MODELLING STREAMFLOW AND SEDIMENT YIELD ON THE LOWER MGENI CATCHMENT

MICHAEL LUTCHMAN SINGH

Submitted in partial fulfilment of the requirements for the degree of M.Sc.

Department of Geographical and Environmental Sciences
University of Natal
Durban

2001

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

Signed:

M.L. Singh

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation for the assistance and support given by the following:

Professor G.G. Garland, Department of Geographical and Environmental Sciences, University of Natal, for his supervision of this dissertation.

Doctor S.W. Kienzle, formerly of the Department of Agricultural Engineering, University of Natal, for his co-supervision of the initial stages of this research.

Doctor S.A. Lorentz, Department of Agricultural Engineering, University of Natal, for his guidance on the application of the sediment yield component of the model.

Professor R.E. Schulze and colleagues, Department of Agricultural Engineering, University of Natal, for all the assistance rendered for the duration of this research.

The staff of the Computing Centre for Water Research, particularly Mr R Nundlall, for his assistance in data acquisition and computing.

My colleagues and friends at the Department of Water Affairs and Forestry, particularly Messers N. Adams and E. Singh, for their invaluable assistance with the figures and layout. Mr D Naidoo, my director, for creating a positive and enabling environment.

The Foundation of Research Development and University of Natal, for financial assistance in conducting this research.

To all my friends, both old and new, for your support and love.

To my family, Polly, Pushpa, Krishnee, Jugu, for their continued love, support and faith.

Veena Naidoo, for editing this dissertation, her efforts and dedication that made completing this dissertation possible. More importantly for being my comrade in and for Life.

Nalin Prashant, for being a source of love and joy; and, inspiration and knowledge.

ABSTRACT

This study involves the application of the *ACRU* Agrohydrological Model to a selected study catchment in the Lower Mgeni Catchment, and its discretized subcatchments, immediately downstream of the Inanda Dam. This study was initiated on the assumption that the Inanda Dam, which came into operation in 1989, would have significant impacts on the downstream (Lower Mgeni) hydrology, geomorphology and ecology. The overall aim of this study, to set up and run the *ACRU* model for the delimited study catchment, was successfully accomplished. This aspect of the study involved firstly, the setting up of an input database for each distributed catchment within the catchment; secondly, the processes and techniques used to translate data into hydrological information; and finally the "running" of the hydrological model, which in turn "drives" the system and simulates the catchment hydrology. Specific objectives of the study entailed the simulation of hydrology, which focussed on simulated runoff and streamflow; and sediment yield responses of the subcatchments and the total study catchment of the Lower Mgeni, with respect to gross volumes and sediment yield rates produced. The streamflow results reported indicated a season of "low" flow, with a monthly flowrate ranging fom1155m^3s^{-1} to 2735m^3s^{-1}, from April to September; and is identified and distinguished from the period of "high" flowrate, ranging from approximately 483m^3s^{-1} to 1747m^3s^{-1}, for the remaining months of the year. The mean annual volume for the delimited subcatchment is 22 278.5 million m^3, exceeding the annual volume required to maintain riverine and estuarine ecology, which according to DWAF (1990) is 18.5 million m^3. The simulated results of sediment yield indicate that Subcatchment 3 and 4 have the lowest sediment yield rates of 32.3 t km^{-2} a^{-1} and 32.6 t km^{-2} a^{-1}, respectively. Subcatchment 2 has the highest yield rate at the value of 617 t km^{-2} a^{-1}, while subcatchment 1 has a rate of 53.2 t km^{-2} a^{-1}. Annual sediment production in the Lower Mgeni subcatchment is 10 855.1 tons per annum with respect to gross mass, resulting in a sediment yield rate of 73.8 t km^{-2} a^{-1}. The outcomes of this study compare very favourably with other studies conducted on hydrology and sediment yield, especially those undertaken within this geographical area. It may be assumed therefore, that the results produced herein can be applied with confidence to enable appropriate planning and management of resources within this catchment. Modelling of hydrology in the Lower Mgeni is expected to contribute significantly towards meeting riverine and estuarine ecological and geomorphological streamflow requirements. It would facilitate the development of an appropriate management and dam release strategy of Inanda Dam, in order to meet these requirements. The modelling of sediment yield is expected to contribute to the development of a

