0	29.7	27.3	25.6	23.4	23.6	25.2	26.9	27.7	28.2	29.7
24	30.7	30.5	29.6	27.8	26.0	23.9	24.0	25.6	27.2	28.1	28.6	30.2
25	30.4	30.3	29.4	27.6	25.9	23.8	23.8	25.4	27.1	27.9	28.4	29.9
26	30.6	30.5	29.6	27.8	26.1	24.1	24.1	25.6	27.2	28.0	28.5	30.1
27	30.5	30.4	29.5	27.7	26.0	24.0	24.0	25.5	27.1	27.8	28.3	29.9
28	30.6	30.5	29.6	27.9	26.3	24.2	24.3	25.7	27.2	28.0	28.4	30.0
29	31.0	30.9	30.0	28.2	26.6	24.5	24.6	26.0	27.5	28.3	28.8	30.4
30	30.7	30.6	29.8	28.0	26.4	24.4	24.4	25.8	27.3	28.1	28.5	30.1
31	30.9	30.8	29.9	28.2	26.6	24.6	24.6	26.1	27.4	28.2	28.7	30.3
32	29.3	29.3	28.5	26.9	25.4	23.4	23.5	24.9	26.2	26.9	27.3	28.8
33	30.9	30.8	29.9	28.1	26.6	24.6	24.6	26.1	27.5	28.2	28.7	30.3
34	30.1	30.2	29.3	27.6	26.2	24.1	24.2	25.6	26.9	27.6	28.0	29.6
35	31.0	31.0	30.1	28.3	26.8	24.8	24.8	26.2	27.6	28.3	28.8	30.5
36	29.3	29.3	28.5	26.8	25.3	23.3	23.4	24.7	26.1	26.8	27.1	28.7
37	30.6	30.5	29.7	27.9	26.4	24.3	24.4	25.8	27.2	27.9	28.4	30.0
38	30.8	30.8	29.9	28.2	26.7	24.7	24.7	26.1	27.4	28.1	28.6	30.2
39	30.0	29.9	29.1	27.5	26.0	24.0	24.0	25.3	26.7	27.4	27.8	29.4
40	30.1	30.2	29.3	27.7	26.2	24.2	24.2	25.6	26.9	27.5	27.9	29.5

Table 4.6 Mbuluzi catchment: Mean monthly values of daily minimum temperature ($^{\circ}$C) per subcatchment (SC)

S C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	14.2	13.9	12.9	10.2	6.7	3.7	3.8	6.1	9.0	11.0	12.4	13.6
2	14.5	14.2	13.1	10.3	6.6	3.5	3.6	6.0	9.1	11.1	12.6	13.9
3	15.2	14.9	13.8	11.1	7.4	4.4	4.5	6.8	9.7	11.7	13.3	14.5
4	16.1	15.8	14.7	11.9	8.0	4.9	4.9	7.4	10.4	12.5	14.2	15.4
5	16.2	16.0	14.9	12.2	8.5	5.5	5.5	7.8	10.7	12.7	14.2	15.5
6	16.4	16.1	15.1	12.3	8.6	5.5	5.6	7.8	10.8	12.8	14.4	15.7
7	17.3	17.1	16.1	13.3	9.4	6.3	6.3	8.6	11.6	13.7	15.3	16.6
8	17.3	17.1	16.1	13.2	9.3	6.2	6.2	8.5	11.6	13.7	15.3	16.6
9	17.6	17.3	16.3	13.5	9.7	6.5	6.6	8.9	11.8	13.9	15.5	16.9
10	18.0	17.8	16.8	13.9	9.9	6.7	6.8	9.1	12.2	14.3	15.9	17.3
11	18.4	18.2	17.2	14.3	10.3	7.1	7.1	9.5	12.6	14.7	16.3	17.7
12	17.7	17.5	16.5	13.6	9.7	6.5	6.6	8.9	11.9	14.0	15.7	17.0
13	19.3	19.1	18.1	15.1	11.0	7.8	7.8	10.1	13.3	15.5	17.2	18.6
14	19.3	19.2	18.2	15.4	11.4	8.3	8.2	10.5	13.5	15.5	17.2	18.6
15	19.9	19.7	18.7	15.7	11.4	8.1	8.1	10.5	13.8	16.0	17.7	19.1
16	19.4	19.3	18.4	15.6	11.7	8.6	8.6	10.8	13.6	15.7	17.3	18.7
17	20.1	20.0	17.2	16.0	11.7	8.4	8.4	10.8	14.3	16.2	17.9	19.4
18	20.1	20.0	18.9	16.0	11.8	8.5	8.5	10.9	14.0	16.2	17.9	19.4
19	20.0	19.9	18.9	16.1	11.9	8.7	8.7	11.0	14.0	16.1	17.8	19.3
20	20.2	20.1	19.0	16.1	11.9	8.6	8.6	11.0	14.1	16.3	18.0	19.5
21	18.3	18.1	17.1	14.1	10.1	6.9	6.9	9.3	12.4	14.6	16.2	17.6
22	18.5	18.4	17.4	14.4	10.4	7.2	7.2	9.6	12.7	14.8	16.4	17.8
23	19.1	18.9	17.9	14.9	10.8	7.5	7.5	9.9	13.1	15.3	16.9	18.4
24	19.5	19.3	18.3	15.3	11.1	7.8	7.8	10.2	13.5	15.7	17.3	18.8
25	19.4	19.2	18.2	15.2	11.0	7.7	7.7	10.2	13.4	15.6	17.3	18.7
26	19.8	19.6	18.6	15.6	11.4	8.1	8.1	10.5	13.7	15.9	17.6	19.1
27	19.7	19.5	18.5	15.6	11.4	8.1	8.1	10.5	13.7	15.8	17.5	19.0
28	20.0	19.8	18.8	15.9	11.7	8.4	8.4	10.8	14.0	16.1	17.8	19.3
29	20.2	20.1	19.0	16.1	11.9	8.6	8.6	11.0	14.1	16.3	18.0	19.5
30	20.1	20.0	19.0	16.1	11.9	8.6	8.6	11.0	14.2	16.3	17.9	19.4
31	20.3	20.2	19.2	16.3	12.1	8.8	8.8	11.2	14.3	16.4	18.1	19.6
32	19.3	19.2	18.4	15.8	12.2	9.2	9.2	11.2	13.8	15.5	17.1	18.6
33	20.2	20.2	19.1	16.3	12.2	8.9	8.9	11.2	14.2	16.3	18.0	19.5
34	20.0	19.9	19.1	16.5	12.7	9.7	9.6	11.7	14.3	16.2	17.7	19.2
35	20.5	20.4	19.4	16.7	12.6	9.4	9.4	11.7	14.6	16.6	18.2	19.7
36	19.4	19.3	18.4	15.6	11.8	8.6	8.6	10.9	13.7	15.7	17.2	18.7
37	20.2	20.0	19.1	16.2	12.0	8.7	8.7	11.1	14.2	16.3	18.0	19.4
38	20.5	20.4	19.4	16.5	12.4	9.1	9.0	11.4	14.5	16.6	18.3	19.8
39	20.0	19.9	19.0	16.3	12.5	9.2	9.3	11.5	14.3	16.2	17.8	19.3
40	20.3	20.2	19.3	16.7	12.9	9.8	9.8	11.9	14.6	16.5	18.0	19.8

as well as saturated soil water redistribution fractions were not explicitly presented. In a few cases where they were given, it was only a brief description in qualitative terms. The spatial distribution and description of soil sets in the Mbuluzi catchment have been shown previously, in **Figures 3.4** and **3.5** respectively.

The digital subcatchment boundaries were used to extract the soil textures and total depths from the digitized national soil map. This was done by overlaying the subcatchments' coverage on the soils coverage and applying GIS functions to extract texture class distributions in each subcatchment. The percentages of each texture class in each subcatchment were input in the soils decision support programs included in the *ACRU* utilities. Algorithms that use texture and depth to estimate soils' hydrological parameters (such as soil water contents at saturation, drained upper limit, permanent wilting point and saturated water redistribution fractions) are embedded within the soil's decision support system.

4.4.2.4 Land cover and land use information

Land cover can have a profound influence on hydrological responses through canopy and litter interception, controlling the available time for rainfall water to be infiltrated into the soil, determining the rates of evaporation of soil water and transpiration from plants as well as protecting the soil from erosion. Land cover input information into the ACRU model includes:

a) a monthly interception loss value, which reflects the estimated amount of rainfall intercepted by the plant's canopy during a rainday at a specified growth stage of the plant,
b) a monthly consumptive water use (or "crop") coefficient, which reflects the ratio of water use by a land cover at a specified stage in its growth cycle under conditions of no soil water stress to reference potential evaporation, with the coefficient being converted within the model to daily values by Fourier Analysis, and
c) the fraction of plant roots that are active in extracting soil moisture from the topsoil horizon on a month-by-month basis.

Another variable that indicates how hydrological responses are modified by land cover is the coefficient of initial abstraction. This variable accounts for the seasonal influence of the roughness of the soil surface resulting from the type of vegetation and land use, tillage practices, as well as seasonal rainfall intensity patterns, on stormflow generation.

4.4.2.4.1 Land cover under assumed baseline conditions

One of the major objectives of this study is to assess the hydrological impacts of dominant land use and water demand sectors on streamflow in the Mbuluzi catchment. The adopted approach was to compare, separately, the resultant streamflow after being affected by each sector against a baseline land cover condition of the catchment. For this purpose, Acocks' (1988) Veld Types were used as the representation for baseline land cover (Schulze, 2000). The digital subcatchment boundaries (**Figure 4.3**) were overlaid on the southern African Acock's Veld Types coverage to determine the Veld Types and their percentages in each subcatchment. The spatial distribution of the Veld Types in the Mbuluzi catchment has been presented in **Figure 3.6.** Each Veld Type was assigned monthly interception loss, water use and root fractions values according to methodologies outlined in Schulze (2000).

4.4.2.4.2 Land use under present conditions

To distinguish between baseline land cover conditions and those prevailing at the present time, the term "land use" is applied for present conditions. This term includes the impacts not only of conversions of baseline land cover to a new use, where this has occurred, but also reflects the potential impacts of different management practices and levels (e.g. tillage, conservation and planting dates as well as grazing) within the same land use.

Present land use information was derived from the Southern African LANDSAT TM coverage for 1996 made available by CSIR (1996). The Mbuluzi catchment portion of the coverage has been shown in **Figure 3.7**. Using a classification devised by Thompson (1996), 18 land use classes were identified in the Mbuluzi catchment. Within each subcatchment, these eighteen classes were re-classified into seven broader classes according to their typical hydrological responses. The grouping criteria are shown in **Table 4.1.** These seven classes are correct, areally, within each subcatchment, but are not spatially explicit.

The hydrological properties of each of the seven land use classes were established by identifying and taking the hydrological properties of land cover and land uses making up each class and area-weighting them accordingly. A list and the corresponding hydrological properties is given as a regularly updated digital ASCII file (COMPOVEG.DAT). The values can either be read and written manually into the menu (as in this study), or be area-weighted and automatically written in the menu using a suite of programs in the *ACRU* model utilities.

A number of variables defining the hydrological variables of present land uses used for modelling the Mbuluzi system are presented in **Table 4.7.** These variables include monthly input values of canopy interception, the crop water use coefficient, the fraction of active root system in the topsoil horizon and a coefficient of initial abstraction.

4.4.2.5 Irrigation information

Information on present and proposed irrigation activites in the Mbuluzi catchment was derived from a number of different sources. These included the 1996 LANDSAT TM coverage, tables (**Table 4.8** and **Table 4.9**) compiled by Murdoch, Gooday, Mlangeni and Shirley (2000), the 1997 Water Resources Branch's permit list (**Table 4.10**) and personal interviews. Murdoch *et al.* (2000) summed the areas under irrigation for each Quaternary subcatchment. It was not, therefore possible to assign spatially explicit irrigation areas to the *ACRU* subcatchments using these tables alone. A similar problem, although to a lesser extent, was encountered with water permit lists, because the exact geographic locations of some farms were not given, nor were the farm numbers marked on 1 : 50000 topographic maps. Although congruent and spatially representative, the 1996 LANDSAT TM coverage was found to overestimate the size of large irrigated areas, while many small (less than a few hundred ha) irrigated farms were not classified under irrigated land. A decision was therefore made to use the other data sources to complement the 1996 LANDSAT TM coverage.

Table 4.7 Mbuluzi catchment: Month-by-month *ACRU* model input variables for present land use menus

Land Cover	Variable	Jan	Feb	Mar	Apr	Mar	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Indigenous Forest	CAY	0.85	0.85	0.85	0.85	0.75	0.70	0.70	0.70	0.75	0.85	0.85	0.85
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Bushveld	CAY	0.83	0.83	0.83	0.80	0.65	0.45	0.45	0.45	0.65	0.75	0.80	0.83
	VEGINT	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
	ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
	COIAM	0.26	0.26	0.26	0.26	0.30	0.30	0.30	0.30	0.30	0.28	0.26	0.26
Riparian	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	2.00	2.00	2.00	2.00	1.90	1.85	1.85	1.85	1.90	1.95	2.00	2.00
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COIAM	0.25	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25
Maize (dryland)	CAY	0.80	0.80	0.64	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.70
	VEGINT	1.10	1.10	0.80	0.60	0.50	0.50	0.50	0.50	0.50	0.20	0.60	1.0
	ROOTA	0.79	0.79	0.78	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90
	COIAM	0.25	0.23	0.22	0.20	0.30	0.30	0.30	0.30	0.30	0.35	0.35	0.30
Irrigated Crop (sugarcane)	CAY	0.92	0.92	0.93	0.91	0.88	0.82	0.78	0.74	0.72	0.74	0.81	0.85
	VEGINT	1.80	1.80	1.80	1.70	1.60	1.60	1.50	1.50	1.50	1.50	1.50	1.50
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Grass (good condition)	CAY	0.70	0.70	0.65	0.60	0.50	0.30	0.22	0.20	0.30	0.55	0.70	0.70
	VEGINT	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.20
	ROOTA	0.85	0.85	0.85	0.85	0.90	1.00	1.00	1.00	0.95	0.90	0.85	0.85
	COIAM	0.20	0.20	0.20	0.20	0.25	0.25	0.25	0.25	0.25	0.25	0.20	0.20
Grass (fair condition)	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	VEGINT	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.20
	ROOTA	0.85	0.85	0.85	0.85	0.90	1.00	1.00	1.00	0.95	0.90	0.85	0.85
	COIAM	0.20	0.20	0.20	0.20	0.25	0.25	0.25	0.25	0.25	0.25	0.20	0.20
Grassland (poor condition)	CAY	0.55	0.55	0.55	0.45	0.20	0.20	0.20	0.20	0.23	0.40	0.50	0.55
	VEGINT	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	ROOTA	0.85	0.85	0.85	0.85	0.90	0.100	0.100	0.100	0.95	0.90	0.85	0.85
	COIAM	0.10	0.10	0.10	0.10	0.15	0.15	0.15	0.15	0.15	0.15	0.10	0.10
Urban/built-up land	CAY	0.70	0.70	0.70	0.60	0.40	0.40	0.30	0.30	0.50	0.70	0.70	0.70
	VEGINT	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.20	1.30	1.40	1.40
	ROOTA	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.90	0.90	0.90	0.90
	COIAM	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20

Key:

CAY Crop water use coefficient
VEGINT Amount of rainfall (mm) intercepted by land use during a rainy day
ROOTA Fraction of roots in the A-horizon (topsoil)
COIAM Coefficient of initial abstraction

Table 4.8 Mbuluzi catchment: Actual water abstractions (l/s) in 2000 (Murdoch *et al.*, 2000)

W60	A	B	C	D	E	F	G	H	J	K	Subtotal	To W60F	To W60G	To W60K	Total
Irrigated sugarcane	0	0	0	125	238	1 642	0	0	2 317	3 698	8 020	6 692	0	1 370	16 082
Other irrigation	60	40	52	105	83	15	102	120	23	664	1 264	314	0	0	1 571
Other uses	194	11	24	19	8	13	17	20	36	174	616	163	20	10	709
QC TOTALS	254	51	76	249	329	1 670	119	140	2 376	4 536	9 800	7 169	20	1 380	18 369
Citrus	0	0	0	9	5	0	0	0	0	518	532	0	0	0	532
Vegetables	29	33	44	61	17	15	35	14	23	10	281	148	0	0	429
Pastures	21	0	4	2	57	0	20	41	0	136	281	65	0	0	346
Maize	10	7	4	33	4	0	42	65	0	0	165	78	0	0	243
Bananas	0	0	0	0	0	0	5	0	0	0	5	23	0	0	28
Cities & towns	174	0	0	0	0	0	0	0	0	27	201	0	20	0	221
Villages	8	0	0	10	0	0	0	0	20	39	68	106	0	10	184
Industry	0	0	0	0	0	0	0	0	0	80	80	57	0	0	137
Railway Station	0	0	0	0	0	0	0	0	12	0	12	0	0	0	12
Rural domestic	6	4	12	8	3	5	9	8	5	12	72	0	0	0	72
Livestock	3	4	10	9	4	5	7	9	4	7	62	0	0	0	62
Wildlife	1	1	1	1	1	2	0	2	4	7	20	0	0	0	20
Wattles	2	2	1	0	0	0	1	0	0	0	6	0	0	0	6
Natural forest	0	0	0	0	0	1	0	1	2	2	6	0	0	0	6
Permits 2000	226	47	66	221	331	2 030	110	183	2 376	4 275	9 874	8 436	20	1 340	19 760

Key:

W60A to W60K are Quaternary Catchments (QC) in the Mbuluzi River system.
To W60F and To W60K represent inter-catchment transfers of water from the Komati River Basin via Mhlume canal to users within the Mbuluzi River system.
To W60G represents inter-catchment transfers from the Little Usuthu River
The row labelled Permits refers to Water Apportionment Board awards, excluding lapsed and discontinued allocations

Table 4.9 Mbuluzi catchment: Areas under different land uses and human and animal populations per Quaternary Catchment in 2000 (Murdoch *et al.*, 2000)

W60	A	B	C	D	E	F	G	H	J	K	Total
Gross ha	17 200	14 300	23 400	18 700	13 500	42 000	22 000	36 500	44 600	66 400	298 600
RSA ha	0	0	0	0	0	1 000	0	0	0	3 300	4 300
Sugarcane ha	0	0	0	200	300	13 200	0	0	5 200	8 100	27 000
Other irrigation ha	100	100	100	200	100	300	100	100	100	900	2 100
Built-up ha	2 000	0	0	100	100	1 100	1 100	0	600	1 900	6 900
Wildlife ha	400	0	0	0	0	0	0	1 200	12 400	26 700	40 700
Wattle ha	2000	15 00	900	0	0	0	300	0	0	0	4 700
Woodland ha	300	400	3 200	10 200	4 800	25 000	11 000	24 800	26 900	43 700	150 300
Urban population 97	14 600	0	0	300	300	5 100	9 600	0	3 300	11 600	44 800
Rural population 97	8 300	5 900	17 500	11 000	4 600	7 600	13 000	12 300	7 200	18 000	105 600
Total population 97	22 900	5 900	17 500	11 300	4 900	12 700	22 600	12 300	10 500	29 600	150 400
Cattle population 94	4 100	6 100	14 800	14 000	6 300	8 100	10 500	13 700	5 500	10 500	93 600
Goat population 94	500	700	1 900	1 800	1 100	400	700	1 100	1 800	2 000	12 000
MAU 94	4 600	6 800	16 700	15 800	7 400	8 500	11 200	14 800	7 300	12 500	105 600
MAP (mm)	1 260	1 230	1 000	850	760	700	900	750	700	800	---------
MAR (mm)	410	430	400	210	80	70	190	90	80	80	--------
Runoff l/s	2 250	2 000	3 070	1 240	320	950	1 320	1 050	1 100	1 600	---------
Boreholes/ Wells number	40	7	17	10	16	30	75	54	32	33	314
Boreholes/Wells blown	58	8	30	18	19	65	123	88	70	44	523

Source: Murdoch *et al.* (2000)

Key and Sources:

Columns W60A to W60K refer to Quaternary Catchments
Gross ha and Republic of South Africa (RSA) ha were measured from 1 : 50 000 maps
Sugarcane and other irrigation ha from fieldwork and local knowledge
Built-up, wildlife, wattle and woodland (i.e. natural woodland, forest, bushveld and savannah) ha from Dell (2000) "Swaziland Forest Policy" Ministry of Agriculture and Cooperatives (MOAC), Mbabane
Built-up and rural populations 1997 from Census Enumeration Areas raw data: To obtain 2000 add 20 % to built-up and 6 % to rural.
Cattle and goats 1994 from last full livestock inventory by MOAC: To obtain 2000 numbers add 15 %:
MAU = mature animal units.
Rainfall and runoff data from Knight Piesold (1997) " Government of Swaziland Water Sector Situation Report", Mbabane.

Table 4.10 Mbuluzi catchment: Water allocation permits (after Water Resources Branch, 1997)

Name	Farm Number	Size (ha)	Abstr. Rate (l/s)	Notes	Latitude	Longitude
Khoza, A. M.	296/188		0.21	Domestic use	26.27	31.11
Malaza, A		1.4	1.3			
Bloxham, E. R. H.	8/392	1.62	1.42	Black Mbuluzi	26.20	31.52
De Beers Holdings			5.26	Industry		
Khoza, A. M.	296/188	0.202	0.16	Only when flow at Mbabane exceeds 5 m^3/s		
Dvokolwako Farm School		3.04	2.7		26.17	31.58
Dvokolwako Farmers Association		20	17		26.18	31.56
Dlamini, E.		4.05	3.68	Sidokodo stream - tributary of White Mbuluzi	26.3	31.57
Tsabedze, G	SNL	0.41	0.35			
ANCO Pty Ltd (Dvokol. Diamond Mine)			28.32	Mining Purposes		
Herbst H S	195	24.28	14.16	White Mbuluzi	26.39	31.5
Ions M H (Glasse Trust)	239	20.24	15.86	Black Mbuluzi	26.19	31.08
Burrel, J. (Timbuti Farm)	1/210		14.16	Kopenkop stream - trout production		
Jacobz, J. H. J.	11/392;REM/392	332.26	290.58	Black Mbuluzi	26.27	31.45
Dlamini, K. H.	563	4.05	3.54	Nsakane River - tributary of Black Mbuluzi		
Kerg, N. G.	10/392	14.16	12.46	Black Mbuluzi	26.20	31.54
Shongwe, K.	SNL	0.81	0.71	Black Mbuluzi		
Magagula, M.		6	5.2	From zone 22 reserve		
Mafuteni Pty Ltd	70;CL191;153;154;155;688;297	45.33	39.65	White Mbuluzi	26.39	31.52
Mbuluzi Estates		647	566.4	Mhlume water - return flows	26.14	31.69
Meyer, I. J.	1087;969	2.83	2.21	Black Mbuluzi	26.18	31.09
Magagula, M.		3	2.6			
Ministry of Agriculture	REM/10;H/101		0.07	Damming		
Mandy, F. E.	642	40.47	35.4	White Mbuluzi	26.32	31.60
Mashigo Neson & Son		0.8	0.7			
National Industrial Development of SWD			2.0 MCM	Nkalashane - tributary of Black Mbuluzi		
Dlamini P. M. (Langishaw Farm)	621	12.14	11.34	White Mbuluzi		
Panata Ranch LTD	403;884;885	80.94	70.8	Mashicane stream - towards Mozambique	26.32	31.63
Malambe, P.		6	5.2	Kopenkop stream - tributary of Black Mbuluzi		
Masilela, P. L.		8	5	Magwanyana stream - domestic use		
Rozwadowski, V. J.	964	18.21	14.16	Domestic use	26.2	31.06
Langwenya, S.	REM/153		0.32	Only when flow at GS3 > 92 m^3/s		
Pefile, S.M.	SNL		0.04			
Sherwood Farms	669;677		21.24		26.18	31.63
Sherwood Ranches	669;673	80.94	42.48	Black Mbuluzi	26.18	31.63
Nxumalo, S.		5	4.4			
Slatem, S. J.	284/188	2.43	1.25	Black Mbuluzi		
Steven & Makhosazana Fletcher			0.04	Tributary of Black Mbuluzi- domestic use		
Swazi Nation	1044	1.62	1.22	Black Mbuluzi		
Swazi Nation	704	0.8094	0.85	White Mbuluzi	26.25	31.68
Swazi Nation	1026;1044	118.17	90.62	Black Mbuluzi		
Swazi Nation	1028;CL154;1029;1075	40.06	74.48	Black Mbuluzi	26.28	31.61

Name	Farm Number	Size (ha)	Abstr. Rate (l/s)	Notes	Latitude	Longitude
Swazi Nation	1027;361;1034	34.8	90.62	Black Mbuluzi	26.29	31.40
Swazi Nation	921;801	5.67	8.78	White Mbuluzi	26.36	31.41
Swaziland Iron Ore Development Company	REM/1112		33.98	Black Mbuluzi		
Swaziland Railway			11.93	White Mbuluzi - industry and domestic		
Mazibuko, T.		5	4.4	White Mbuluzi		
Tabankulu Estates	1/95	743.84	650.65	Black Mbuluzi	26.15	31.94
Terence Gray		2	1.6			
Thomas Mkhonta	SNL	2.52	2.2			
Tryphinah Mavuso		0.5	0.4	Matete stream - tributary of Black Mbuluzi	26.15	31.93
Umbeluzi Estates	175;?REM176;1/77	853.11	746.23	Black Mbuluzi		
V Mkhatshwa		1	0.87	White Mbuluzi	26.38	31.56
Wallis G	A/165;B/165;C/165;D/165;5/165	40.47	20.67	White Mbuluzi		
Water & Sewerage Board			2.75 MCM		26.23	31.09
White T.W	7/392	14.16	12.46	Black Mbuluzi	26.22	31.51
Inter-catchment transfers from Komati Basin			3488		26.00	31.80

Source: After Water Resources Branch (1997)

Notes:
Abstraction rates are in litre/second (l/s) unless stated otherwise
Farm size is in hectares (ha)
SWD Swaziland

First, it was assumed that the overestimation was a result of not isolating some unirrigated areas such as riparian areas, land between farms, roads and some built up areas. Therefore, where it was known that in any subcatchment with irrigation, a significant area was covered by built-up areas such as communities and villages, yet did not appear in the land classification, then the total area of irrigated land was reduced by 20%. This percentage was established from fieldwork. If no built-up areas were found to exist, only 10% was subtracted to account for fallow lands, poor soils, uncultivated or riparian areas, again established from fieldwork.

Secondly, to account for the smaller farms that were not identified, such farms were assumed to have been lumped with temporary, semi-commercial agriculture and subsistence agriculture. For any Quaternary subcatchment that Murdoch *et al.* (2000) indicated has some irrigation, yet such irrigation was not identified in the classification of the LANDSAT TM image, the corresponding area was partitioned to the subset *ACRU* subcatchments by weighting it according to the areas of land under temporary, semi-commercial or subsistence agriculture in each *ACRU* subcatchment.

Through personal communications with staff members of the Royal Swaziland Sugar Company (RSSC), it was ascertained that expansion of the size of the land under irrigation is underway in Simunye. This will result in an increase of about 2000 ha. Owing to water resources and land limitations, further expansions are not expected in the other major estates.

For each subcatchment with irrigated land, model input parameters such as area under of irrigation, soil properties, crop characteristics, mode of irrigation scheduling, length of cycle and amount of water applied per irrigation cycle, conveyance as well as farm dam and application losses and sources the source of irrigation water were determined and input. In **Table 4.11**, the values of some of these parameters are shown. These were determined from fieldwork.

Table 4.11 Mbuluzi catchment: Irrigation input information for the *ACRU* model

Estate Name	Farm Size (ha)	Irrigation Type	Sources of Water	Application amount (mm)	Cycle Length (days)
RSSC	10 500	Sprinkler	Dam	13	4
Mhlume Sugar Co.	9 540	Furrow	Dam	to DUL	RAM </= 10mm
Tabankulu Estates	3 712	Sprinkler	Stream	20	5
Other	725	Furrow	Stream	to DUL	RAM </= 10mm

Key:

RSSC Royal Swaziland Sugar Company (Simunye)
DUL Drained upper limit
RAM Readily available moisture
Other Individual farmers and small- to medium-scale irrigation schemes

4.4.2.6 Information on dams

There are two major dams in the Mbuluzi catchment. These are the Mnjoli Dam, which has a storage capacity of 130.68×10^6 m^3 and a surface area of about 909 ha at full capacity, and the Hawana Dam which can store 3×10^6 m^3 of water and covers 46 ha when full. The Hawana Dam is located in the headwater reaches of the catchment (**Figure 4.6**) and provides a part of the water supplies of Mbabane (the capital of Swaziland) and all the water demands of the Ngwenya Village. The Mnjoli Dam, on the other hand, is located in the mid-section of the catchment (**Figure 4.6**). This dam was constructed solely to provide water for irrigating sugarcane fields at Simunye for the Royal Swaziland Sugar Company (RSSC) in the lower section of the catchment. Both these dams are on-channel, but are meant to store only excess flows or flood water. Only one year's (1993) values of daily "legal" flow releases from the Mnjoli Dam were obtained from the WRB and none were provided for the Hawana Dam. Inasmuch as the one year long record was not long enough, for both dams, the daily legal flow releases were set to be equivalent to the 20th percentile of flow of the driest month, based on the single year's values. A daily average value of abstractions of water for irrigation, domestic and industrial purposes from the Mnjoli Dam was provided by the RSSC and abstractions from the Hawana Dam were provided by the WRB.

4.4.2.7 Abstractions of water from stream channels other than for irrigation

Water is abstracted from both the main stem and tributaries of the Mbuluzi river for purposes such as domestic use in rural areas, domestic and industrial use in municipalities as well as livestock watering. An average daily amount of water used in each of the sectors in each subcatchment was estimated. These averages of each sector were then summed up to provide a single subcatchment value. In the following subsections, the procedure of estimating the average daily water abstraction for each month is described.

4.4.2.7.1 Estimation of rural water demands

The first step towards estimating water requirements for rural communities was to estimate the size of the population served by the river. Owing to unavailability of primary (raw) national population data from the 1997 census, secondary data had to be used. The source of these data was a table compiled by Murdoch *et al.* (2000). This data set shows the rural population sizes in each Quaternary Subcatchment. The population of each Quaternary Subcatchment was partitioned to each of the subset subcatchments. This was done by firstly identifying those subcatchments that had subsistence agriculture, degraded grasslands, degraded bushvelds, degraded forests and woodlands. It was assumed that these land covers indicate anthropogenic activity and hence occupation. The population was then partitioned by weighting it according to the total areas of the above land use classes. The population of each subcatchment was multiplied by the per capita water use per day (40 litres), to obtain the daily rural water demand.

The future rural water demands were estimated after the present subcatchment populations were mathematically projected to 2050. A continuous growth curve or equation was used for this study. This curve is described as (Shryock *et al.*, 1976) as

$$P_t = P_0 e^{rt}$$

where P_t is population after t number of years, P_0 is the initial population, r is the population growth rate over projection period (t), and e is base of the natural logarithm system. A major limitation of this equation is that it does not account for migrations. Hence, it may overestimate rural populations, while the general trend is migration to urban areas. However, this was not viewed as a disadvantage in this study as the overestimated populations would result in conservative future demands. Population growth rates for both rural and urban areas in Swaziland are shown **Table 4.12,** while in **Table 4.13** the present and projected populations per subcatchment are given.

Table 4.12 Annual percentage population growth rates in Swaziland (Meigh *et al.*, 1998)

Urban			Rural		
1990-2000	**2000-2025**	**2025-2050**	**1990-2000**	**2000-2025**	**2025-2050**
5.83	3.88	1.94	1.43	0.53	0.27

4.4.2.7.2 Estimation of municipal water demands

Information about these water requirements was obtained from water demand tables and water permit lists compiled, respectively, by Murdoch *et al.* (2000) and the Ministry of Natural Resources and Energy. From both these sources, a distinction cannot be made whether the water is for domestic and industrial purposes or any other services, since the water supplied is given as a lumped figure. For the purpose of projecting a future demand, the present water demand was linked to population. The Government of Swaziland's (1981) Water Resources Related Framework Plan gives a figure of 440 litres per capita per day of water supplied to the human population of a municipality. Dividing the known daily supply of water by 440 litres gave the estimate of the population served. Using the continuous compounding curve, the resultant population values for each municipality were also projected to the year 2050 (**Table 4.13**) to estimate future water demand. Estimates of urban population growth rates between 1990 and 2050 are shown in **Table 4.12.**

4.4.2.7.3 Estimation of livestock water demands

An approach similar to the one use in estimating rural water demands was used to estimate livestock water demands. Murdoch *et al.* (2000) compiled a table (**Table 4.9**) with the estimates of the numbers of livestock in each Quaternary subcatchment. For each Quaternary subcatchment, the cattle population was partitioned to each subset *ACRU* subcatchment by weighting it according to total area of grasslands (pastures), degraded grasslands, degraded bushveld, and degraded forests as well as woodlands in each Quaternary subcatchment. It was assumed that the presence of each of these land classes indicates livestock activity in the form of grazing and browsing. Goat and sheep populations were each assumed to be a third of the cattle population. It is estimated that cattle drink between 25 and 40 litres a day per livestock unit while a goat or a sheep drinks 20 litres per day (Maree and Casey, 1993 cited Murdoch *et al.*, 2000). These values were then multiplied by the livestock populations (**Table 4.13**) to obtain the daily water demand for livestock in each subcatchment.

For this study, it was assumed that livestock populations will not change significantly in the future. Meigh *et al.* (1998) observe a tendency for livestock populations to increase along with rural human populations. With the possible decrease of rural human population growth rates from 1.43 to 0.27 % between 2000 and 2050 in Swaziland (Meigh *et al.*, 1998), a similar trend was envisaged for livestock populations. An increase in livestock numbers may be limited by availability of grazing land (Meigh *et al.*, 1998), which will most likely be reduced following urbanisation and conversion of pastures towards the production of other crops.

Table 4.13 Mbuluzi Catchment: Human and livestock populations per subcatchment (SC)

SC	Present (1999)					Future (2050)	
	Human		Livestock			Human	
	Rural	Urban	Cattle	Goats	Sheep	Rural	Urban
1	2 957	0	1 584	1 217	57	3 663	0
2	555	0	51	39	2	687	0
3	5 897	38 091	6 400	4 916	231	7 306	194 392
4	263	0	272	209	10	326	0
5	4 007	0	3 398	2 610	123	4 965	0
6	2 446	0	2 140	1 644	77	3 031	0
7	6 650	0	2 620	2 013	95	8 240	0
8	2 105	0	2 673	2 053	97	2 608	0
9	2	0	3 108	2 388	112	2	0
10	3 358	0	2 745	2 109	99	4 160	0
11	5 658	0	1 322	1 016	48	7 010	0
12	1 583	0	4 146	3 185	150	1 961	0
13	12 903	0	15 070	11 576	545	15 987	0
14	172	0	295	226	11	214	0
15	4 667	6 591	3 859	2 964	140	5 782	33 636
16	145	0	572	439	21	180	0
17	6 403	0	2 754	2 115	100	7 933	0
18	2	0	1 127	866	41	3	0
19	2	64 795	1 121	861	41	2	330 675
20	1513	0	1 349	1 036	49	1 874	0
21	6 454	0	5 577	4 284	202	7 996	0
22	5 236	0	4 899	3 763	177	6 487	0
23	2 827	0	1 985	1 525	72	3 503	0
24	406	10 136	5 519	4 239	200	503	51 730
25	6 138	0	3 241	2 489	117	7 605	0
26	6 359	0	2 317	1 780	84	7 879	0
27	7 177	0	2 610	2 004	94	8 892	0
28	260	0	1 886	1 449	68	322	0
29	584	0	540	415	20	724	0
30	44	0	1 888	1 450	68	54	0
31	35	80 636	401	308	15	43	411 517
32	6 060	0	6 839	5 253	247	7 508	0
33	3 102	0	601	462	22	3 843	0
34	1 944	0	2 164	1 662	78	2 409	0
35	132	0	225	173	8	164	0
36	8 080	0	4 518	3 471	163	10 011	0
37	0	0	138	106	5	0	0
38	0	0	66	51	2	0	0
39	0	0	245	188	9	0	0
40	2	0	1 417	1 089	51	2	0
Sum	116 128	200 249	103 682	79 643	3 751	143 879	1 021 960

4.4.2.8 Inter-catchment water transfers

According to the Water Permit list, 108 x 10^6 m^3 of water are imported per annum from the neighbouring Komati catchment into the Mbuluzi catchment for irrigation, domestic and industrial purposes in Mhlume. Return flows from Mhlume are used for irrigation in Tabankulu. Murdoch *et al.* (2000) also identify other smaller transfers that take place between from the Usuthu to Mbuluzi (**Table 4.8**). At less than 10 litres per second, they were considered to be too small to have a significant impacts on the streamflow in Mbuluzi. Hence they were not incorporated for purposes of modelling.

4.5 Verification Studies

Verification studies were undertaken to assess the performance of *ACRU* model streamflow output in the Mbuluzi catchment. For the verification studies, it was assumed that the present land cover was static and representative of the entire simulation period. The length of the verification period was therefore limited by continuity of the observed data. Monthly totals of simulated daily streamflow values were matched against observed data from the GS4, GS3 and GS32 streamflow gauging stations (**Figure 4.6**). A summary of the results of the verification studies are presented in **Figures 4.8** to **4.10**, each showing the following information:

a) time series plots of simulated and observed monthly totals of daily streamflows,

b) comparisons of accumulated monthly totals of daily streamflows for simulated and observed values,

c) scatter plots of simulated vs observed monthly totals of streamflows and

d) summaries of statistical comparisons of simulated and observed monthly totals of streamflows.

In the following **Sections 4.5.1** to **4.5.3**, the verification results of the three observation locations are presented individually, starting with the most upstream location and then progressing to the downstream end of the catchment. An evaluation of the verifications and problems associated with them is presented in **Section 4.5.4.** It should be noted at the outset, however, that these were "blind" verifications with no model calibration to force good fits.

4.5.1 Verification of modelled streamflows at GS4

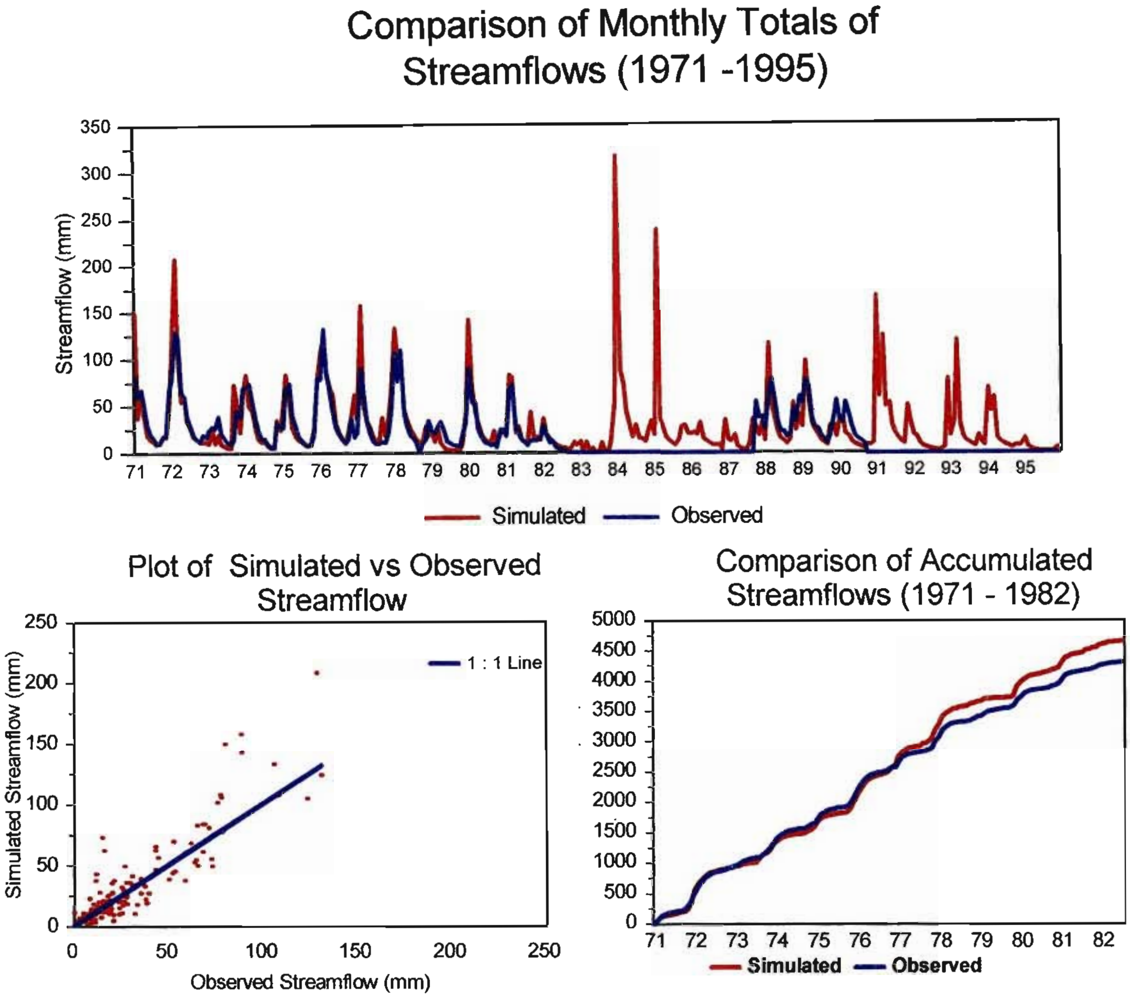
The gauging weir at GS4 commands a 173.7 km^2 area at the upstream end of the Mbuluzi catchment (**Figure 4.6**). Other than the Hawana Dam, this part of the catchment is least impacted by humans. From this station, flow records are available from 1960 to 1984 when the weir was washed away by the Cyclone Domonia floods.

The verification results indicate that the intra- and inter-annual high and low flow trends are well matched (**Figure 4.8**). The coefficient of determination (r^2) is 77%. The sum of simulated monthly streamflows differs from that of observed values by only 9.2 %. From the time series and scatter plots (**Figure 4.8**), it can be seen that while the total streamflows and baseflows are well reproduced, the peak flows or floods are slightly exaggerated by the model. The standard deviation of the simulated monthly totals is 27% higher than the observed values, indicating a more attenuated natural hydrograph than that modelled.

4.5.2 Verification of modelled streamflow at GS3

The GS3 weir has a contributing area of 713 km^2 (**Figure 4.6**). It is less than 5 km upstream of the Mnjoli Dam. The land upstream of the weir is predominantly occupied by rural communities. The most common land uses are subsistence agriculture, communal grazing on poorly managed pastures. Verification studies at GS3 were undertaken for the period beginning in 1971 to 1983.

Verification of Output from *ACRU* Model at GS4



Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows

Catchment Area (km^2)	=	173.0
Mean Annual Precipitation (mm)	=	1219.0
Mean Annual Runoff (mm)	=	301.9
Runoff Coefficient (MAR / MAP, %)	=	24.8
Number of months of observations	=	140
Sum of observed values (mm)	=	44433.2
Sum of simulated values (mm)	=	48539.0
% difference between the sums	=	9.2
Correlation coefficient (r)	=	0.88
Coefficient of determination (r^2)	=	0.77
Standard deviation of observed values (mm)	=	28.2
Standard deviation of simulated values (mm)	=	35.8
% difference between standard deviations	=	27.1
Kurtosis of observed values	=	2.0
Kurtosis of simulated values	=	5.1
Skewness coefficient of observed values	=	1.6
Skewness coefficient of simulated values	=	2.1
1 mm streamflow	=	$173 \times 10^3 m^3$

Figure 4.8 Verification study of modelled streamflows for GS4

This is the longest spell of continuous recording available for the weir. In **Figure 4.9**, it can be seen that the model mimics the seasonal and annual trends of streamflow relatively well. The correlation coefficient between the observed and simulated values of streamflow is 0.85 and hence the coefficient of determination is 71%. However, the model appears to consistently under-simulate baseflows (cf. **Section 4.5.4**). The sum of simulated monthly totals of streamflows is 14.2 % less than the sum of the observed values. The difference between the standard deviations is 20.3 %.

4.5.3 Verification of modelled streamflows at GS32

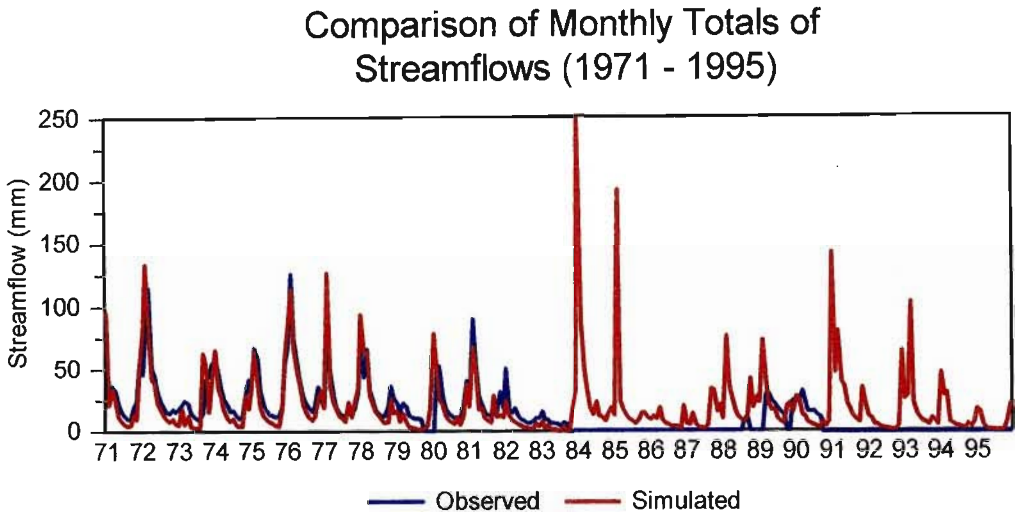
The GS32 station is located strategically as the last gauging weir before the Mbuluzi river crosses the international boundary into Mozambique (**Figure 4.6**). Its contributing area of 2597 km^2 constitutes more than 87 % of the total area of the Mbuluzi catchment. Streamflow measured at this point is heavily impacted by the expansive irrigated agriculture practised upstream.