sustainable sandwinning policy and strategy for the Lower Mgeni, as current extraction rates exceed the annual sediment production. Once the model has been applied to a selected catchment, it has the ability to consider different scenarios, providing an invaluable tool for planning. Based on the results of this study, the *ACRU* model may be applied, with confidence, to other similar ungauged catchments.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The Lower Mgeni catchment, in the immediate downstream vicinity of the Inanda dam (Figure 1.1), is situated in rural Kwazulu-Natal, in the Valley of a Thousand Hills. This predominantly rural/peri-urban environment is located in the area bordered by the former formal Black townships of KwaMashu and Ntuzuma; the informal Inanda settlement to the northeast and the former white urban corridor towns of Pinetown, Kloof and Drummond to the southwest. It falls within the Durban Metro area. The Lower Mgeni catchment forms part of the 4353 km^2 Mgeni catchment. The Mgeni catchment is the primary source of water supply for the Pietermaritzburg Metropolitan Region and the Durban Metro. Considering future growth for this area, the Water Plan 2025 (Horne Glasson Partners, 1989) predicted an increase of population, estimated to be between 9 to 12 million by the year 2025. According to the Department of Water Affairs, DWAF, (1986) the population of the Durban-Pinetown-Pietermaritzburg area is expected to increase at a rate of 3% per year from 1.7 million in 1980 to 4.1 million in the year 2010, an increase of 141%, and that corresponding water demand will increase by 166% from 210 million m^3 per annum to 558 million m^3 per annum. Concomitant with the population growth, the anticipated rural, urban and industrial development will increase water demand to exceed presently available water resources, making effective water resource management within the Mgeni catchment vital (Tarboton and Schulze, 1992).

It was within this context that the Water Research Commission's initiated a project called the "Development of a Systems Hydrological Model to Assist with Water Quantity and Quality in the Mgeni Catchment" project, and was undertaken by the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg. This resulted in the development and application of a distributed hydrological modelling system for the Mgeni catchment (Tarboton and Schulze, 1992). As part of the project, Kienzle, Lorentz and Schulze (1997) completed a further phase titled: “Hydrology and Water Quality of the Mgeni Catchment”.

As part of that study, the subcatchments in the Mgeni catchment were initially delimited according to Pitman, Middleton and Midgley (1981), and subsequently modified in Tarboton and Schulze (1992) and Kienzle *et.al.* (1997). The hydrology of the Mgeni catchment was modelled, and the hydrological simulation was performed. The simulation of catchment hydrology, to date, does not include that part of the catchment downstream of the Inanda dam (Figure 1.1). Further modelling, which contributes towards the completion of the entire catchment, is essential for providing vital hydrological information. This is necessary for the management of water resources in the Mgeni catchment, within a framework of integrated planning and development for the area.

1.2 IMPACT OF DAM CONSTRUCTION

The Inanda dam, constructed immediately upstream of the study area, came into operation in 1989. This resulted in the separation of the lower Mgeni from the rest of the catchment. Hydrological input from the total Mgeni catchment area into the lower Mgeni is basically restricted to dam outflow and its constituents, that is,

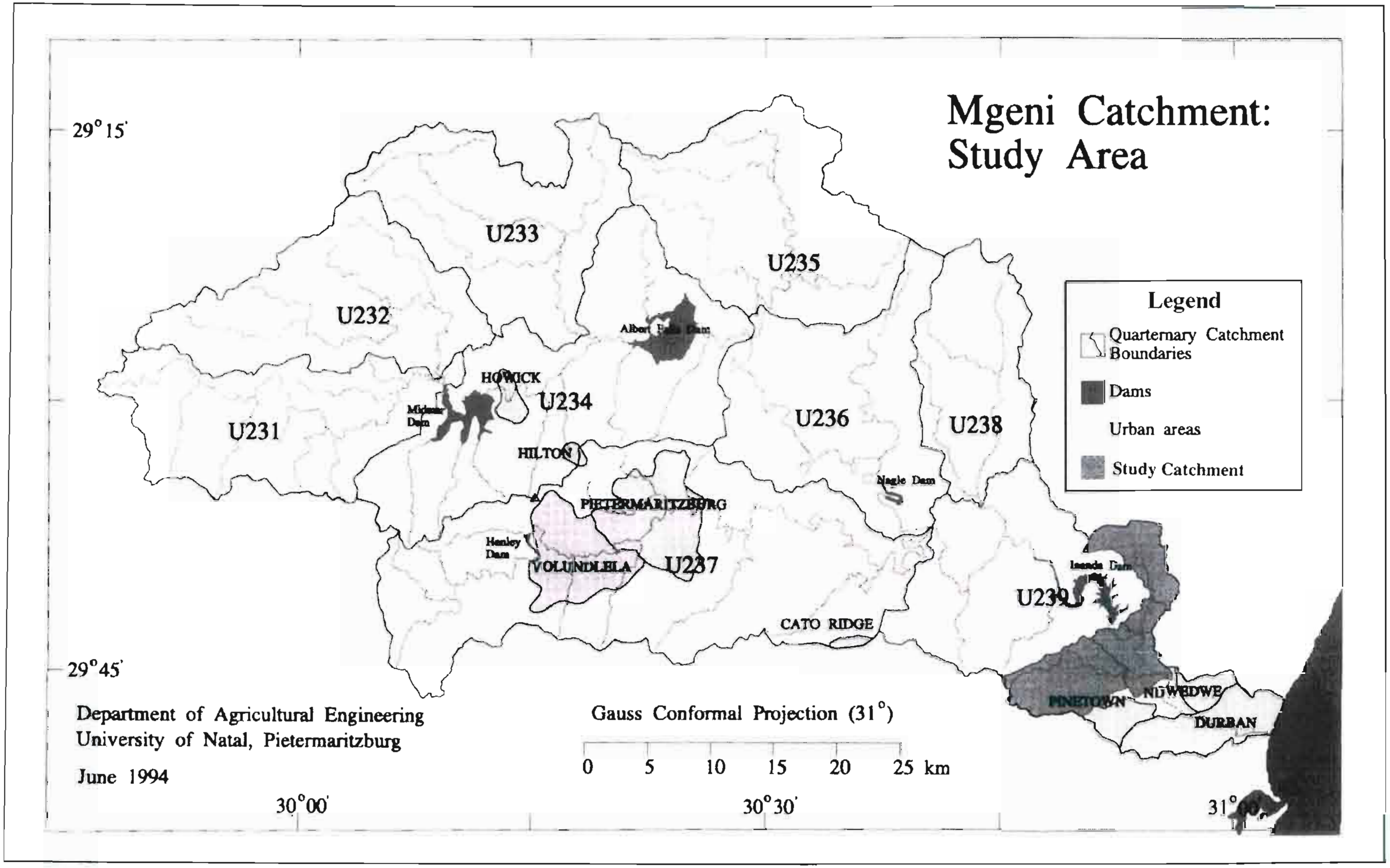


FIGURE 1.1: Location of the Lower Mgeni study catchment

the dissolved and suspended loads. As fluvial systems are among the most dynamic components of the landscape, it is expected that the construction of Inanda Dam would have, in addition to the immediate effects, a number of long-term environmental and social impacts. In a study on the Brazos river in central Texas (Allen *et.al.*,1989), it was found that the construction of large dams resulted in the following geomorphological changes:

(1) growth and stabilisation of bars upstream from the dam;
(2) reduced channel width where bars are stabilised by bedrock;
(3) growth of tributary deltas at confluences with the main river;
(4) due to tributary delta growth, bank erosion occurring opposite confluence entry points;
(5) significant loss of sediment in the river downstream of the dam after one major flood event; and
(6) significant decrease in streamflow during flood events.

The last two observations are relevant to this project, in that this study is an investigation into the volume of streamflow and sediment load in the fluvial system of the Lower Mgeni catchment. Alterations of streamflow and sediment supply are expected to have concomitant impacts on various hydrological, ecological and socio-economic processes.

In a study on the Lower Mgeni, Garland (1998), predicts the following impacts:

(1) a massive reduction in the quantity of coarse and fine sediments in the Lower Mgeni System;
(2) continued flushing of existing channel sediments down river towards the estuary, without replacement from up-stream sources;
(3) site specific channel bed erosion at times of peak water releases;
(4) approximate volume equilibrium at the main sediment sink – the estuary – until such time as sediments stored in the channel have all been flushed through the system;
(5) gradual build up of sediments near the estuary mouth until an exceptionally high discharge event capable of moving material through the opening and out to sea against tidal and coastal currents occurs;
(6) gradual fining of bedload channel and estuarine sediments, due to the retention of most coarse sediments in the system behind Inanda Dam, poor coarse sediment contributions from the main tributaries below the dam, and continued extraction of this fraction by sandwinning activities; and
(7) if the same water release policy is maintained, then a gradual reduction in fluvial sediment volume of the estuary once channel flushing is complete. In sections near the mouth this could be balanced some degree by incoming material transported by tidal and coastal currents.

According Garland (1998), based on the evidence generated from his study, and noting that the time scale for this sequence of events depends on the relaxation time of the river, stages (1) to (5) are well underway, and stage (7) could begin shortly.