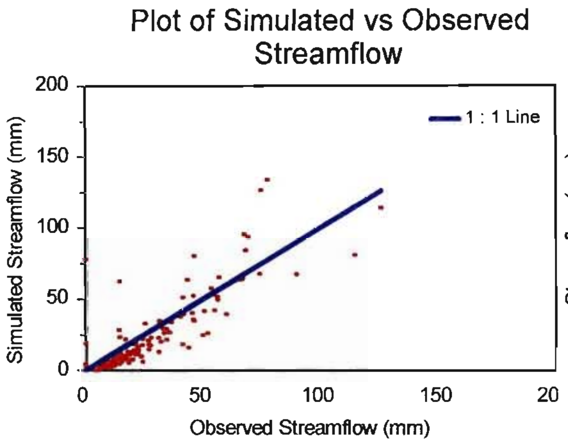
A summary of the results of the verification studies at Mlawula is presented in **Figure 4.10.** The analysis is for a total of 76 months from 1979 to 1984. Although the trends were well modelled ($r = 0.89$ and $r^2 = 0.80$), there are marked deviations on some statistics (cf. **Section 4.5.4**). The difference between the sums of the monthly totals of streamflow is 25 %, while the standard deviations of the simulated streamflow is about twice that of observed streamflow.

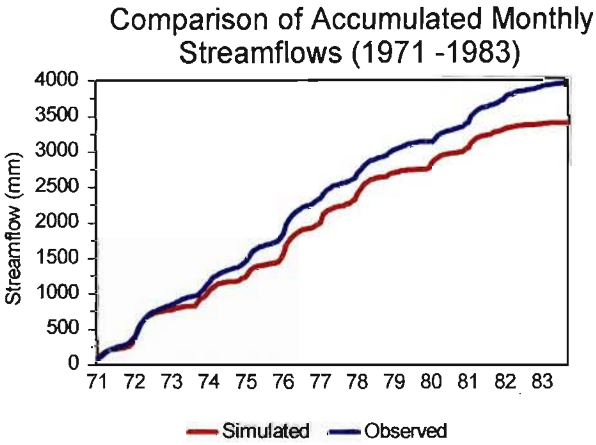
4.5.4 Comments on the verification studies

Inasmuch as a near perfect match between the observed and simulated streamflows is desirable, the discrepancies noted above were not unexpected. Kienzle *et al.* (1997), working in the Mgeni catchment in South Africa, discuss problems associated with simulation exercises that may be possible causes of discrepancies during comparisons of simulated and observed time series of streamflow. The same discussion points are applicable to the Mbuluzi catchment. A list of the problems includes:

Verification of the Output from the *ACRU* Model at GS3





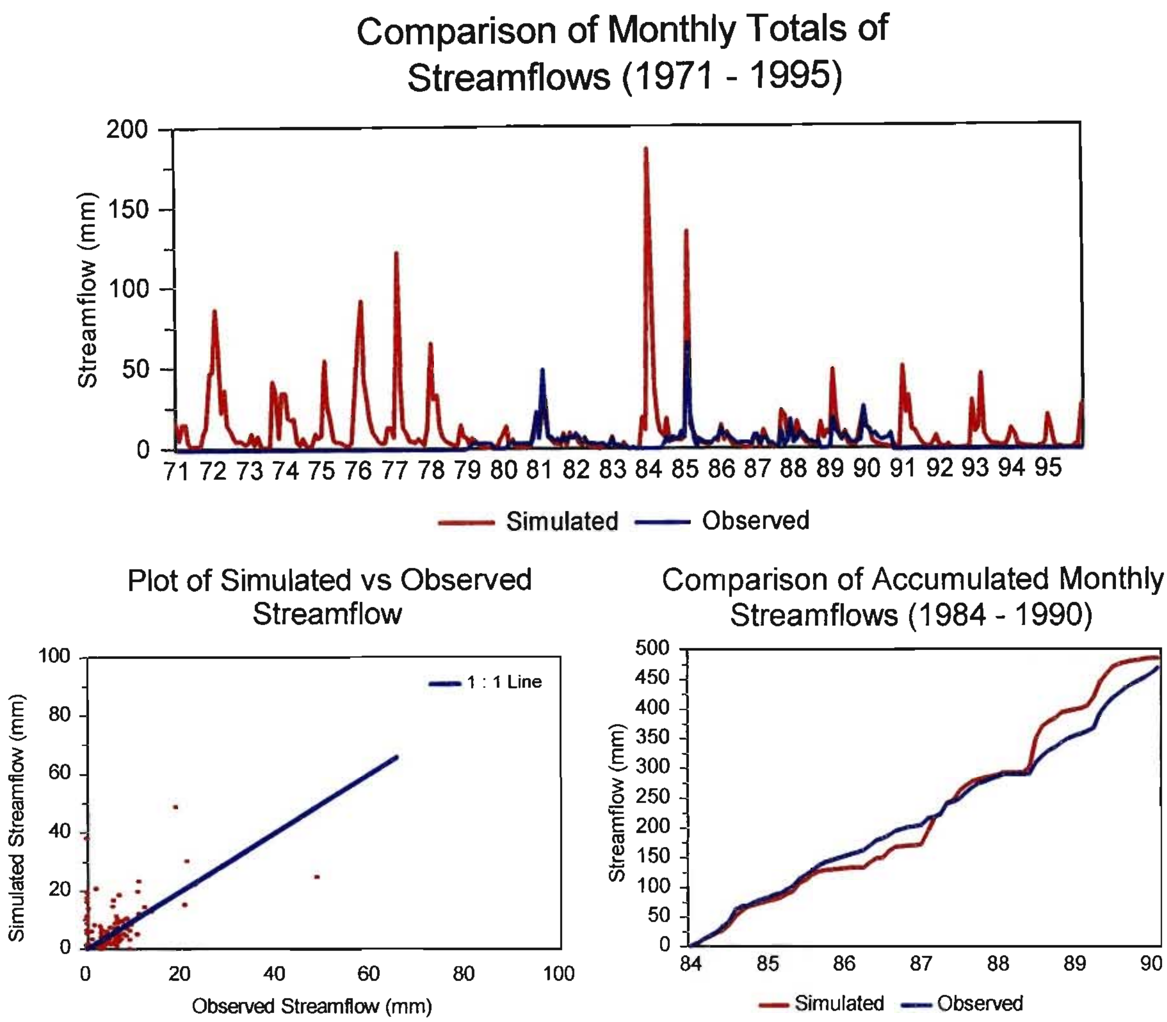


Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows

Catchment Area (km^2)	=	713.0
Mean Annual Precipitation (mm)	=	895.4
Mean Annual Runoff (mm)	=	222.5
Runoff Coefficient (MAR / MAP, %)	=	24.8
Number of monthly observations	=	153
Sum of observed values	=	3938.7
Sum of simulated values	=	3379.9
% difference between the sums	=	-14.2
Correlation coefficient (r)	=	0. 85
Coefficient of determination (r^2)	=	0.71
Standard deviation of observed values (mm)	=	21.1
Standard deviation of simulated values (mm)	=	25.4
% difference between standard deviations	=	20.3
Kurtosis of observed values	=	4.6
Kurtosis of simulated values	=	4.7
Skewness coefficient of observed values	=	1.9
Skewness coefficient of simulated values	=	2.1
1 mm streamflow	=	713 x 10^3 m^3

Figure 4.9 Verification study of modelled streamflows for GS3

Verification of the Output from the *ACRU* Model at GS32



Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows		
Catchment Area (km^2)	=	2597.0
Mean Annual Precipitation (mm)	=	747.6
Mean Annual Runoff (mm)	=	111.4
Runoff Coefficient (MAR / MAP, %)	=	14.9
Number of monthly observations	=	76
Sum of observed values	=	542.2
Sum of simulated values	=	677.7
% difference between the sums	=	25.0
Correlation coefficient (r)	=	0. 89
Coefficient of determination (r^2)	=	0.80
Standard deviation of observed values (mm)	=	8.1
Standard deviation of simulated values (mm)	=	16.4
% difference between standard deviations	=	102.1
Kurtosis of observed values	=	36.0
Kurtoses of simulated values	=	46.5
Skewness coefficient of observed values	=	5.3
Skewness coefficient of simulated values	=	6.3
1mm streamflow	=	2.597 x 10^6 m ^{3}

Figure 4.10 Verification study of modelled streamflows for GS32

a) the inevitable simplification of representing each subcatchment's daily rainfall by data from a single rainfall station,

b) averaging the heterogeneous soil properties to obtain representative values for an entire subcatchment,

c) systematic and random errors associated with the monitoring of both rainfall and streamflow,

d) the assumption that the land cover did not change significantly during the period of simulation, and

e) assumptions associated with river/dam abstractions and return flows.

The last two problems were of particular concern in the Mbuluzi catchment. At all the locations, the verification studies were performed for periods ending at the latest in 1984, before the weirs were either washed away by floods (GS4 and GS32) or buried under deposited debris and sediments (GS3) following Cyclone Domonia, while the a 1996 land cover was used as model input.

The lower section of the catchment has several large irrigation projects (**Table 4.11**) with different and complex scheduling systems and management. Besides the situation being difficult to model, critical input information such as return flows from irrigated fields was not available.
In the light of these problems, the results of the verification studies were considered relatively good and acceptable.

4.5.5 Conclusions

This Chapter commenced with a review of the *ACRU* model. The model, its widespread application especially in Southern Africa (but also in Chile and Germany as reviewed by Schulze in 1995), input information requirements and suitability for simulating the hydrological responses of the Mbuluzi catchment were discussed to some detail. This was followed by an in-depth description and presentation of the configuration of Mbuluzi system as well as the solutions to problems encountered during the collection and preparation of input information. Despite some apparent problems associated with hydrological simulation modelling, results of "blind" verification studies of the model output against observed streamflows showed that the *ACRU* system provided acceptable simulations of present hydrological responses in the Mbuluzi catchment. It was therefore concluded that the *ACRU* model can be used to simulate the hydrological dynamics and anticipated hydrological responses of possible land use changes in the Mbuluzi catchment with confidence, particularly in relative terms. In the chapters which follow, the model is used to undertake impact studies in the catchment. Chapters 5 and 6, respectively, present the results of investigations of the impacts of different present and anticipated future land and water use scenarios on runoff and sediment yields.

5. MODELLING IMPACTS OF DIFFERENT LAND AND WATER USE SECTORS ON STREAMFLOWS

5.1 Runoff Producing Areas within the Mbuluzi Catchment

Following successful configuration and verification studies of output simulated for the Mbuluzi catchment and bearing in mind the modelling complexities discussed above, the *ACRU* model was used to generate daily streamflows for the 40 subcatchments for the period beginning in 1950 to 1995. From the simulated daily streamflows, mean annual runoff (MAR) values were calculated for each subcatchment. The spatial distribution of simulated MAR over the study area under present land use conditions is presented in **Figure 5.1**.

The average MAR for the Mbuluzi catchment is simulated to be 113 mm. The MAR values for the individual subcatchments vary widely from 78 mm in Subcatchment 29 in the lower middle section up to 545 mm in Subcatchment 3, at the upper end of the catchment. The inter-subcatchment variation of MAR generally corresponds with that of rainfall. Subcatchment 3, which produces the highest runoff also receives the highest MAP (1360 mm) and Subcatchment 29, on the other hand, is among those that receive the lowest MAP at less than 800mm. There are several exceptions to this observation, however.

Subcatchments 39 and 40 receive the least amount of rainfall at 724 and 713 mm MAP respectively, yet they are not the lowest runoff producers. The cause of this hypothesized to be the nature of the ground cover. These catchments have relatively high fractions of impervious areas in the form of rock outcrops (**Figure 3.5**) and hence have high runoff coefficients.

Large percentages of Subcatchments 19, 20, 30, 31, 33, 35 and 38 are under intensive agricultural usage for sugarcane production. It would be expected that these subcatchments have the lowest water yields owing the high water demand of sugarcane as well as the fact that they are in the drier parts of the catchment. However, their runoff yield is not as low as expected, being up to 200 mm a year. The proposed causes for this could the nature of the soils, which are mostly clayey and the fact that irrigation of sugarcane takes place.

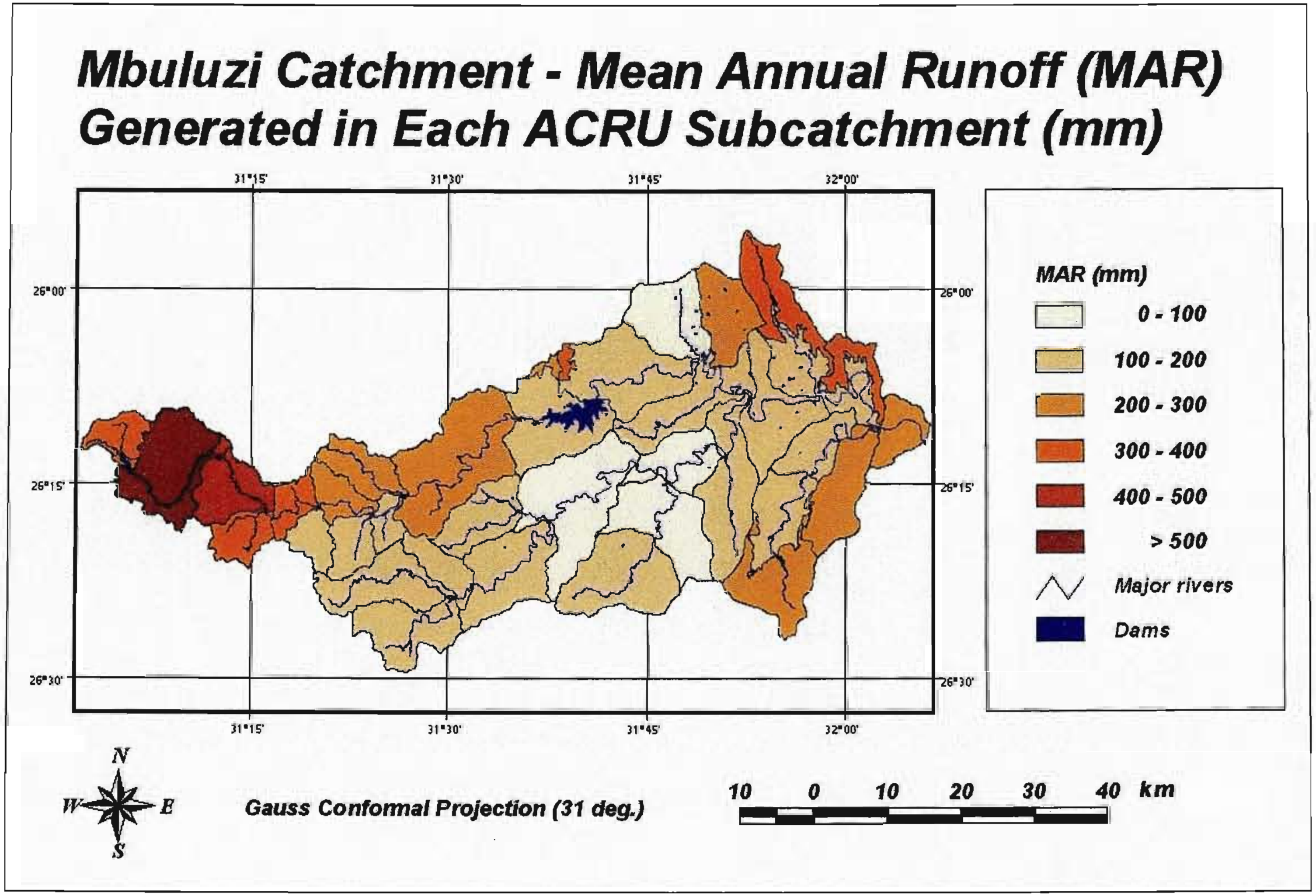


Figure 5.1 Spatial distribution of mean annual runoff produced within the Mbuluzi catchment under present land use conditions

The irrigation frequently leads to high antecedent moisture conditions before rainfall events, thus producing relatively high stormflows as well as deep percolation while clays in general have high runoff generation potential.

Besides catchment MAP, runoff generation in Mbuluzi appears to also be influenced by the dominant land cover. Therefore, Subcatchment 6, which has several different land cover and uses, was selected for the comparative study of total runoff (i.e. sum of baseflows and stormflows), stormflows and baseflows generated under each of the major land covers as shown in **Figure 5.2**, **5.3** and **5.4** respectively, when the rainfall and other physical catchment characteristics remain the same.

The highest runoff was simulated on land under subsistence agriculture, followed by the grassland and bushland, both of which are used as communal grazing land. The least runoff was simulated from the forested land. Most of the runoff generated in the cultivated and grazed lands consists of stormflow, especially during the wet summer season between October and March.

However, **Figure 5.5** indicates that relative to the runoff produced from each land cover, the percentages of stormflows from cultivated fields and forest are lower than those from the bushland and grassland, owing to their higher infiltration rates. The runoff starts decreasing under all the land covers from April until it reaches lowest values in August and September. The reduction rates are slowest under the forested land. In fact, the total runoff of forest is more than that of grassland and bushland from April to August. The reason for this is that higher baseflows occur over this period (cf. **Figure 5.4**) in the forested land, derived from the higher infiltration which led to higher groundwater recharge in the rainy season starting in October and ending in March.

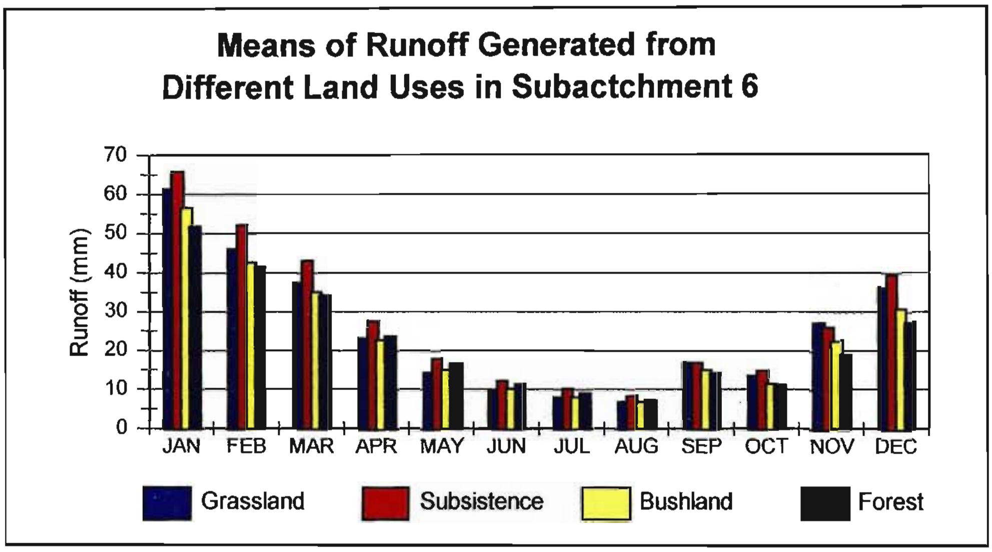


Figure 5.2 Comparison of simulated mean monthly runoff from different land uses in Subcatchment 6

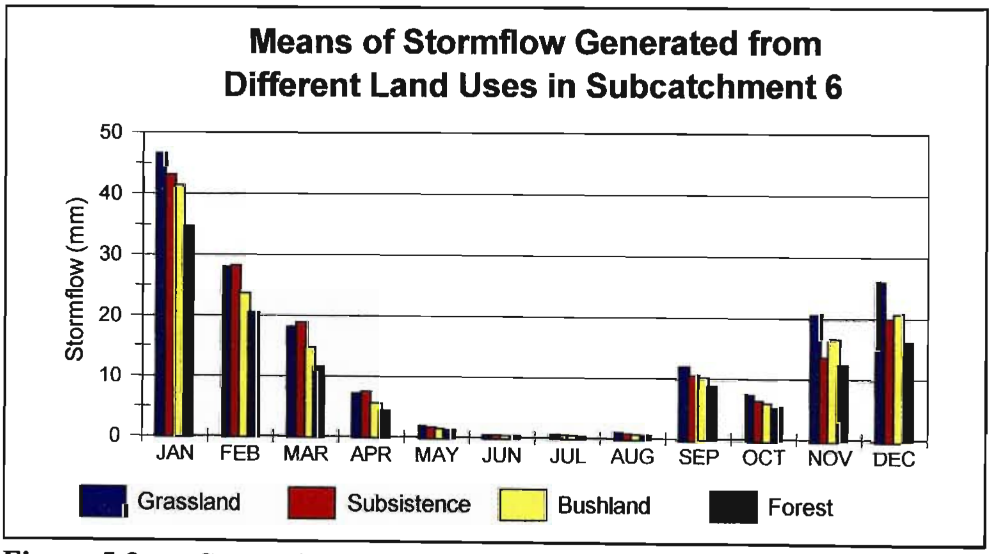


Figure 5.3 Comparison of simulated mean monthly stormflows generated from different land uses in Subcatchment 6

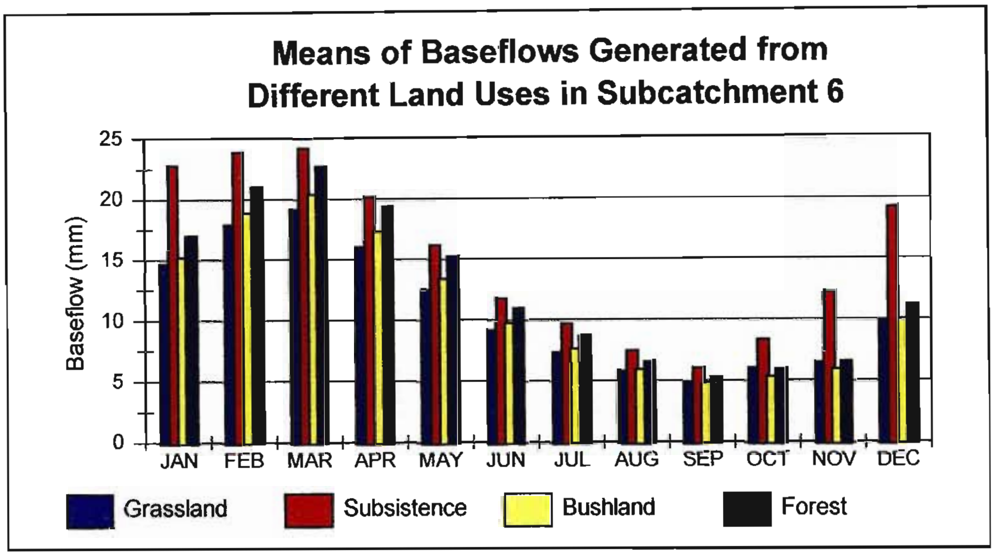


Figure 5.4 Comparison of simulated mean monthly baseflows generated from different land uses in Subcatchment 6

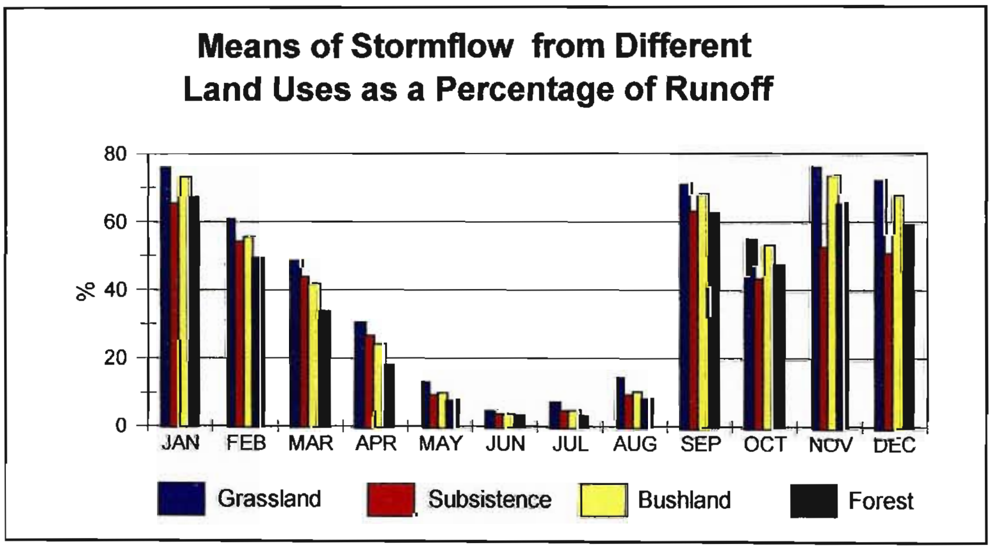


Figure 5.5 Comparison of simulated mean monthly stormflows generated from different land uses in Subcatchment 6 as a percentage of total runoff

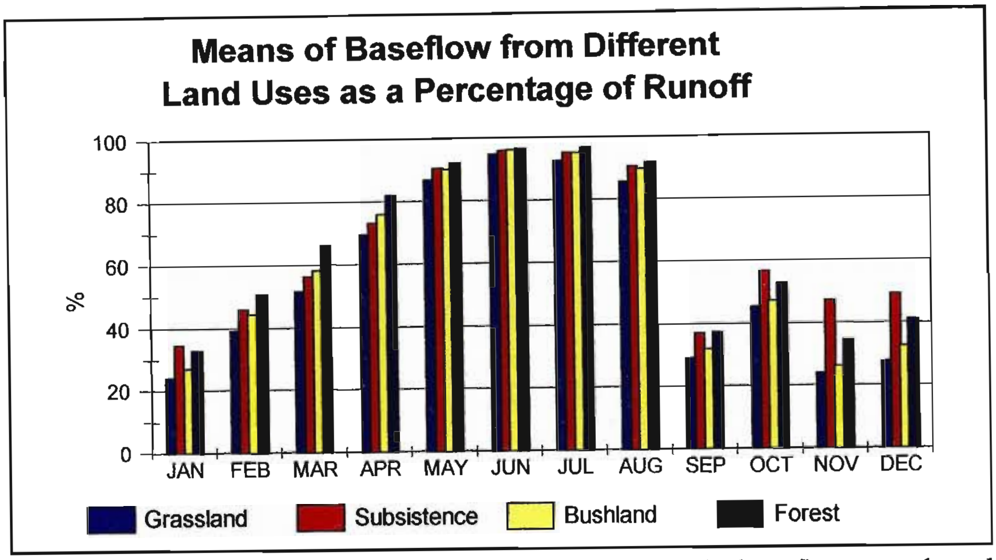


Figure 5.6 Comparison of simulated mean monthly baseflows produced from different land uses in Subcatchment 6 as a percentage of total runoff

5.2 Simulating Streamflows Under Baseline Conditions

One of the strengths of the *ACRU* model is its physical-conceptual structure. This makes it possible to reasonably represent the important hydrological characteristics of different land covers and uses by the model and subsequently derive appropriate runoff responses. The responses that can be modelled are not only for the present, but also for past or even future climate and land use and cover conditions of the catchment.

In the assessment of the type and extent of impacts of anthropogenic activities on streamflows, it is necessary to compare the impacted streamflows against a simulated "benchmark-like" streamflow. This is termed the baseline hydrological response and it consists of streamflows or sediment yields that are simulated to have occurred under climatic conditions identical to those of the present, but with the catchment assumed to be entirely covered by a baseline land cover assumed to be under conditions undisturbed by humans. The estimation of baseline hydrology is not a simple matter, however, because first there is no record of what the natural vegetation actually was, secondly there are no measured values of their hydrological attributes such as water use coefficients or fraction of roots in the topsoil. Certain decisions and assumptions on baseline land cover therefore have to be made (Schulze, 2000).

The *ACRU* model was set up to simulate the hydrological responses of the catchment under baseline conditions by:

a) replacing present land uses such as urban areas, both irrigated and dryland agriculture as well as exotic forest plantations, with a more natural vegetation which is represented in southern Africa by the vegetation as described in Acocks' (1988) Veld Types (**Figure 3.7**); furthermore,

b) assuming all farm dams and reservoirs not to have existed, and

c) disregarding all water abstractions and transfers.

Several *ACRU* variables were input to represent the baseline land cover to account for their characteristic hydrological responses. These variables include:

a) water use coefficients (month-by-month),

b) canopy interception values in mm per rainy day (month-by-month),

c) fraction of active roots in the topsoil horizon (month-by-month),

d) the variable which specifies whether the catchment is predominantly under forest, in which case enhanced wet canopy evaporation rates are activated in *ACRU*,

e) the effective depth of the soil considered to be contributing to stormflow generation,

f) porosity values of the topsoil (which increase due to tillage of agricultural land, thereby changing the topsoil's bulk density and hence soil water content at porosity),

g) coefficients of initial abstraction (month-by-month), which are used to estimate the rainfall abstracted by surface depression storage and infiltration before runoff begins, and

h) the fraction of impervious areas.

Values of all the above variables for each Acocks' Veld Type in each subcatchment were area-weighted to obtain input that may be considered representative of the entire subcatchment. Other (such as climatic) variables were not changed and the model was rerun to simulate streamflow sequences for the study area under baseline conditions, against which the impacts of present land use and different water use sectors could be assessed.

5.3 Modelling the Impacts of Present Land Use on Baseline Runoff for Individual Subcatchments

Impacts of present land use was evaluated by comparing the mean annual runoff (MAR) generated within the individual subcatchments, excluding upstream subcatchments' contributions, under present land use *vs* land cover under baseline conditions. **Figure 5.7** shows the differences in MAR as percentages of MAR produced under baseline conditions. Significant runoff reductions of up to 41% and increases of up to 53% were simulated.

High reductions ranging from 20% to more than 40% occur in Subcatchments 29 - 31, 33, 35, 37 and 38, all of which are under intensive irrigated agriculture (**Figure 3.8**). In Subcatchments 17, 18 and 20 significant decreases of between 10% and 20% are noted. These subcatchments have intensive agriculture which covers less than 10% of the total area, while over 76% of each of these subcatchments is covered by each of or a combination of thicket and bushveld and forest and woodland (**Figure 3.8**). This gives an indication of the higher consumptive water use of the sugarcane than the original cover. The reductions are pronounced, even though the area under sugarcane is less than 10%, because this is in the drier part of the catchment.

Subcatchment 19, being the recipient of the inter-catchment transfers from the adjacent Komati basin, was found to have the highest increase (up to 53%) in MAR despite having over 59% of its area under intensive irrigated agriculture. Over and above that, more than 0.5% of the catchment is urbanised. Other notable increases, but of less than 10%, were found in subcatchments around the upper middle sections of the Mbuluzi catchment. These increases could be a consequence of substituting the original land cover with either bare or compacted surfaces, as these areas are mostly covered by overgrazed grasslands and are predominantly occupied by rural communities.

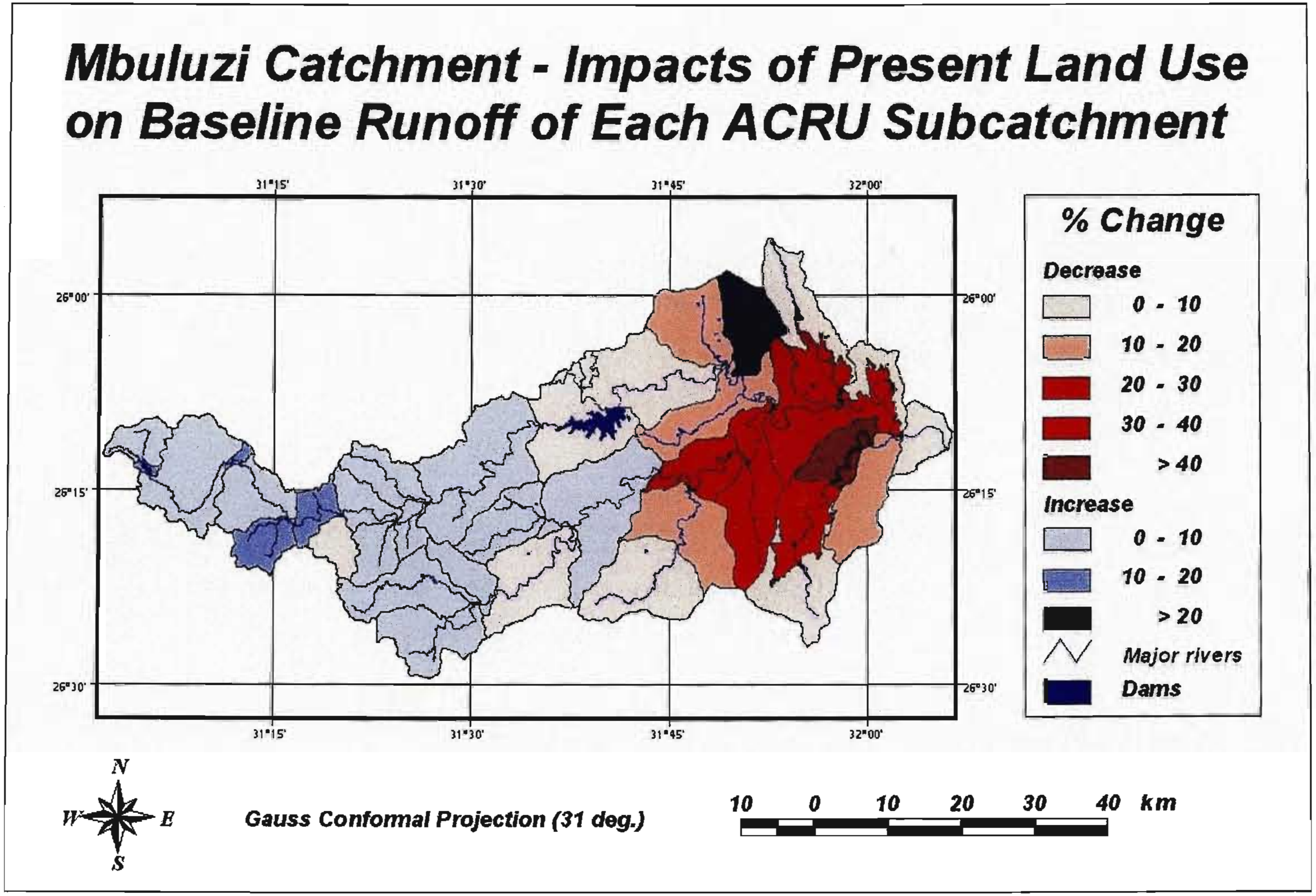


Figure 5.7 Impacts of present land use on MAR generated in individual subcatchments, i.e. excluding contributions from upstream subcatchments

Subcatchments 1- 3 also showed similar increases in runoff even though they are neither degraded nor predominantly occupied by rural communities. In these subcatchments, the original North Eastern Mountain Sourveld has been replaced by grasslands with lower canopy interception values and lower consumptive water use, thus leading to higher runoff production.

5.4 Modelling the Impacts of Different Present Land and Water Use Sectors on Accumulated Streamflows

The streamflow sequences generated under baseline land cover conditions were compared against streamflows produced under different present land and water use sectors. The different land and water use sectors were organised into four scenarios and their individual streamflow responses were generated and investigated for both present and projected future conditions. A fifth scenario combines the effects of the first four. These scenarios are listed and described as follows:

Scenario A: *Impacts of domestic water usage in rural areas.* Acocks' Veld Types were assumed to be the baseline land cover for all the subcatchments and water abstractions by rural communities for primary use only were accounted for in this scenario. The resultant streamflows are therefore from the baseline hydrology minus the rural water abstractions.

Scenario B: *Impacts of both industrial and domestic water usage in municipalities.* For this study, municipalities refer to all areas with nucleated human populations such as villages, towns, mines and cities. Acocks' Veld Types (1988) were again used as the baseline land cover and abstractions of water from dams and streams in each subcatchment were included in this impact study.

Scenario C: *Impacts of livestock water use.* Water used to water livestock was abstracted from the baseline hydrology run.

Scenario D: *Impacts of irrigated agriculture.* Present irrigated agricultural water demands were subtracted from the baseline hydrology run. Dams and external water sources (inter-catchment water transfers) and management practices that are known to have an impact on streamflows are represented in this scenario.

Scenario E: Impacts of the combination of the current land uses with the all the water demands of the sectors in Scenarios A to D were simulated in Scenario E.

Several variables representing the various hydrological attributes of the different land use and influences of water demand situations were adjusted accordingly when setting up the *ACRU* model for the individual simulations. In addition to variables described in the section on modelling baseline conditions, there were those that characterise dams and their operating rules, irrigation projects and management practices as well as water abstractions directly from the streams. These variables included:

a) storage capacity of dams,
b) surface area of dams,
c) legal daily flow releases from a reservoir, in order to maintain minimum flow to downstream riparian water users,
d) seepage from earth walled dams,
e) irrigated areas (varying monthly),
f) irrigation scheduling methods (varying month-by-month),
g) amount of net water application per irrigation cycle (varying month-by-month),
h) length of the irrigation cycle,
i) irrigation application efficiencies,
j) conveyance losses,
k) water use coefficients of irrigated crops (month-by-month),
l) coefficients of initial abstraction for irrigated fields (month-by-month)
m) soil properties of irrigated fields, and
n) a variable specifying the fraction of plant available water of a soil horizon at which total (actual) evaporation is assumed to reduce to below maximum (potential) rates during drying of the soil.

5.5 Results and Discussions of the Modelling Scenarios

The results of the individual scenario simulations are summarised in **Tables 5.1** and **5.2** and the spatial distributions of the impacts of each scenario are displayed in **Figures 5.8** to **5.12**. The variable for which the change was assessed is streamflow at each subcatchment outlet *including* contributions from upstream subcatchments. It should be noted that in each individual figure, the same legend (map colour coding) is used for both present and future conditions to facilitate easy visual comparison.

5.5.1 Scenario A : *Impacts of domestic water usage in rural areas*

Streamflow reductions as a result of water abstractions for domestic use in rural areas are spread throughout the catchment, as shown in **Figure 5.8**. High reductions that range between 0.8 to 1.4 mm equivalent are found in subcatchments along the main channel upstream of the Mnjoli Dam. This indicates a good correspondence with those subcatchments that have high rural populations. High percentage reductions of 0.5 to 1.0% are found in subcatchments that are along tributaries, suggesting high abstractions in relation to streamflow volumes. Subcatchments 18, 19, 21 and 22 have reductions that are less than 0.2 mm equivalent. Subcatchment 18 and 19 consist mainly of agricultural lands with large-scale irrigated sugarcane plantations while 21 and 22 are bordering Manzini City, all of which have low rural populations. Water supplies for this municipality are from the Usuthu catchment and have little or no influence in the Mbuluzi catchment if return flows are assumed to be negligible. The average rural water demand in the catchment is about 0.5 mm which is equivalent to 1.48 million m^3 per year. With the rural populations projected to the year 2050, there appears to be no change in the spatial distribution pattern of the population and thus of the water demand. The present demand is likely to increase catchment wide to more than 4.20 million m^3 per year in the future, if the rural populations increases as projected (**Table 5.1**). At the broad scale, domestic abstractions for rural communities are relatively insignificant. They constitute less than 1% of the overall catchment demand at present and the contribution is expected to be about 1.4% in the future.

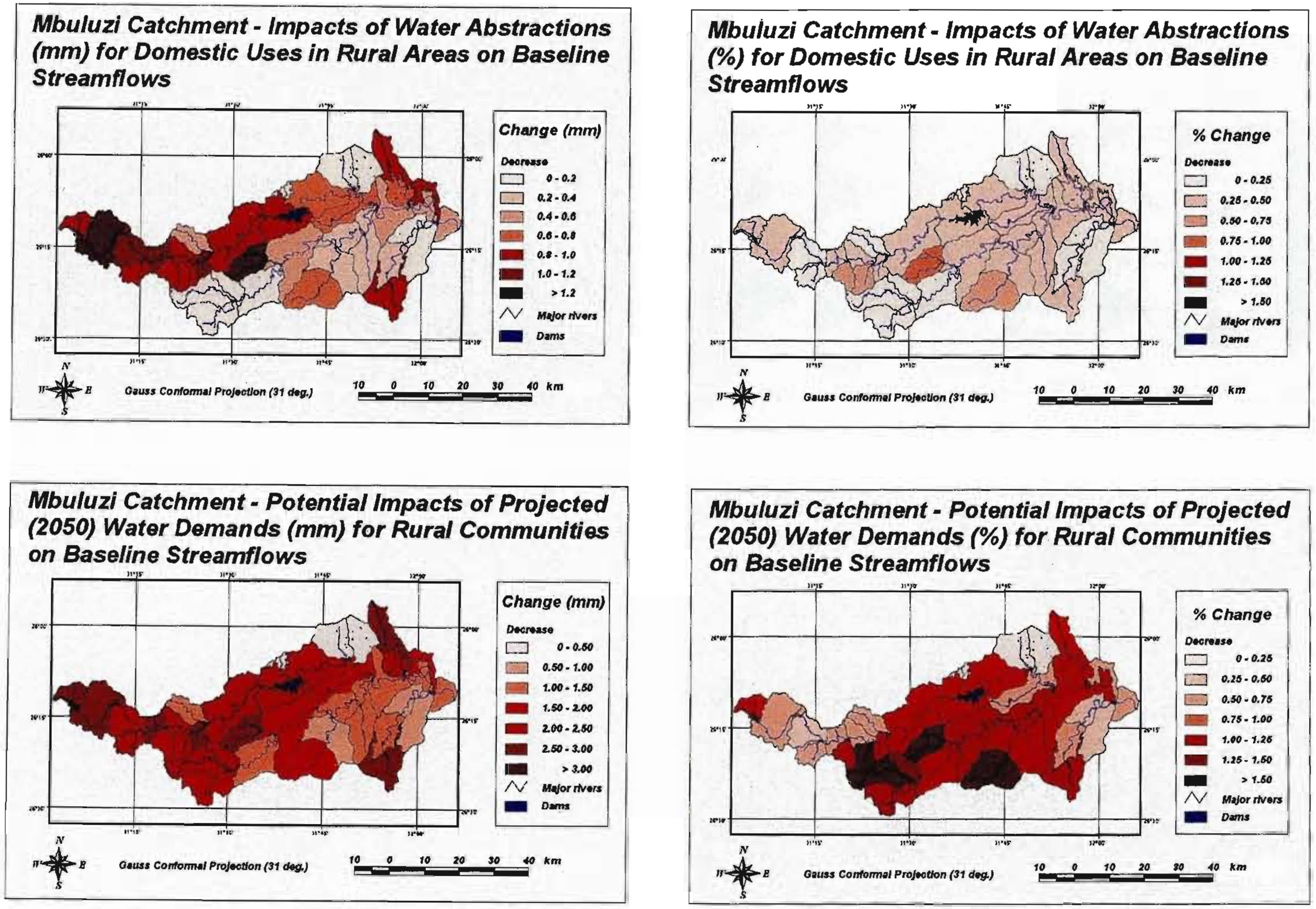


Figure 5.8 Present and projected future impacts of water abstractions, in both absolute and relative terms, for domestic use in rural areas on accumulated streamflows

5.5.2 Scenario B : *Impacts of both industrial and domestic water usage in municipalities*

There are only five subcatchments with major water abstractions for industrial and domestic use in municipalities in the Mbuluzi catchment (**Figure 5.9**). Thus the impacts of such withdrawals are intense at those particular subcatchments with abstraction points, but are attenuated in the downstream direction (**Figure 5.9**).

Presently, the overall annual municipal water demand is equivalent about 9.30 mm, which represent slightly more than 11% of the baseline catchment runoff yield and might increase up to about 18.6% in future if estimated population growth rates are realistic. The highest reductions which are more than 12% occur in Subcatchment 17. This indicates the impacts of the Mnjoli dam from which the abstractions of water for industrial (e.g. sugar mills) and domestic uses in Simunye (Lusoti and Ngomane) and Tabankulu are made. Other high reductions were simulated in Subcatchments 3 and 24. Subcatchment 3 is the first downstream subcatchment after the Hawana Dam from which water is drawn for supplying Mbabane City and Ngwenya village while water for domestic and industrial use in Mafutseni and Mpaka is pumped from the stream in Subcatchment 24.