Within fluvial systems, a number of different, but interacting variables influence the rates and types of processes, namely: human activity; climatic factors; geological and soil characteristics; land cover; sediment load;and movement of water in the channels. According to Dardis, Beckedahl and Stone (1988), discharge is the single most important variable, as it influences the erosion and transport of both particulate and dissolved loads. The rate of flow (discharge) is the product of a cross-sectional area of flowing water and its velocity, and it is usually expressed in terms of volume per unit time (for example, $m^3 s^{-1}$). The variables noted above do not have to act independently, but may rather act in different combinations to produce different results.

It is the tendency of fluvial systems to move towards a state of dynamic equilibrium. Taking into account the debate conducted in the Annals of the Association of American Geographers 84(4), on the definition and application of the concept of dynamic equilibrium (Thorn and Welford, 1994; Phillips and Gomez, 1994; Kennedy, 1994), a brief explanation is noted. To cite this study as an example, it is assumed that the fluvio-hydrological system and processes had operated in a specific manner prior to the construction of the dam; and this specific manner is assumed to be the "equilibrium state of the system". However, due to the construction of the dam, changes have resulted in the processes that occur within the system. According to the concept of dynamic equilibrium, in geomorphological terms, the fluvial system is expected to adjust, that is, the type and rates of processes are altered in order to compensate for the changes. Although variables may change, implying reaction, the river need not change immediately, adjustment can be delayed, with changes in some of the processes being very slow to appear. This adjustment of fluvio-geomorphological systems to "disturbances" is described as dynamic equilibrium.

According to the National Water Act 36 of 1998, Part 2: Classification of water resources and resource quality objectives, requires the determination of class and resource quality objectives of all or part of water resources considered being significant. The purpose of the resource quality objectives is to establish clear goals relating to the quality of relevant water resources. Furthermore it is noted that in determining resource quality objectives, a balance must be sought between the need to protect and sustain water resources on the one hand, and on the other hand the need to develop and use it. Part 3 of the National Water Act 36, 1998, deals with the Reserve, which is that portion of the water resources set-aside for "basic human needs and ecological functioning". In addition, the Reserve will have to take into account the resource quality objectives, as noted above. The basic human needs reserve provides for the essential needs of individuals served by the water resource in question, and includes water for drinking, food preparation and personal hygiene. The ecological reserve, relates to the water required to protect the aquatic ecosystems of the water resource. These legislative requirement places further significance on the outcomes of this study, which contributes information on the hydrology and streamflow production of the Lower Mgeni.

1.2.1 Ecological impacts

The most immediate and notable consequence of dam construction is the decrease in streamflow below the dam site. This will invariably impact on the ecology of the area. Change in the environmental regime is bound to have significant consequences, given that the catchment area and section of the river under study is located upstream from two ecologically sensitive areas, namely, the Mgeni River Park (upper section) as delimited by the Durban Metropolitan Openspace System (D'MOSS, 1989) and the Mgeni estuary which includes the Beachwood Mangroves. The section of river upstream and within the Mgeni River Park is relatively pristine, with opportunities for conservation in the Mamba valley and the valley below Annet Drive. In addition to snakes, the Mamba valley contains a large patch of well preserved Coastal Forest, still populated by the elusive blue Duiker (D'MOSS, 1989). This forms one of the wider and larger "corridors" that contributes to linking the natural areas within Durban. These corridors ensure that the genetic and species diversity of the smaller reserves is maintained by the larger areas; the "corridors" facilitate the "migration" of animal and plant species (D. Roberts, pers. comm.,1991). The change in streamflow is expected to alter existing ecosystems, with concomitant impact on the animal and plant species. Survival of floral and faunal species found in this location is dependent on specific environmental conditions, including streamflow. It is expected that these changes could have a negative impact on the role of Mgeni River Park as a "corridor", if the biota present were to have low tolerance levels to changes in the environmental regime, especially the hydrological regime. This illustrates a necessity for intensive management of the area to ensure the effective functioning of the "corridor".

Prior to determining on management strategies, it is essential to establish minimum streamflow for safe ecological functioning. The Department of Water Affairs (1990) cites a volume of 18.5 x $10^6 m^3$ of water per annum as the amount necessary to maintain riverine and estuarine ecology. Although water is released and streamflow is measured immediately downstream of Inanda dam, human priorities, not ecological needs, will determine the dam release policy and volume. This implies the need for the measurement of streamflow generated downstream of the dam to estimate the lower Mgeni's contribution to streamflow, in order to maintain the ecology. Given that the streamflow measurements are lacking, the hydrology of the catchment has to be simulated to estimate streamflow for different rainfall events and periods of time (for example, daily; weekly; monthly; annual; or seasonal). Information on the water requirements and water availability makes it possible then for appropriate management strategies to be implemented. For example, if streamflow were to fall below critical (ecological) levels, despite having considered the catchment's estimated input to streamflow, it may be supplemented by an increased dam release in order to meet the minimum in streamflow requirements. This example of an application of hydrological simulation, that is, the estimation of streamflow "generated" by the Lower Mgeni catchment, serves to illustrate the critical need for hydrological modelling. In other words, it can act as a preventative measure against ecological disasters.