5.5.3 Scenario C : *Impacts of livestock water use*

The major impact of livestock water use is the reduction of streamflow all over the catchment with values that are up to 2 mm equivalent (cf. **Figure 5.10**). High values are found around the upper middle parts of the Mbuluzi catchment, corresponding with overgrazed areas. In relative terms, high values of 0.8 to more than 1.0% are also observed in the same region, except that they are in subcatchments upstream of the major tributary, *viz.* the Mbuluzana river. This reflects the high demands relative to the low water volumes in the stream at that stage. The overall reduction for the whole catchment is 0.9 mm i.e. 0.46%, of the average annual streamflow produced under baseline conditions. This represents only 2.66 million m^3 of water per annum which, like abstractions for domestic use in rural areas, is insignificant in the big picture as it accounts for only slightly less than 1% of the overall water demand in the catchment. It should

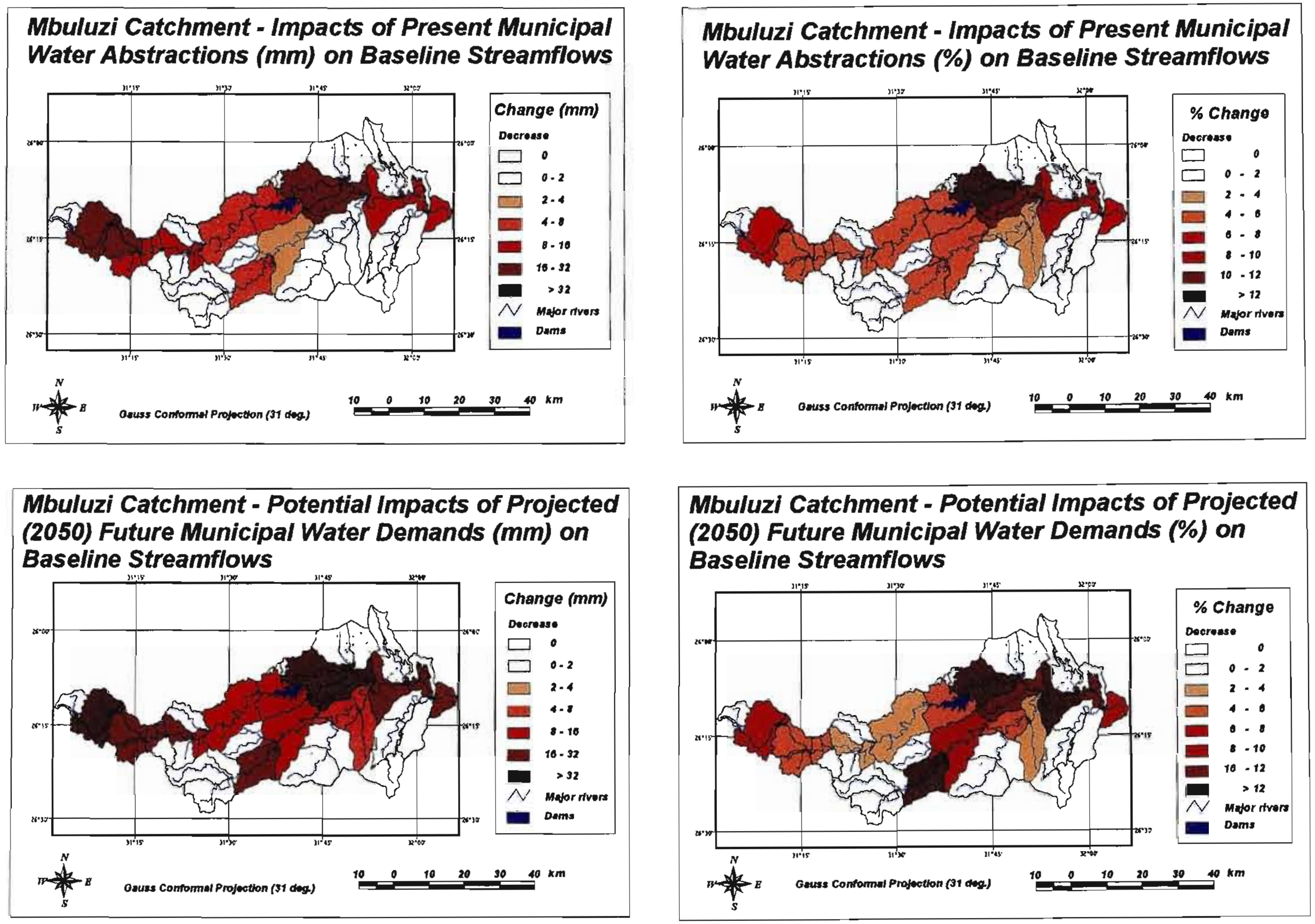
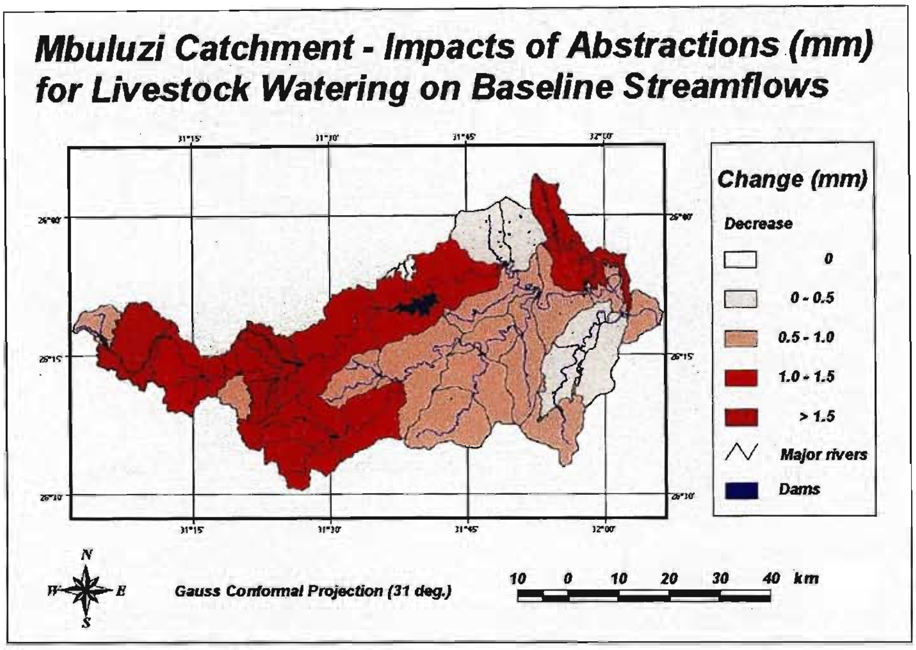


Figure 5.9 Present and projected future impacts of water abstractions, in both absolute and relative terms, for use in municipalities on accumulated streamflows



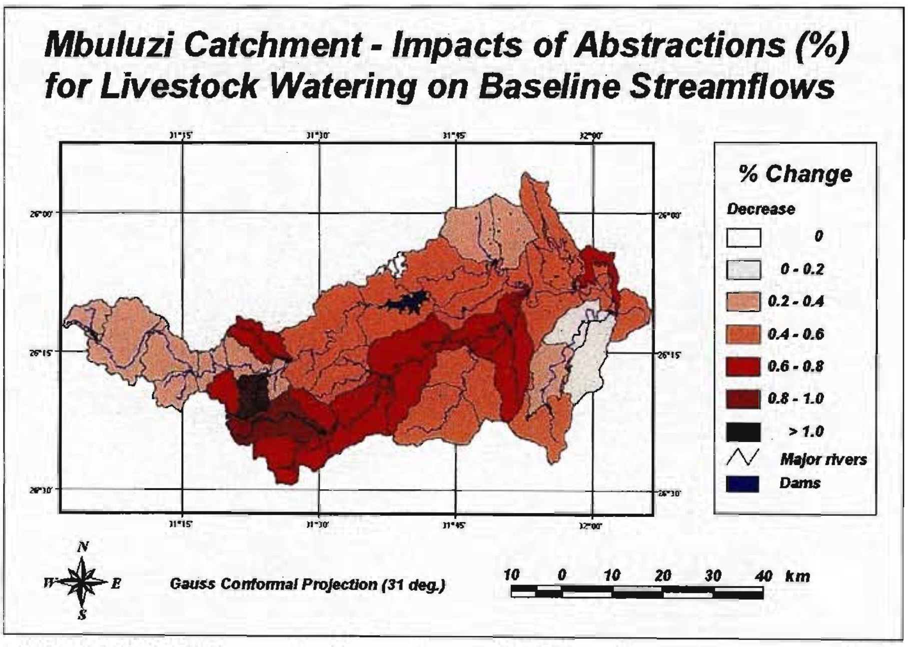


Figure 5.10 Present impacts of abstractions on accumulated streamflows, in both absolute and relative terms, for livestock watering

be noted that the future demand remains unchanged in absolute terms and decreases in relative terms (**Table 5.1**) because livestock populations are not expected to change in the future because of the possibility of conversion of what is currently grazing areas into agricultural land and urbanization.

Table 5.1 Mbuluzi catchment: Reduction of mean annual streamflow yield of the catchment by different water use sectors

Time Period	Demand Sector	Reduction (mm)	Reduction ($10^6 m^3$)	Reduction ($\%_{BS}$)	Demand ($\%_{OD}$)
Present	Irrigation	72.60	214.81	37.25	87.16
	Municipal	9.30	27.52	4.77	11.16
	Livestock	0.90	2.66	0.46	1.08
	Rural	0.50	1.48	0.26	0.60
Future	Irrigation	79.45	235.08	40.76	79.13
	Municipal	18.63	55.12	9.56	9.56
	Livestock	0.90	2.66	0.46	0.90
	Rural	1.42	4.20	0.72	1.41

Table 5.2 Mbuluzi catchment: Reduction of mean annual streamflow yield of the catchment by the combination of water use by different sectors and present vegetation

Time Period	Demand Sector	Reduction (mm)	Reduction ($10^6 m^3$)	Reduction ($\%_{BS}$)	Demand ($\%_{OD}$)
Present	Combined	83.25	246.33	42.71	100
Future	Combined	100.40	297.07	51.51	100

Key:

$\%_{BS}$ - Reduction by each sector as a fraction of baseline flows

$\%_{OD}$ - Reduction by each sector as a fraction of the overall demand

5.5.4 Scenario D : *Impacts of irrigated agriculture*

Irrigation activities in the Mbuluzi catchments show a general tendency of reducing streamflows, as shown in **Figure 5.11**. The streamflow reduction varies from catchment to catchment. High reductions occur along the main channel downstream of the Mnjoli Dam. All these subcatchments are in the sugarcane belt and show reductions that are greater than the 10% of the baseline flows. The highest decrease is 100.40 mm, i.e. equivalent to 38.9%, at the outlet of Subcatchment 17 which is immediately downstream of the dam. The irrigated land in subcatchments outside of the large-scale sugarcane plantations are owned by individuals or farmers grouped into small-scale irrigation schemes. These cause a reduction of no more than 10% in respective subcatchments. This is an indication of the smaller size of land under irrigation rather than differences in irrigation and management practices.

Contrary to the general trend of flow reduction, the streamflows are enhanced by 162.1 mm, i.e. 113% in Subcatchment 19. This subcatchment receives water imports from the adjacent Komati basin for irrigating all the fields of the Mhlume Sugar Company (MSCo) and those of Tabankulu Estates. Over 63% of the irrigation in Mhlume is by furrow methods, which are simulated by *ACRU* to result in large return flows. These return flows and imported flows for Tabankulu Estates, which is downstream of the MSCo, is the cause of the significant increases in the streamflow at the outlet of this subactchment.

The general trends of the impacts of future irrigation on streamflow are similar to those of the present scenario. Differences appear to be only in the magnitudes of the change of flows. The overall reduction for the future scenario is 79.45 mm, i.e. 40.76%, compared to 72.60 mm, i.e. 37.25%, for the present situation. The higher reductions are an indication of larger water demands for irrigation in the future following increases in the area under irrigation in some subcatchments and introduction of irrigation activities in other subcatchments (such as 27, 34 and 36) where there is none at present. An additional 2000 ha in the Royal Swaziland Sugar Company (RSSC) in Simunye is currently being developed for irrigated sugarcane production in Subcatchments 29 and 30. The present impact of irrigation on streamflow in Subcatchment 19

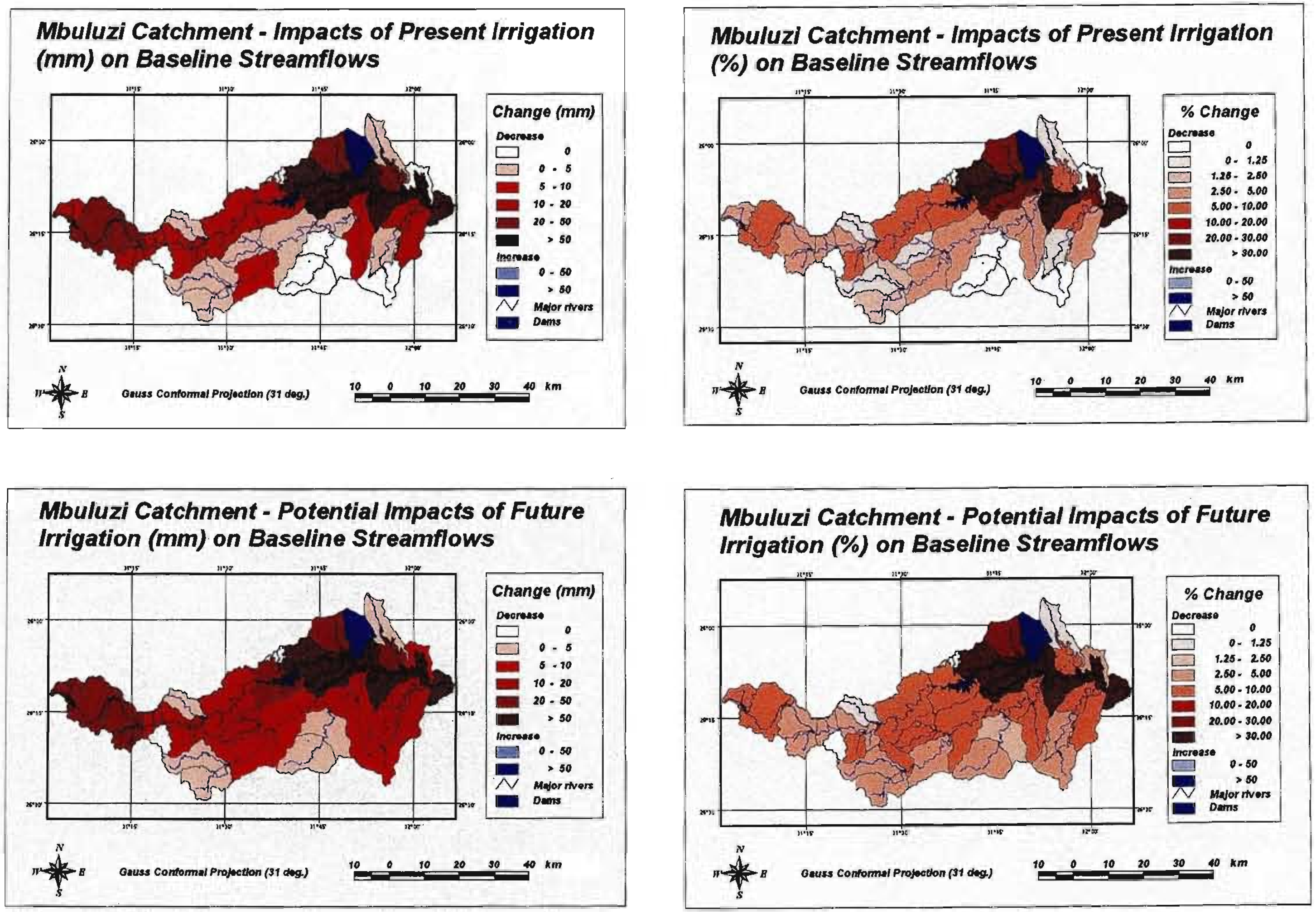


Figure 5.11 Present and projected future impacts of irrigation, in both absolute and relative terms, on accumulated streamflows

is not expected to change in the near future. The inter-catchment transfers are not expected to change either, because there are no long-term plans for expansions. It was, furthermore, assumed that furrow irrigation will continue to be the main application method used.

5.5.5 Scenario E : *Impacts of the combination of the current land uses and all the water demand scenarios*

The baseline land cover for the combined land use and water demand scenarios is the LANDSAT TM image of 1996 (**Figure 3.7**). Streamflows generated under this scenario vary from subcatchment to subcatchment, with reductions in some and enhancements in others, as shown in **Figure 5.12**. Major reductions range from 8 mm equivalent in the middle to more than 100 mm equivalent in the lower sections of the catchment. A similar picture is evident in relative terms, where the reductions range from about 5 to 45%.

Streamflow enhancements are found in the upper middle sections (1.6 to 3.6 mm) and in Subcatchment 19 (162.1 mm). In the former case, the cause could the replacement of baseline land cover by current land uses with hydrological characteristics that favour higher runoff generation. Subcatchments in this part consist of overgrazed communal rangelands and subsistence agriculture. The influence of the enhanced runoff generation is obscured by the higher future water demands for domestic use in rural areas, domestic and industrial use in municipalities and irrigation. The high flow increase in Subcatchment 19 is attributed to the water imports from the Komati Basin for irrigation at Mhlume Sugar Company and Tabankulu Estates.

The overall impact of present land use and water demands is a reduction of streamflows by 83.25 mm, i.e. 42.7%, of the average streamflows volume generated under baseline conditions (**Table 5.2**). This is equivalent to 248.9 million cubic metres per year and represents the current total water demand in the Mbuluzi catchment. This demand is expected to increase by about 20% in the future (**Table 5.2**). More than 87% of the present demand is for irrigation while the remainder is for primary, livestock and industrial use, as summarised in **Table 5.1**. The demand for irrigation in future, while increasing in absolute terms, will be slightly reduced to 79% of the total demand.

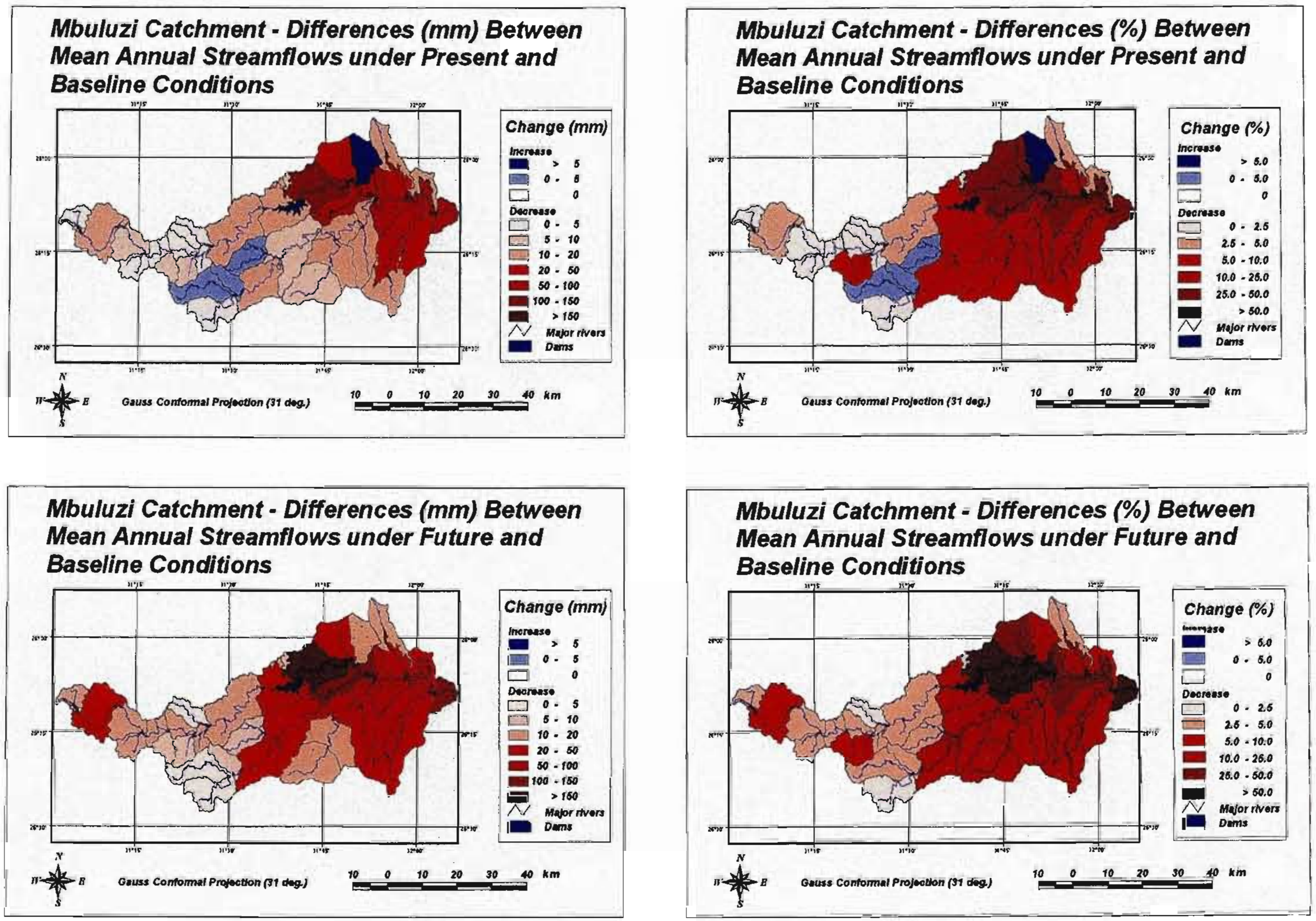


Figure 5.12 Present and projected future combined impacts, in both absolute and relative terms, of all land and water use scenarios on accumulated streamflows

5.6 Downstream International Flow Obligations

All the major rivers in Swaziland are international streams. Though the Mbuluzi river originates within Swaziland, it eventually flows into Mozambique. In line with international regulations regarding international river systems, Swaziland and Mozambique, through a Joint Water Commission, defined and agreed on the flow to be passed into the latter country. Thus, according to Knight Piesold Consulting Engineers (1997), Swaziland in September 1976 agreed to pass to Mozambique 40% of the Mbuluzi's flow as measured at gauging station GS3 and 40% of the Mbuluzane's flow as measured at gauging station GS10, and extrapolated to the border, during any hydrological year (i.e. 1 October through to 30 September).

In addition to water quality concerns regarding water that is passed from Swaziland to Mozambique, Matola (1999) states that Swaziland has over-allocated the water resources of the Mbuluzi river. He also concedes, however, that not all the allocations are utilised. This warrants an investigation to establish whether Swaziland will be able to meet the agreed streamflow releases to Mozambique, especially when all its present and future the allocations are utilised.

5.7 Assessment of the Flow Releases to Mozambique

The streamflows simulated under present and future land uses and water demands were used to establish whether Swaziland is at present, or will in future be, able to meet downstream international water release obligations. This was undertaken by summing 40% of the flows at GS3 and 40% of flows at GS10 and comparing values with the flows at the border as a time series plot from October 1976 to December 1995, as shown in **Figure 5.13**. It may be seen that these obligations are met during all the wet seasons, but are not satisfied during some dry seasons. Under present land use and water demand conditions, **Figure 5.14** shows that during September once in more than ten years, there is a likelihood of failure to met the obligations. The obligations will likely exceed, or equal the flows at the border in August and September at worst once in ten years in future (2050), as shown in **Figure 5.15.**

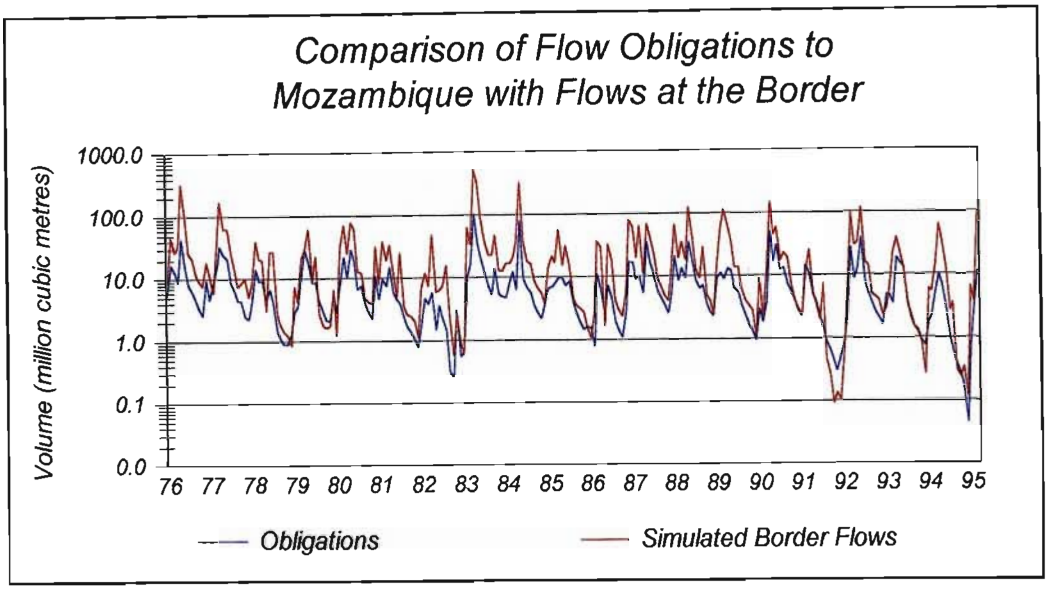


Figure 5.13 Comparison of present Mozambican streamflow obligations and simulated flows at the border

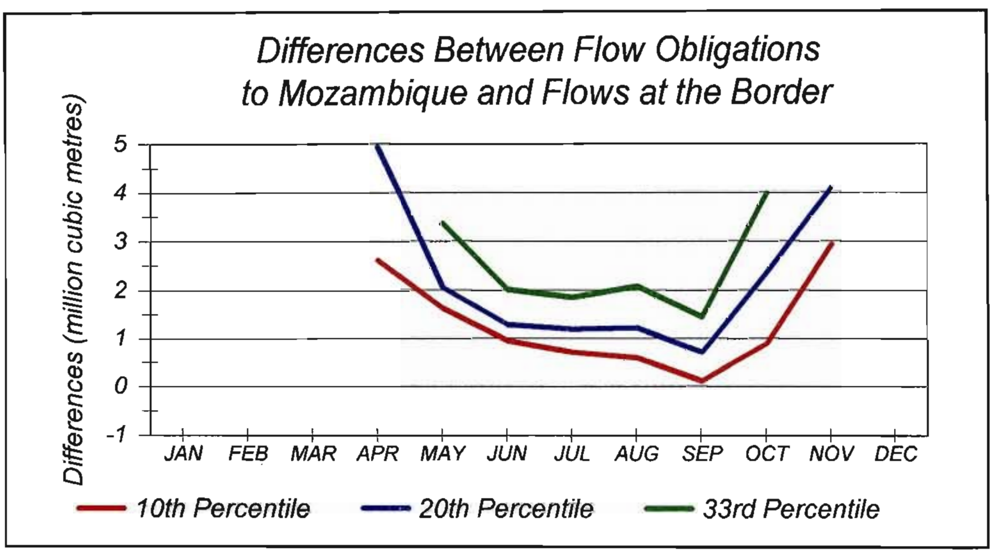


Figure 5.14 Present differences in low flow months between the Mbuluzi System's flows at the border and downstream international obligations to Mozambique, simulated with the *ACRU* model

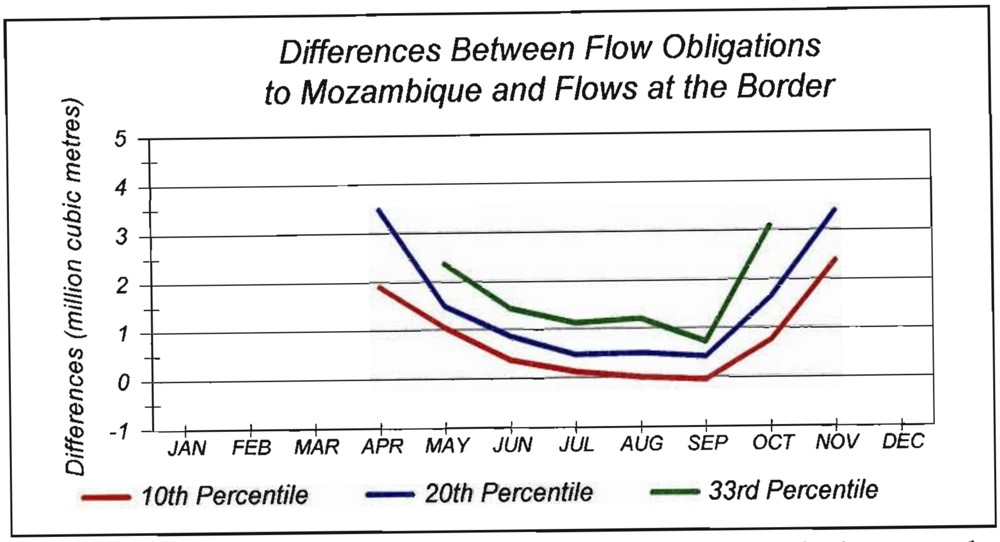


Figure 5.15 Projected future differences in low flow months between the Mbuluzi System's flows at the border and downstream international obligations to Mozambique, simulated with the *ACRU* model

Meeting the quantity of flow is not the only concern regarding the Mozambican flow requirements, but the quality is as well. Matola (1999) speculates that the quality of the released water may not be of the required standards. The basis of his speculation is that the water that is flowing to Mozambique also includes return flows from irrigated sugarcane fields, together with the effluents from the sugar mills. The quality of the water released into Mozambique was not investigated in this study owing to model limitations. However, the latest version (*ACRU*2000) will have a water quality module to simulate nitrogen and phosphorus loads in streamflow (Campbell, Kiker and Clark, 2001). It is worth mentioning, however, that if the quality is not satisfactory, it is likely to be worse in periods of low flows when there would be less water to dilute the effluents.

5.8 Conclusions

One of the objectives of this study was to assess both the impacts of land use and management changes on runoff and available water resources by evaluating present and future sectoral water demands. Findings of the evaluation have been presented in this Chapter. The Chapter also contains the outcomes of the investigation of the downstream international obligations. This investigation is only quantitative, hence did not analyse the quality of the water that flows into Mozambique. In both the impact study and international flow assessment, the results are only presented and described. Findings and their implications are comprehensively discussed in Chapter 7.

6. MODELLING SEDIMENT YIELD IN THE MBULUZI CATCHMENT

6.1 Introduction

Soil erosion is a serious concern in the Mbuluzi catchment, especially upstream of the Mnjoli Dam. Sediments deposited in reservoirs result in the reduction of their storage capacities. Besides scouring and washing away topsoil which leads to the loss of crop production media, soil erosion and sediment transportation may have negative impacts on water resources availability and management. An increase in the concentrations of suspended solids in flowing water causes degradation of the environmental quality of rivers. Depending on their chemical composition, sediments may carry plant-usable nutrients such as phosphorus and other fertiliser residues from agricultural lands. Nutrient-rich water leads to eutrophication in reservoirs. Eutrophication may, furthermore, lead to excessive evaporation and hence increase water losses. The dense vegetation in dams may also clog pipes and kill aquatic fauna through reduction of dissolved oxygen. Sediments, particularly those which are derived from densely populated areas without proper sanitary facilities may also carry pathogens such as *E.coli*. High concentrations of suspended solids, nutrients and pathogens in water creates the need for expensive purification, especially before it is suitable for domestic and industrial (manufacturing) use.

With the potential problems related to soil erosion and sediment transport highlighted above, it becomes necessary to study these processes in the Mbuluzi catchment where a concern already exists. There is a need to:

a) identify high sediment producing areas,
b) estimate sediment loads in streams and reservoirs,
c) determine the influences of storm events of different magnitudes on sediment yields,
d) evaluate the seasonal variation of sediment production in the catchment, and
e) establish the effects of land use changes on sediment yields within the catchment.

Owing to the unavailability of any measured records of sediment loads of the streams in the Mbuluzi catchment to analyse and to make generalisations from the above research objectives, the *ACRU* model was used to simulate sediment yield for individual events on a day-by-day basis in order to investigate research needs a), c), d) and e). The simulations were for individual subcatchments and did not involve routing of the sediments from one subcatchment outlet to the next downstream.

6.2 Using *ACRU* to Model Sediment Yield

The sediment yield routine in the *ACRU* model uses the fundamental approach of the Universal Soil Loss Equation (USLE). The USLE (Wischmeier and Smith, 1978) was developed empirically from a large database and the component factors of the equation, while individual determinants of soil loss, are multiplicative statistical, and not strictly physical, relationships. The original USLE and the Revised USLE (RUSLE) equation (Renard *et al.*, 1991) are both given as

$$A_{sy} = R \bullet K \bullet LS \bullet C \bullet P$$

where

A_{sy}	=	long term average soil loss per unit area (tonne.ha^{-1}.annum^{-1}),
R	=	an index of annual rainfall erosivity (MJ.mm.ha^{-1}.ha^{-1}.annum^{-1}),
K	=	soil erodibility factor (tonne.h.MJ^{-1}.mm^{-1}),
LS	=	slope length and gradient factor (dimensionless),
C	=	cover and management factor (dimensionless), and
P	=	support practice factor (dimensionless).

Though valid for estimating the long term average annual soil loss, the equation in the form above is not directly applicable for determining soil loss estimates of individual storm events. To address that limitation, Williams (1975) modified the USLE by replacing the rainfall erosivity factor with a stormflow factor. This resulted in a version known as the Modified Soil Universal Loss Equation (MUSLE), which allows for the prediction of sediment yields directly, thereby eliminating the need for sediment delivery ratios which were used to estimate the proportion of eroded soil which leaves the catchment, and is also applicable for individual storm events (Williams and Berndt, 1977). The MUSLE is expressed as

$$Y_{sd} = \alpha_{sy}(Q_v \bullet q_p)^{\beta_{sy}} K \bullet LS \bullet C \bullet P$$

in which the newly defined terms are

Y_{sd}	=	sediment yield for an individual event (tonne per area of the catchment),
Q_v	=	stormflow volume of the event (m^3),
q_p	=	peak discharge for the event ($m^3.s^{-1}$),
K	=	soil erodibility factor ($tonne.h.N^{-1}.ha^{-1}$),
α_{sy}	=	location specific MUSLE coefficient, and
β_{sy}	=	location specific MUSLE coefficient.

It is therefore the MUSLE which is used to model the sediment yields of individual events in *ACRU* with the factors K, LS, C and P taken directly from the RUSLE. The soil's erodibility factor is in appropriate SI units.

The *ACRU* model makes use of equations developed by the Soil Conservation Service (SCS) of the United States Department of Agriculture and adapted for southern African conditions by Schulze (1984), Schmidt and Schulze (1987), Schulze, Schmidt and Smithers (1993) and Schulze (1995) to calculate event-based stormflow.

The United States Department of Agriculture (1985) and Schmidt and Schulze (1987) derive the SCS stormflow equation from initial principles as follows:

$$Q = \frac{(P_g - I_a)^2}{P_g - I_a + S} \quad \text{for } P_g > I_a$$

where

Q	=	stormflow depth (mm),

P_g = gross daily precipitation amount (mm),

I_a = initial abstractions (mm) before stormflow commences, consisting mainly of interception, initial infiltration and depression storages, and

S = potential maximum retention (mm), which is equated to a soil water deficit.

In order to eliminate the necessity of estimating both I_a and S, I_a may be expressed in terms of S by the empirical relationship

$$I_a = cS$$

where

c = coefficient of initial abstraction.

The stormflow equation thus becomes

$$Q = \frac{(P_g - cS)^2}{P_g + S(1-c)}$$

Subsequent adaptations and developments to the SCS equations for use in the *ACRU* model, explained in detail in Schulze (1995) include replacing P_g by net rainfall, P_n, thereby removing interception from the expression of I_a because of more sophisticated interception routines are available in *ACRU*; also rendering the 'c' of I_a a monthly variable dependent on rainfall intensity characteristics, tillage practices and infiltration enhancing and retarding surface cover properties; as well a computing S from a daily two soil layer water budget and making it dependent on a variable critical stormflow generating layer. The product of the catchment area and stormflow depth yield the stormflow volume in m^3, Q_v.

The SCS unit hydrograph concepts are utilized in *ACRU* to compute the peak discharge from the generated daily stormflow volume (United States Department of Agriculture, 1972). In most instances where continuous or recording rainfall data are not available, it is assumed that the rainfall distribution over time is uniform, hence a single triangular rather than an incremental unit hydrograph is used to compute peak discharge. The SCS peak discharge procedures have been adapted for, tested and applied in southern African conditions by, *inter alia* Schulze and Arnold (1979) and Schmidt and Schulze (1987). For an assumed single triangular unit hydrograph, the equation for peak discharge, q_p, was originally expressed in SI units as

$$q_p = \frac{0.2083AQ}{(D_e/2)+L}$$

where

q_p	=	peak discharge ($m^3.s^{-1}$),
Q	=	stormflow depth (mm),
A	=	catchment area (km^2),
L	=	catchment lag time (h), i.e. and index of the catchment's response time, and
D_e	=	effective storm duration (h).

In the absence of detailed information for individual storm event hydrographs, the effective storm duration, D_e, is assumed to equal the catchment's time of concentration, T_c, which is related empirically to lag time, L. The peak discharge equation as used in the *ACRU* model, and assuming a so-called Type-2 rainfall intensity distribution over a day, which is typical for Swaziland (Schulze *et al.*, 1993) then becomes

$$q_p = \frac{02083AQ}{1.83L}$$

L, the index of catchment response time, may be estimated by a number of equations developed by the United States Department of Agriculture (1972) and by Schmidt and Schulze (1987) to give reliable estimates of lag under a range of hydroclimatic conditions. Because, in this study, the impact of land use and its change plays a major role in sediment yield simulations, the USDA (1972) equation was selected, because it is more sensitive to land use and management then the the other lag equations. It is expressed as

$$L = \frac{H_l^{0.8}(S'+25.4)^{0.7}}{7069\ S_{c\%}^{0.5}}$$

where

H_l	=	hydraulic length (m), i.e. the length of the main channel in the catchment,
$S_{c\%}$	=	average catchment slope (%), and
S'	=	catchment response retardance factor.
	=	$\frac{25400}{CN - II} - 254$

with

CN-II	=	runoff curve number, the dimensionless SCS index of catchment hydrological response unadjusted for catchment antecedent wetness. Typical values of CN-II for selected land uses, management scenarios, hydrological soil groups and storm flow potentials are given in Schulze *et al.* (1993).

6.3 Preparation of Input Information for Sediment Yield Modelling

The *ACRU* sediment yield module uses the same factors (stormflow volume, peak discharge, soil erodibilty index, slope length/steepness, an index of vegetation cover and of management practice) as the MUSLE. Owing to constraints of resources and time, comprehensive field surveys and measurements of these factors were not undertaken. It was therefore essential that the reasonable estimates of the factors be obtained using other methods, or from other sources, to make realistic simulations of sediment yields. Based on the 18 land cover classes identified in the Mbuluzi catchment (cf. Table 4.1), decision support systems, figures and tables (from the *ACRU* user manual) with generic values were used to estimate some of the important factors. The following sections describe methods of estimating the values of the parameters, the assumptions made and references to information sources.

6.3.1 Soil erodibility factor, K

There is a dearth of soil physical data for the Mbuluzi catchment. Hence the soil erodibility factor had to be estimated using information in **Table 6.1**. A value of 0.6, which depicts rather highly erodible soils, was applied for the entire catchment based on the information which can be deduced from Mushala (2000). This value was kept constant in the entire catchments to avoid the introduction of spatial variability on the sediment yields by a factor whose values could not be estimated with greater levels of confidence. While 0.6 was found to slightly exaggerate sediment yield, especially in the lower middle sections of the catchment which experiences no serious soil erosion concerns, it gave reasonable and acceptable sediment yields in the middle and upper middle parts of the catchment where numerous erosion studies have been undertaken by, *inter alia*, Scholten, Felix-Henningsen and Mushala (1995), Mushala, Scholten and Felix-Henningsen (1996), Mushala, Scholten, Felix-Henningsen, Morgan and Rickson (1997) and Mushala (2000). These researchers have all showed that the soils in these parts of the catchment are susceptible to high erosion rates owing to the presence of saprolitic material.

Table 6.1 Erodibility factors for various soil erodibility classes (Lorentz and Schulze, 1995)

Soils Erodibility Class	Soil K-Factor
Very High	> 0.70
High	0.50 - 0.70
Moderate	0.25 - 0.50
Low	0.13 - 0.25
Very Low	< 0.13

6.3.2 Slope length and gradient factor, LS

Field measurements of slope lengths and gradients were not conducted. The *ACRU* model internally computes the average slope length and gradient factor from average slope (%) using algorithms developed by Schulze (1979). The coverage of the Mbuluzi catchment with its subcatchment delineation was overlaid on a 200m x 200m DEM and the average slope for each subcatchment was calculated using GIS. This value was input into *ACRU* and the LS was computed internally in the model.

6.3.3 Land cover and management factor, C

The calculation of cover factors requires detailed vegetation information such as canopy cover, drop fall height from the canopy and mulch cover. A combination of information collected during fieldwork in the catchment, including close-up photographs of the different land uses shown in **Figure 6.1**, was then used together with expert opinion (Schulze, 2000; Lorentz, 2000, personal communication) and information contained in *ACRU* user manual (Smithers and Schulze, 1995) to estimate monthly cover factors for the dominant land cover and use classes in the Mbuluzi catchment.The estimates of the cover factors for each major land use in the Mbuluzi catchment are given in **Table 6.2**.

6.3.4 Conservation practices, P

Conservation practices have a reduction effect on overall soil loss. Factors representing the effects of support practices were estimated from **Table 6.3** in conjunction with slope and farming practices that are found in the Mbuluzi catchment. The values of the conservative practices factor was estimated only for the cultivation-oriented land uses, i.e. subsistence and large-scale irrigated agriculture. Generally, there are no management practices in the communal rangelands (consisting of combinations of grasslands, bushlands, forests and woodlands), hence their practice factors were kept at unity.

Grassland in good condition

Grassland in poor conditions

Degraded rangeland

Exposed saprolitic soil

Contour strips in a harvested maize field

Bushland

Undisturbed indigenous forests and woodlands

Wattle stands upstream of the catchment

Figure 6.1 Photographs of some of the major land covers in the Mbuluzi catchment, information from which was used in estimating C-factors

Table 6.2 Estimates of cover factors for dominant land covers and land uses used in modelling the responses of the Mbuluzi catchment

Land Cover	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Grass(G)	0.009	0.008	0.008	0.030	0.050	0.050	0.050	0.050	0.050	0.030	0.010	0.009
Grass(F)	0.089	0.087	0.087	0.120	0.200	0.200	0.200	0.200	0.200	0.180	0.120	0.090
Grass(P)	0.150	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.350	0.350	0.300	0.200
Bush(G)	0.050	0.050	0.050	0.050	0.060	0.080	0.080	0.080	0.080	0.080	0.050	0.050
Bush(P)	0.070	0.070	0.070	0.070	0.080	0.100	0.100	0.100	0.100	0.100	0.070	0.070
Forest & woodland(G)	0.047	0.044	0.046	0.049	0.052	0.060	0.060	0.060	0.060	0.052	0.049	0.047
Forest & woodland (P)	0.056	0.053	0.055	0.059	0.062	0.072	0.072	0.072	0.072	0.062	0.059	0.056
Indigenous forest	0.008	0.007	0.007	0.008	0.009	0.009	0.010	0.010	0.010	0.010	0.009	0.008
Subsistence agriculture	0.150	0.090	0.030	0.150	0.340	0.360	0.380	0.400	0.450	0.750	0.700	0.350
Irrigated agriculture	0.009	0.009	0.009	0.009	0.200	0.200	0.200	0.150	0.080	0.030	0.010	0.009
Urban settlements	0.006	0.006	0.006	0.006	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.006
Bare ground (compacted)	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439

Key:
G Good hydrological condition, i.e cover > 75%
F Fair hydrological condition, i.e 50% > cover < 75%
P Poor hydrological condition, i.e cover < 50%
NB All the crops under subsistence agriculture were assumed to be maize (planted in mid-November and maturing in March) while the irrigated crops were assumed to be sugarcane (ratoon crop with harvesting period beginning in May and ending in August).

6.3.5 The MUSLE coefficients, α_{sy} and β_{sy}

According to Simons and Senturk (1992), cited by Lorentz and Schulze (1995), the MUSLE coefficients, α_{sy} and β_{sy} are location specific, hence must be determined for specific catchments in specific climatic regions. Kienzle and Lorentz (1993) report that very little research has been undertaken on calibrating these coefficients. In this study, default values of 8.934 and 0.56 for α_{sy} and β_{sy} respectively were used. Having been originally calibrated for catchments in selected catchments in the USA by Williams (1975), these values for α_{sy} and β_{sy} have been adopted extensively with varying degrees of success (Williams and Berndt, 1977; Williams, 1991; Kienzle, Lorentz and Schulze, 1997).

Table 6.3 P-values for different land uses in the Mbuluzi catchment (after Wischmeier and Smith, 1978)

Land Use	Land Slope (%)	Contour Tilled
Cultivated lands (subsistence and large-scale irrigated agriculture)	1 - 2	0.60
	3 - 8	0.50
	9 - 12	0.60
	13 - 16	0.70
	17 - 20	0.80
	21 - 25	0.90
Private pastures & communal rangelands	all	1

6.4 Revisiting the Selection of the MUSLE Approach in *ACRU* for Sediment Yield Estimates

The importance of verification studies in simulation is undisputed. However, the possibility of conducting them relies entirely on the availability of good quality and sufficiently long observed or measured data that are congruent with the period of simulation. Lack of measured sediment yield data in the Mbuluzi catchment rendered it impossible to conduct conventional verification studies. Several considerations made it scientifically sensible, however, to nevertheless apply the MUSLE-based *ACRU* routine to model the sediment yields without the ability to verifying the results. Firstly, *ACRU* is a physical-conceptual model which was verified for its streamflow responses in the Mbuluzi catchment and produced highly acceptable results. Secondly, USLE and RUSLE from which the MUSLE was derived are used and their results are accepted worldwide. Rosewell (1997), for example, used the RUSLE to map potential sources of sediments in Australia. A similar study was conducted by Kienzle, Lorentz and Schulze (1997) in Mngeni catchment in South Africa using both the RUSLE and the *ACRU*-MUSLE routine. Their successful verifications at several sites with observed sediment information is used in this study as an indicator of the validity of using this approach under southern African conditions.

6.5 Sediment Producing Areas in the Mbuluzi Catchment

The *ACRU* model was used to simulate daily sediment loads for each subcatchment for the period 1945 - 1995. From the daily values, monthly and annual average sediment yields were computed for each of the 40 *ACRU* subcatchments. For comparison sake, the catchment sediment yields were converted to a unit yield in $t.ha^{-1}$. Mean annual values are presented in **Figure 6.2**. **Figure 6.3** and **6.4** respectively show sediment yields for selected subcatchments and sediment yields generated under different land uses, again choosing Subcatchment 6 which displays a range of land uses.

The mean annual simulated sediment yield for the 40 *ACRU* subcatchments ranged from 0.59 to 96 $t.ha^{-1}$. The highest (greater than 50 $t.ha^{-1}$) values of sediment yields were simulated in SC32 in the northeastern part of the catchment (cf. **Figure 6.2**). This subcatchment has the highest average slope, at 16%, and is occupied by rural communities with more than 20% of the land under subsistence agriculture and the remainder being grazed and browsed bushlands and forests. Other high sediment yields were simulated in the upper-middle parts of the catchment (e.g. SC7). This region also is predominantly rural with subsistence agriculture being the main farming activity, while all the unimproved grasslands (which cover more than 70% of the land) is used as communal pastures (cf. **Figure 3.8**). During fieldwork, lands with relatively steep slopes were found to be cultivated. Bare patches of land, badlands (gullies) and livestock and human pathways, which are sources of sediments, were also observed in the rangelands, as shown in photograph series making up in **Figure 6.1** taken during fieldwork.

Moderate to high sediment yields were generated in the subcatchments with MAP greater than 1000mm in the higher altitude areas (e.g. SC1). Subcatchments such as SC24 in the middle and lower-middle sections exhibit the lowest mean annual simulated sediment yields, with values less than 2.5 $t.ha^{-1}$.

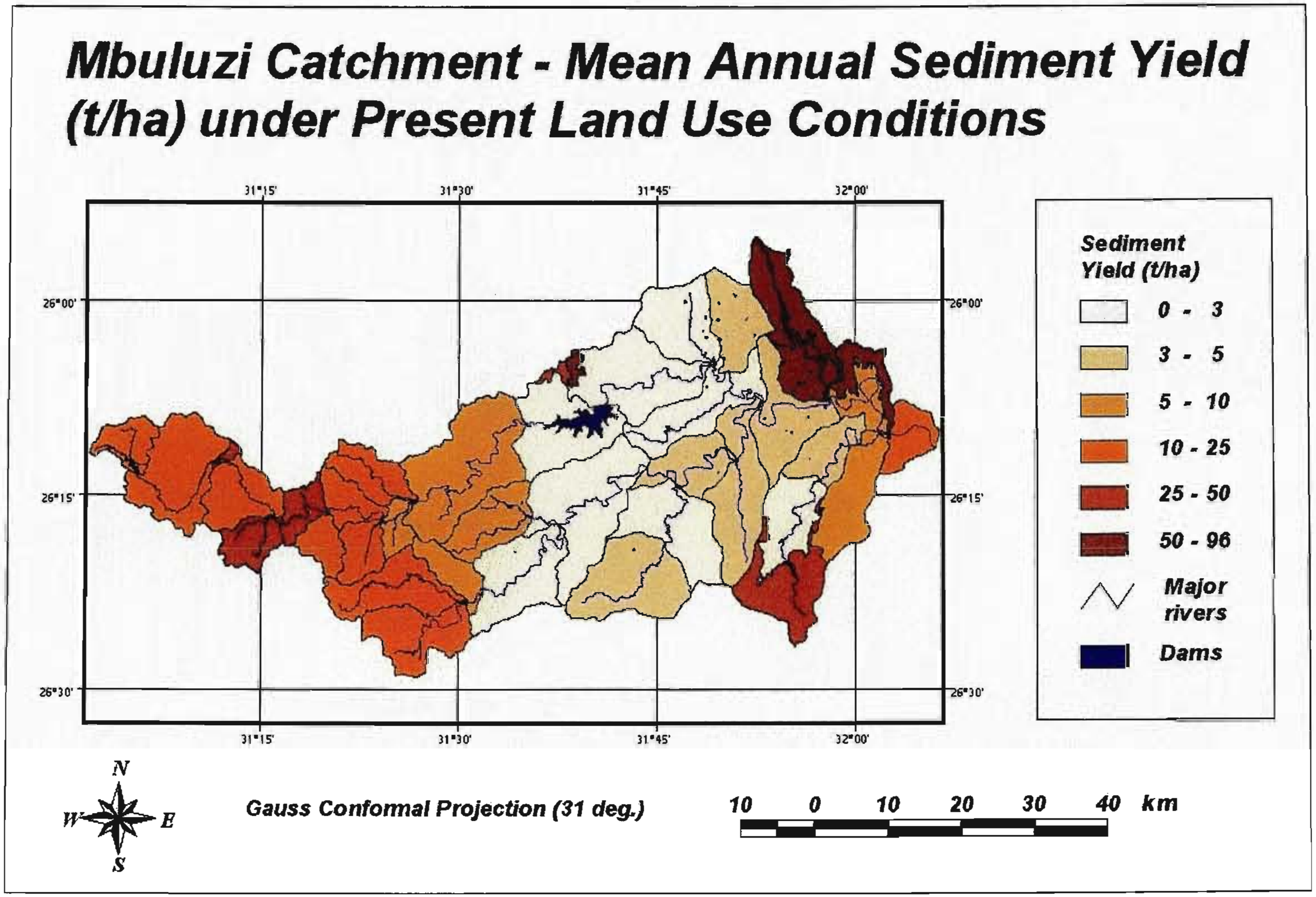


Figure 6.2 Mean annual sediment yield (t.ha^{-1}) under present land use conditions in the Mbuluzi catchment

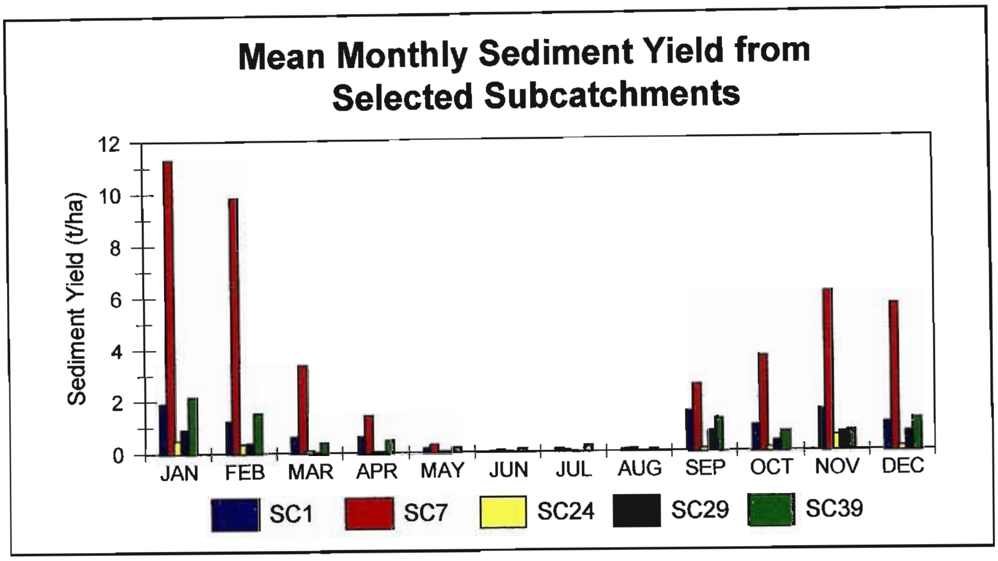


Figure 6.3 Mean monthly sediment yield from selected subcatchments

These subcatchments have low average slopes (cf. **Figure 3.4**) of less than 4% and the land use is mainly well managed privately-owned and government-owned demonstration cattle ranches. Moderately low mean annual sediment yields between 2.5 and 5 $t.ha^{-1}$ were simulated in the subcatchments with large-scale irrigated sugarcane estates (e.g. SC29). Besides these areas having low slopes, the land is covered by good crop canopy for most part of the year, especially during the rainy season (**Table 4.7**).

A comparison of sediment yields simulated under different land uses (**Figure 6.4**) indicates that subsistence agriculture and rangelands, i.e. grasslands in poor hydrological condition, produce the highest and second highest sediment yields respectively, while land under forest and rehabilitated grasslands generate the least sediment yields. The sediments yields under subsistence agriculture are highest in November, which is the ploughing and planting month for maize (staple food for rural Swazis), when the soil is exposed. Of note is that sediment yields simulated in the grassland in poor hydrological condition are higher than those of subsistence agriculture between February and March. This is a consequence of the mature stage maize has reached then, plus the improvement in ground cover following the growth of weeds, coinciding with the continued grazing and degradation of the grasslands.

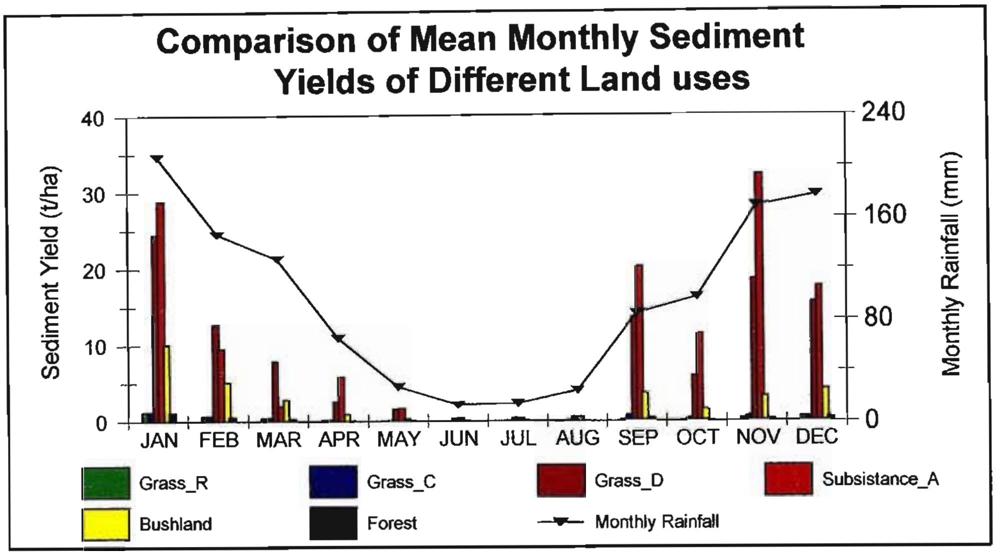


Figure 6.4 Sediment yields from different land uses in Subcatchment 6. (Grass_R - grasseld in good conditions; Grass_C - current grassveld conditions; Grass_D - grassveld in poor conditions)

It is common practice in the rural areas to allow livestock to freely roam the maize fields after harvesting between April and the beginning of planting period, leaving rangelands to recover. Hence the higher sediment yields under the subsistence agriculture over that period.

Figure 6.5 shows that a strong relationship between rainfall and sediment yield generally exists. Years of high sediment yields generally correspond with wet years, while the converse is also true (**Figure 6.5**). This relationship is not described well by one linear equation, however. All the points may nevertheless be enveloped between two straight lines (**Figure 6.6**). Not all wet years show corresponding high sediment yields, e.g. 1990/1. During that hydrological year, Subcatchment 6 received 1614 mm of rainfall, an amount that is comparable to the 1659 mm which was received 1983/4, while the sediment yield simulated for 1990/1 is only 63% of the amount simulated for 1983/4 (**Figure 6.5**). Closer scrutiny of the sediment generating events in **Figure 6.7**, on a daily basis, shows that most of the sediments in 1990/1 came from several storm events spread across the summer season. On the other hand, 70% of the 1983/4's yield was derived from a single storm event on January 29. This observation indicates that in any one catchment, one value of annual rainfall may result in different

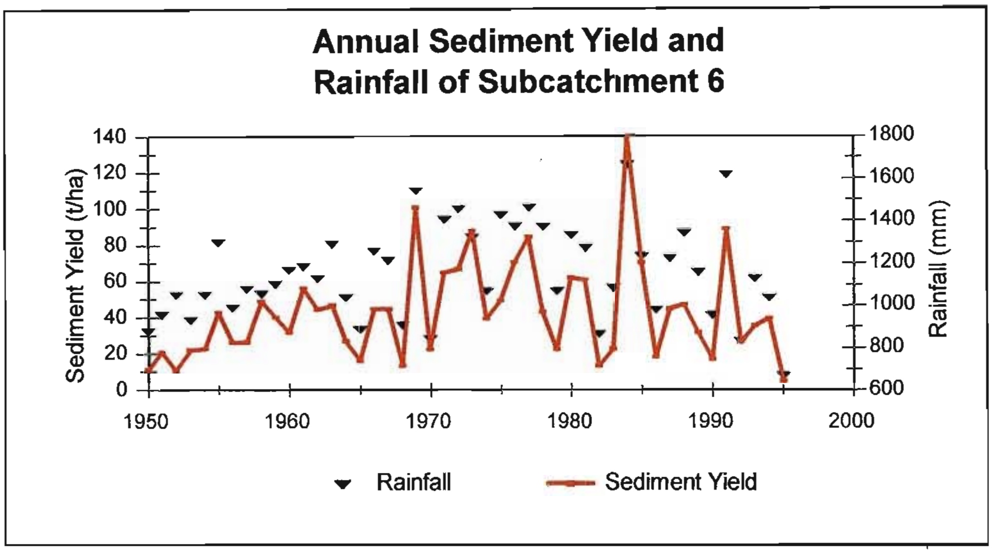


Figure 6.5 Time series of annual sediment yield and rainfall in Subcatchment 6

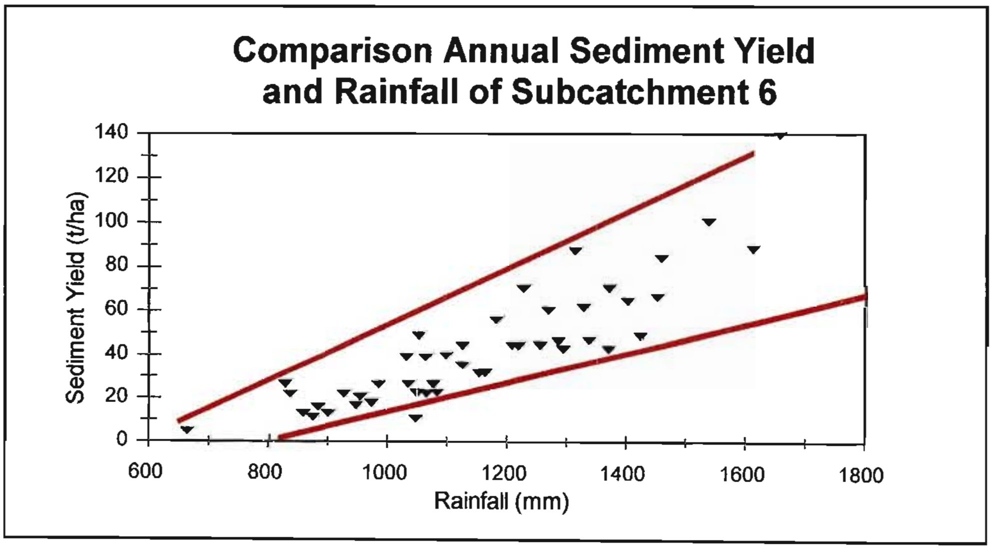


Figure 6.6 Plot of annual sediment yield vs annual rainfall of Subcatchment 6

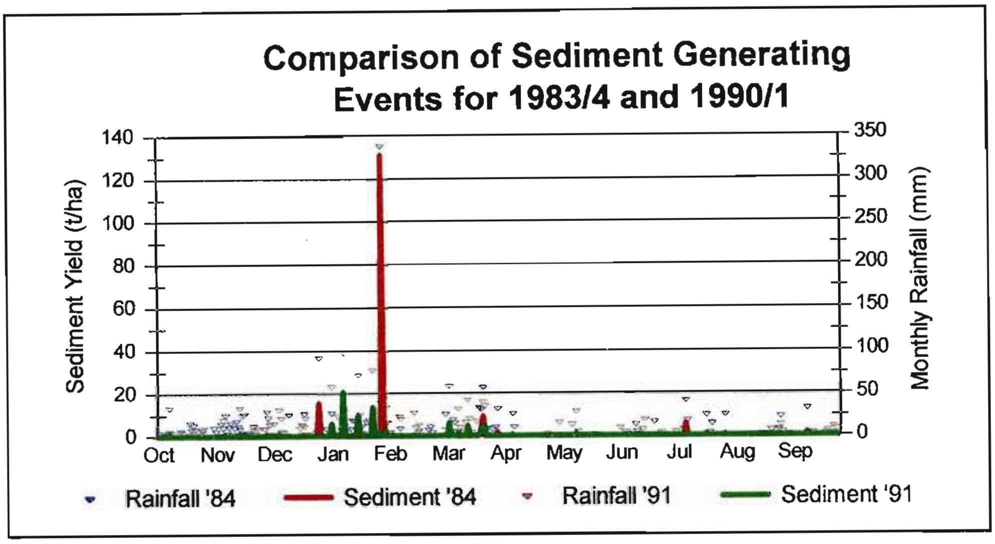


Figure 6.7 Comparison of sediment generating events in Subcatchment 6 for the hydrological years 1983/4 and 1990/1

sediment yields in different years, depending on the magnitude of the individual storm events that contribute to the annual rainfall and antecedent catchment conditions, even if all the other catchment characteristics remain the same.

On an intra-annual basis, the highest sediment yields are simulated between September and March, which is the wet summer season, while negligibly low yields are generated during the dry winter months of June, July and August, irrespective of the land use. An interesting observation is made when studying the amount of sediment generated per unit (i.e. 1 mm) of rainfall, as shown in **Figure 6.8**. The highest amount of sediments detached by a single millimetre of rainfall occurs in September. This does not correspond with either of the wettest months, which are January and December, nor with periods of high antecedent soil moisture. This is hypothesised to be evidence of the "first-flush effect", a phenomenon that *ACRU*-MUSLE can simulate, whereby the first storms of the season find the soil surface dry. Additionally, cover may be sparse, especially under vegetation types that have undergone senescence during the dry season.

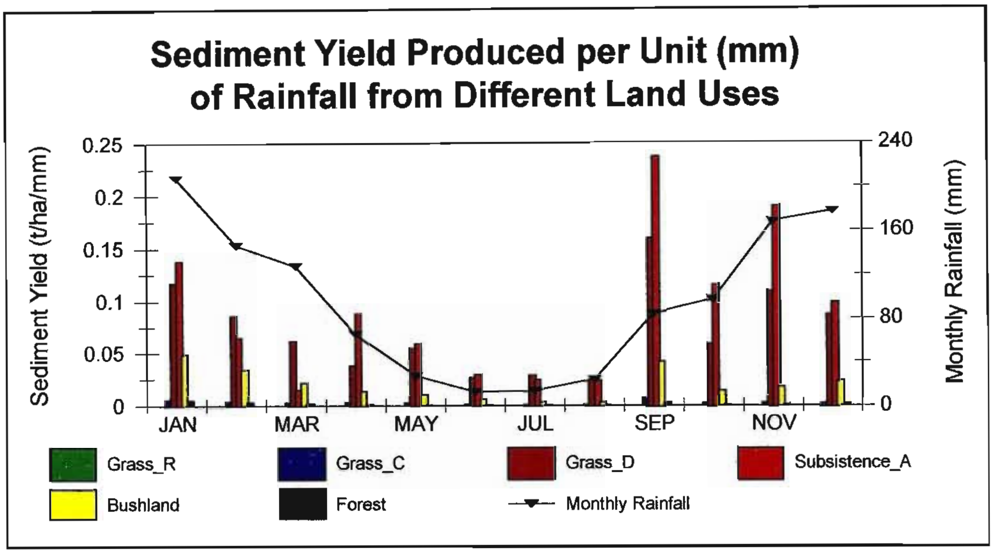


Figure 6.8 Sediment yield produced per unit (mm) of rainfall from different land uses in Subcatchment 6. (Grass_R - grassveld in good conditions; Grass_C - current grassveld conditions; Grass_D - grassveld in poor conditions)

This is pronounced in grazed grasslands and land under subsistence agriculture (cf. **Table 4.7**). Another occurrence that stands out is the increase again of the values in November after a decrease in October. In the cultivated land, this could be a result of the effect of larger storms finding land bare after ploughing.

6.6 Modelling Scenarios for Assessing the Effects of Land Use Changes on Sediment Yields

One objective of this study was to assess the effects of land use change on sediment yields. The following "what-if" scenarios were developed and their resultant sediment yields were analysed in relation to yields generated under present land use conditions:

Scenario A: *Worst case scenario*, where the present land covers and uses were replaced with a grassland in very poor hydrological condition (i.e. < 25% canopy cover with < 20% mulch) to represent land that is badly degraded as a result of deforestation and overgrazing, and

Scenario B: *Best case scenario*, where all present land covers and uses were substituted with a grassland in good hydrological condition (i.e. grassland with average drop height of 0.5 m, canopy cover > 75% and > 50% mulch cover).

For each of the above scenarios, peak discharge and sediment yield-related *ACRU* model variables were adjusted accordingly before performing separate simulations. The variables that were modified are:

a) monthly water use coefficients (cf. **Table 4.7**),
b) monthly interception values in mm per rainday (cf. **Table 4.7**),
c) fraction of active root system in the topsoil horizon (month-by-month) (cf. **Table 4.7**),
d) coefficient of initial abstractions (month-by-month) (cf. **Table 4.7**),
e) runoff curve numbers (Smithers and Schulze, 1995),
f) cover factors (month-by-month) (cf. **Table 6.2**), and
g) practice support factors (cf. **Table 6.3**).

Results of these simulations are presented as maps in **Figures 6.9** to **6.12**, showing differences between sediment yields under current land use conditions and those simulated under both degraded and rehabilitated scenarios for each of the 40 subcatchments. Substituting those areas of the present land cover on which grazing can take place and use with grass cover in poor hydrological conditions resulted in the increases of simulated sediment yields in all the subcatchments. The mean annual sediment yields increased by between 3 and more than 355 $t.ha^{-1}annum^{-1}$ **(Figures 6.9)**. In relative terms, the increments vary between twice and more than 20 times the current sediment yields **(Figures 6.10)**. The highest increases correspond with those subcatchments that are generating moderate to high sediment yields at present, while the subcatchments with low yields show smaller changes. This observation could imply that most of the areas currently generating high sediment yield may not yet have reached maximum sediment production capacity, i.e. soil loss potential. These are the areas where conservation and remediation efforts should be focussed, in order to minimise already occurring land degradation and avert the deterioration of the current situation.

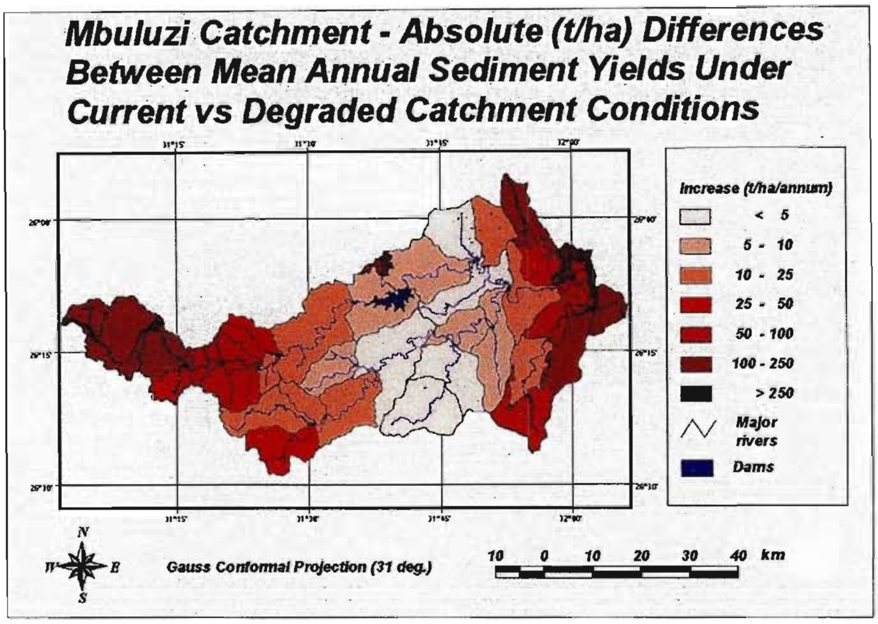


Figure 6.9 Absolute (t.ha^{-1}) differences between simulated mean annual sediment yield under current vs degraded conditions

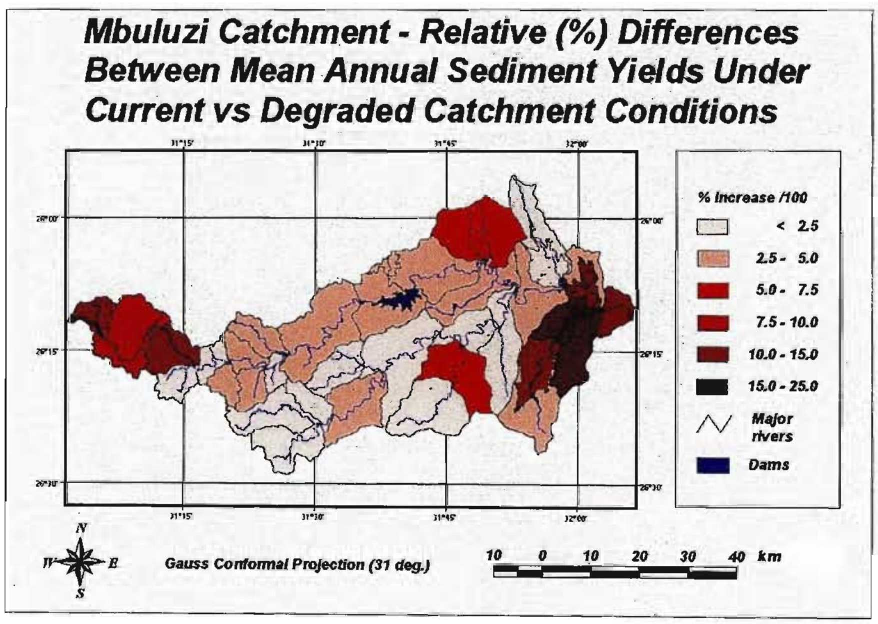


Figure 6.10 Relative (percentage) differences between simulated mean annual sediment yield under current vs degraded conditions

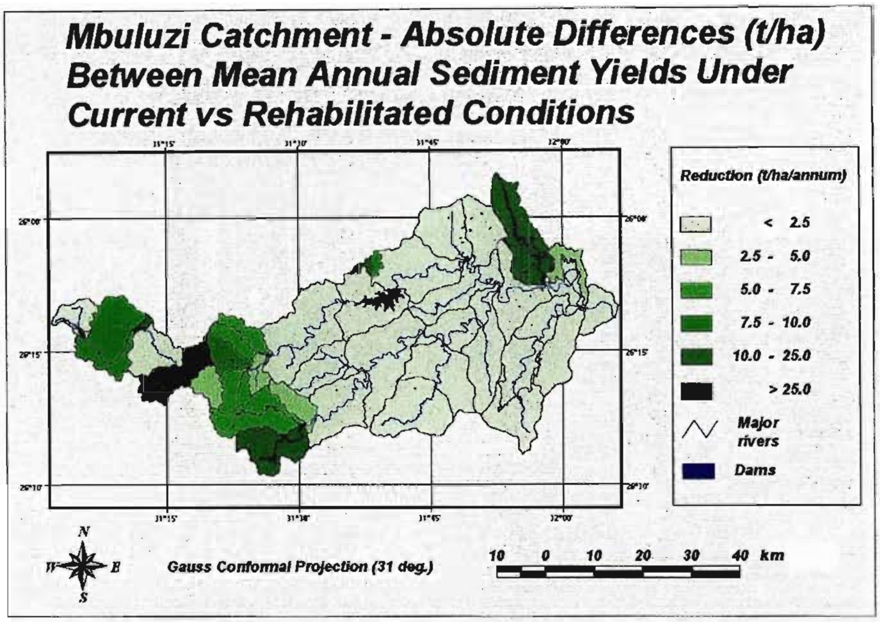


Figure 6.11 Absolute ($t.ha^{-1}$) differences between simulated mean annual sediment yield under current vs rehabilitated conditions

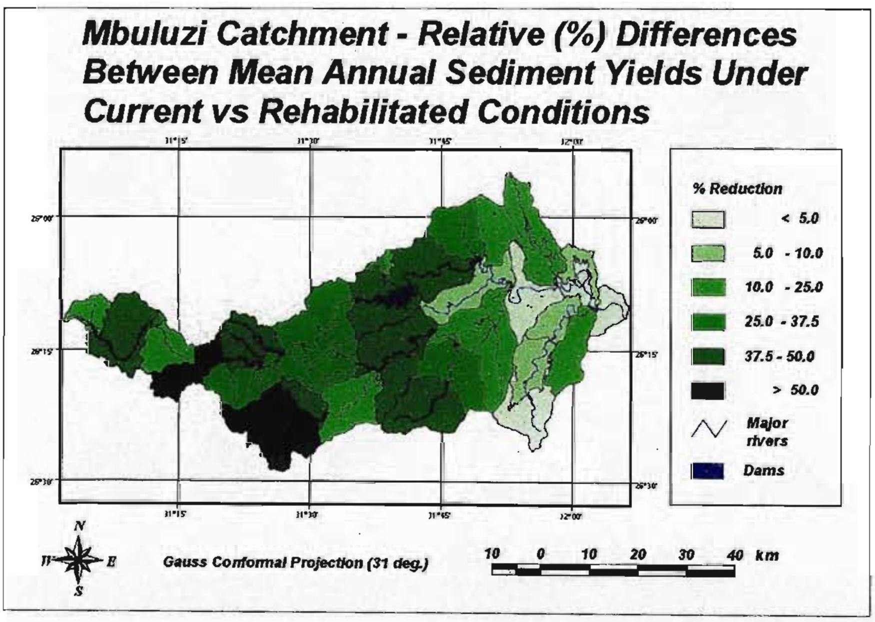


Figure 6.12 Relative (percentage) differences between simulated mean annual sediment yield under current vs rehabilitated conditions

The mean annual sediment yields were reduced in all the subcatchments after replacing those areas of the present land cover which can be grazed with a grass cover in good hydrological condition. High reductions ranging from 5 to more than 25 $t.ha^{-1}.annum^{-1}$ are found in subcatchments in the upper-middle and upper sections of the catchment. Again, these are the subcatchments that are presently producing high sediment yields. The middle region has low annual reductions of less than 2.5 $t.ha^{-1}$ (**Figures 6.11**). There are some relatively high percentage reductions (ranging from 37.5 to more than 50%) in certain subcatchments, however (**Figures 6.12**). This may be explained by the fact that the present sediment yields are low, hence an insignificant change in absolute terms will become significant in relative terms. Considering that the same subcatchments showed minimal increments of sediment yields in the degraded scenario, it may be assumed that this region is relatively stable and not a high risk one in terms of the severity soil erosion.

6.7 Conclusions

Soil erosion and large sediment loads in the Mbuluzi catchment is a serious concern to some of the stakeholders, especially to the large scale irrigaters who draw water from the Mnjoli Dam. In this Chapter, the spatial distribution of major sediment generating areas as well as land uses susceptible to high sediment yields were presented. High sediments yields were simulated in lands under subsistence agriculture and communal grazing, most of which are upstream of the Mnjoli Dam. An assessment of the potential effects of allowing the catchment land cover to be further degraded indicates that sediment yields would increase in all parts of the catchment, even those that are generating relatively less sediments currently, while employing soil conservation and land rehabilitation measures can reduce soil loss significantly. Other findings presented here and preceding Chapters are discussed in detail in the context of IWRM in Chapter 7 below.

7. DISCUSSION AND CONCLUSIONS IN THE LIGHT OF INTEGRATED WATER RESOURCES MANAGEMENT

The assessment of the spatial variation of water demand as well as runoff and sediment generating areas reveal both scientifically interesting and hydrologically important patterns. The highest water demand is for the sugarcane irrigation and processing industry which is located in the drier areas at lower altitudes of the catchment, while the upper, higher altitude areas with lower water demands, do not only generate most of the catchment runoff, but most of the sediments as well. A large portion of the water requirements of the sugar industry is abstracted from the Mnjoli Dam, which is downstream of the rural communities which practise subsistence agriculture and communal grazing, both of which were found in this study to produce high sediment yields. Although it was not established explicitly in this study, besides environmental degradation at source areas, the sediments may have serious negative implications on the well developed water resources downstream, especially at the Mnjoli Dam, including the economic activities dependent on the dam.

It is ironic that besides market forces, the important and powerful sugar industry is also threatened by aftermaths of hydrologically related problems originating within rural communities, which may be considered economically poor and politically powerless. At first, it may seem that a solution would be to engage the rural communities in soil conservation practices, or advise them to reduce livestock numbers. However, an interplay of physical and socio-economic factors could limit the effectiveness of, or lead to resistance to, such prescribed remedies.

Livestock has many traditional and functional uses as well as prestige-related values. Hence the perception is often that the larger the livestock numbers the better. Large numbers may be kept as security against loss due to disease, theft and drought. Levin (1987) cited by Mushala (1997) and Mushala (2000) observe that overgrazing in Swaziland is related to issues of land tenure. In almost all cases, rural communities are in Swazi Nation Land (SNL). This implies that the families do not own "their land" and thus may not feel obliged to take good care for it. The same argument may be valid in the communal grazing areas, where no one is charged with the responsibility of keeping them in good grazing, and thus hydrological, condition.

In Swazi custom, when a young man starts a family, he moves out of his father's home, asks for land from the chief and constructs his home. With the rapid population growth against finite land, encroachment into marginal and sensitive ecosystems becomes inevitable. This could be the reason for the cultivation of steep slopes, which was observed during extensive fieldwork. Even though some soil conservation measures such as grass strips were in place, there are slope steepness thresholds beyond which their effectiveness is limited.

The problem of soil erosion in the Mbuluzi catchment exemplifies a situation where integrated catchment management is called for. It begins at a local scale, extends to water resources at catchment scale and has far-reaching impacts on economic issues at national level. Mushala (2000) recommends that the management of the catchment should be based on an integrated approach. The adoption and implementation of IWRM appears to be an appropriate approach towards reaching the goal of sustainable development, utilisation and management of catchment resources. The problem of implementing the integrated approaches is put in perspective by Mitchell and Hollick (1993), who equate the ambiguity of the integrated management concept to that of sustainable development which most people can intuitively relate to, but which is difficult to translate into operational terms. It is for reasons such as lack of understanding of the concepts, as well as suitable legal instruments and organisational structures, that only a few cases of the success of IWRM have been documented, and those mostly in the developed world. Even there, the success up to now has been limited mainly to adoption of the IWRM concept rather than its implementation (Heathcote, 1998). Therefore, the first step towards implementation of IWRM is to promote its understanding by explaining the important underlying principles to individuals and groups responsible for ensuring sustainable development and utilization, for example, to lawmakers and water resources managers. This should be done with the view to identifying obstacles to the successful implementation of IWRM, which was part of this study.

The fundamental principle of IWRM is the recognition of the fact that water is an integral part of a complex system comprising of the physical and human components of the environment, which are themselves characterised by intricate linkages and interdependences. The IWRM approach recommends that management of water resources be backed by an understanding of the nature and behaviour of the environment and its sub-systems, forms and extents of the system responses to natural and anthropogenic disturbances and how they eventually affect the availability, status and distribution of water resources.

In IWRM the catchment is favoured as an appropriate management unit (cf. Chapter 2). Catchments are clearly bounded, hydrologically logical and simplify water budgeting. However, one critical issue that needs attention and clarification is that if the desired IWRM is to be adopted, there is a need to change from the presently used administrative and political to more hydrological boundaries. The feasibility, merits and limitations of re-drawing administrative and political boundaries should be assessed.

Of the same magnitude in importance as the technical, or physical, aspect of water resource is the understanding of human systems in water management. From the human perspective, a change in way of life, sacrifices and compromises are the costs that have to be incurred by affected communities so that the goal of sustainable development and management of water resources can be met (Mitchell and Hollick, 1993). The resistance, or willingness, of the affected people to change is a function of the prevailing socio-political and economic climate. No matter how ideal, suitable or necessary an innovation is, if it is unpopular with people in influential positions, is in conflict with cultural, historical or religious beliefs or is economically unfeasible, it is not likely to be implemented. This point is well illustrated by the soil erosion problem in Swaziland. Despite the straightforward nature of the often suggested methods of curbing excessive soil erosion and of rehabilitating affected land, they are either not implemented or implemented, but not followed up and maintained for any of several reasons. Decisions to engage in land conservation and rehabilitation often came top down from the government, and the communities expect the government to be responsible for maintenance. Such expectation would not always be an indication of a protest, but simply because the communities can not afford it. Reducing livestock numbers and stopping occupation of marginal ecosystems may be viewed by communities as compromising their primary effort of ensuring livelihood. If affordable alternatives of making a living with governmental support instead of promises are not provided, controlling soil erosion will remain a futile exercise.

Participation of stakeholders in decision making is of paramount importance in IWRM. Decisions should only be made after all necessary information on issues underpinning the availability of water resources has been provided. This allows decision makers (including stakeholders) to understand the system, thus fostering informed negotiations. In that way, skeptics of IWRM are reassured and the resistance associated with imposed decisions is reduced, thereby enhancing the possibility of reaching compromises. Stakeholder-water manager meetings provide a platform for identification of potential conflicts and a means for dealing with them up-front. The passing of the new water bill in Swaziland into a law has suffered some delays. It is interesting and forgivable that the delays have been to a large extent a result of extensive stakeholder consultation. This is of critical importance considering that the bill contains some of the somewhat controversial issues associated with contemporary water management, such as demand management, water pricing and elimination of water ownership on riparian grounds. Engaging all stakeholders may have delayed passing the bill, but it has the long term benefit of ensuring broad acceptance once consensus has been achieved.

Broad participation by itself is not sufficient, but the ultimate goal is to engage in informed negotiation towards an uncoerced compromise of ideas. Understanding water resources related issues and a multilateral flow of information among scientists and stakeholders of different backgrounds is essential if participation has to be informed and effective, rather than merely being "a stamp of approval". Establishing this communication is a daunting task which requires appropriate means and decision support tools, of which only a few exist and their efficacy has not been established yet. Because of the diversity of cultures among developing countries, the tools should be tested and modified, or new ones should be developed if possible, to suit the needs of individual countries.

Hydrological models and decision support systems are integral parts of, and will continue to have a pivotal role in, water resources management. With water management being more and more integrated, so should be its tools. This presents model developers with new challenges, in addition to those associated with trying to model an already complex system, not yet fully understood, across different spatial and temporal scales. While proper representation of physical processes, excellent reproduction of observed streamflows, availability of suitable input data, suitably qualified personnel to operate a model and affordability of the costs of running it in terms of time and money remain crucial, a model's potential to be linked with other models (e.g. economic or ecological), together with its ability to address "what if scenarios" have become other key issues in model development for IWRM. The *ACRU* model, which was used in this study for both water demand evaluation and assessment of impacts of land use changes on hydrological responses and sediment yield, has a modular structure which makes it suitable as a modelling tool for integrated water resources management. Its ability to run "what if scenarios" was utilised in this study.

At this stage (first half of 2001), one major weakness is that *ACRU* does not have a sediment routing and deposition routine, which would be useful in assessing deposition rates in reservoirs. The reservoir yield module requires improvement regarding legal and environmental flow releases. In its present public version, only one flow release value is specified and this value is kept constant throughout the year. This issue is, however, currently being addressed in a research project (Butler, 2001). The irrigation module should be rendered more flexible when specifying a source of water in irrigation scheduling mode, when the *loopback* option is activated, as was the case in this study. Irrigation water is only abstracted from the stream until the requirement cannot anymore be met before drawing from an upstream dam located in other subcatchments, even if water is conveyed from the dam through canals into balancing dams in the subcatchment with irrigation. This implies that in the model the streams will dry out more frequently than they actually do in reality. The level of integration of the model at this stage is only between components of the physical system, i.e. the water and land use. It has not yet been linked to economic, ecological or demographic models, although, again, all these linkages are under research currently (Pott and Creemers, 2001). A new Java-coded, object oriented version of *ACRU*, *viz.* *ACRU*2000 (Lynch and Kiker, 2001), at this stage (first half of 2001) is still being coded and tested. It will offer easier means of linking with new modules. Campbell *et al.* (2001) describe a water quality module to simulate phosphate and nitrate loads in streamflow. This will address a major weakness regarding water quality simulation, thus improving the potential and suitability of the *ACRU* modelling system as a tool for IWRM.

Ahead of the promulgation of the new water law which will promote IWRM, the Water Resources Branch of Swaziland is upgrading its data capture, manipulation and storage systems to meet the information demands of IWRM. It should be borne in mind that all the relevant information for water management, ranging from climatic and hydrological data to population census information, should itself be managed in an integrated manner. There should be a centre which houses most of the data in easily accessible databases and in standard formats which could be easily converted to and from other widely used formats. An allowance should be made for the establishment of networks to connect remote licenced or accredited users to access it directly, and be able to contribute their data for sharing and storage. To recover the costs of setting up and maintaining the system,one suggestion is that profit making users of the data such as consulting firms should buy rights to use it. Use of data for non-profit making purposes such as academic research should not be subject to tariffs.

Integrated water management plans should make provisions for international communications and cooperation where water systems are shared by more than one country. Measures devised from broad consultative and transparent processes must be put in place to ensure equitable sharing of water resources, thereby providing means of effectively minimising and managing potential conflicts. Development of water resources projects in shared rivers should be undertaken jointly by the riparian states. In this study, it was established that an agreement exists between Swaziland and Mozambique in regard to sharing the waters of the Mbuluzi river. There is a general feeling that the water resources of the Mbuluzi river have been over-allocated in Swaziland, a sentiment also expressed by Matola (1999). Assuming that all the allocations are being utilised, it was found in Chapter 5 that Swaziland still manages to release to Mozambique the amount of flow as per the agreement, although the quality of the water is not known. Protection of the environment and maintenance of biodiversity are important aspects of IWRM. It is not explicitly spelt out in the Swaziland-Mozambique agreement whether or not it covers instream flow requirements (IFRs). The issue of IFRs needs attention, concerning not only the flow releases to Mozambique, but along the entire reach of the stream, within the borders of Swaziland as well.

The current institutional system for water resources management in Swaziland presented as a the case study in Chapter 2 is a typical example of a fragmented management structure. With so many departments and organisations involved in the development and management of water resources, the likelihood of duplication of responsibilities becomes inevitable. This is one problem in water management in Swaziland that is blamed for over-allocation of water resources, a factor which was exposed during the 1992-94 drought. There is a need to bring water management under one umbrella body in which all the water sectors will be represented. Even though a first step has been taken by drafting the new Water Act, it still appears as though too many bodies are retained. The potential for overlap of responsibility could still exist. The number of bodies should be reduced and their responsibilities be clearly defined. The trimmer and more practical structure proposed by Knight Piesold Consulting Engineers (1997), as shown on **Figure 2.5,** should be considered for Swaziland.

The proposed structure appears to be feasible and in line with the requirements of an integrated form of water management. However, as in most developing countries, the Water Resources Branch in Swaziland is plagued by lack of sufficient funding as well as the few adequately trained and experienced staff leaving for 'greener pastures', which could be limiting factor to the adoption and implemention of the IWRM, even if the political will and enabling legal framework are present. Developed countries, together with international funding agencies, should provide funding and technical assistance to the developing countries. The assistance should be directed towards capacity building and training of local expertise in water resources management. Effort should be also be placed in educating stakeholders, especially rural and indigenous communities about important considerations in water resources management in order to foster informed negotiations in stakeholder forums. The developing countries themselves should demonstrate willingness to change to good water resources management by, for example, establishing suitable institutional structures, putting proper legal tools in place and committing to improving and maintaining the technical aspect of water resources management.

This study has shown that implementing IWRM poses challenges even to the so-called developed countries, mainly because of the difficulties associated with incorporating social issues into water management, a discipline previously dominated technocratic thinking. With added limitations of lack of funds and capacity, as well as complications resulting from complex cultures and traditions, putting IWRM into practice in developing countries will almost be impossible without external support. Irrespective of the difficulties, IWRM nevertheless remains the best approach towards sound and effective management of water resources. Hence, no effort should be spared in trying to make it work.

8. RECOMMENDATIONS FOR FUTURE CONSIDERATION AND RESEARCH

The major objective of this study was to review the principles of IWRM and their applicability in a developing country, *viz.* Swaziland. A study of water resources management and results of modelling the Mbuluzi catchment were used to illustrate some problems facing developing countries in regard to adopting and implementing IWRM. In-depth discussions and conclusions have been presented in Chapter 7. The following are recommendations for future consideration and research emanating from this study:

a) Communication between scientists and non-scientist decision makers was found to be critical for the success of IWRM. Suitable tools to foster that communication are few and their efficacy has not been established yet, especially in developing countries. Research is necessary to provide information for testing the existing tools, or to develop new ones, to enable easier knowledge flow between role players of different backgrounds.

b) Rural areas were found to be prone to soil erosion because of the land uses practised there, such as subsistence agriculture and communal grazing. Owing to the deep entrenchment of a livestock oriented culture in socio-economic issues, it is necessary to ascertain the rural farmers' perceptions of the problem this causes in terms of soil erosion and what solutions they would suggest.

c) Sugarcane irrigation is by far the largest water use in the catchment. It would be essential to investigate the water use efficiency of this activity to establish whether or not other irrigation methods, schedules and farm practices can lead to reduced water use for comparable yields, thus freeing water to other uses.

d) Unavailability of complete and sufficiently long observed model input data (climatological and hydrological) made the modelling exercise arduous. Maintenance of, and supplementing, the recording networks and regularly updating records would make acquisition and generation of information necessary for sound water resources management less time consuming and more reliable.

e) The *ACRU* model was found to be a hydrological model with a great potential in generating information for decision making in IWRM. However, equipping it with sediment routing and deposition algorithms, as well as routines to account more explicitly for dam operating rules and ecological issues will make its output even more useful to water managers.

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