Certain impacts of dam construction on the Mgeni estuary are related to the reduction of freshwater flushing, which could generate an increase in the salinity levels in the estuary. This problem will be exacerbated during times of drought when human needs take precedence over environmental concerns.

The occurrence of silt deposition in the estuary is likely to increase and can be accounted for by various contributing factors. The primary factors are: the reduction in streamflow velocity; poor farming practices and other human practices in the area between the dam and the estuary. Silt deposition has significant negative implications and, according to Preston-Whyte (1991), these include the smothering of organisms living on the estuary bottom, increased turbidity, decreasing light penetration and the development of a sandbar across the mouth of the Mgeni. With respect to the latter, the cause is more likely to be the decrease in streamflow, rather than increased siltation as suggested by Preston-Whyte (1991). This would subsequently result in the closure of the estuary, giving rise to a number of secondary impacts produced by the changing and decreasing water quality, oxygen and nutrient levels. Therefore, in the opinion of Preston-Whyte (1991), the habitat of organisms that had become adapted to tidal action would be destroyed and the mangroves (*Avicennia marina*, *Bruguiera gymnorrhiza*) damaged and eventually lost. The biology, including both the flora and fauna, is described in Begg (1978). It is further noted that the migration of many species would be influenced by the closure of the estuary; these include marine species that utilise estuaries for breeding and as nurseries, including fish species that are of food and commercial value and bird species that feed at estuaries. The Department of Water Affairs (1990) estimate a volume of 18.5 x 106 m^3 of water per annum, as the amount necessary for flushing the estuary. Once again it can be seen, as in the case for the Mgeni River Park, that it is essential to estimate streamflow so that appropriate and effective management strategies can be adopted and implemented to minimise negative impact.

1.2.2 Geomorphological impacts

The most immediate impact of dam construction is an alteration in streamflow characteristics, which is usually a reduction in the volume and velocity of streamflow (Chian,1985; Erskine,1985). The decrease in streamflow velocity reduces the capacity to transport the sediment load of the river, resulting in increased sedimentation and siltation. This resultant effect of increased sedimentation, however, is temporary as the residual sediment within that section of river is usually "lost" in major streamflow or flood events that occur after dam construction. Therefore, the long-term effect is decreased sediment availability in that section of the river below the dam. Inanda Dam also performs the function of an efficient sediment trap, capturing material that would otherwise pass through the study catchment, travelling the remaining length of the river, settling eventually in the estuary, and finally the Indian Ocean.

The construction of the dam retards sediment delivery along the river channel to the Indian Ocean in two ways. First, the dam traps the coarser fraction of the sediment load, that is, the bedload and the coarsest fraction of suspended load. Second, due to the decrease in the velocity of streamflow the efficiency of sediment transport is inhibited. This decrease in sediment delivery could possibly result in two concomitant geomorphological impacts, namely, beach erosion and/or fluvial channel erosion. These effects create the potential for further secondary impacts. In the absence of any dam construction, the Mgeni river would have contributed significant amounts of sediment to the beach deposits in the vicinity of the Mgeni mouth. The local ocean currents subsequently redistribute these sediment deposits. If there is a decrease in sediment delivery to the beach, then beach erosion may be expected. Disturbance of a "stable" beach could result in dune instability and migration (J.A.G. Cooper, pers. comm., 1993), which may negatively affect properties and other engineered structures, for example roads and bridges. Reparation of damage or construction of engineered structures to prevent damage, implies financial expenses.

The other possible geomorphological impact is related to the absence of adequate sediment in the river channel which could result in channel erosion, that is, erosion of the river banks and channel bed (Guy,1980/81; Allen *et. al.*, 1989). It is understood that most fluvial systems operate in a state of dynamic equilibrium, that is, interacting variables, including discharge and sediment load, act together to produce a particular equilibrium regime. Changes such as the diminishing availability of sediment for transport, destabilise the state of equilibrium. In this situation, there is more energy available (streamflow) than the energy required (decrease in sediment to be transported). Consequently, this manifests an excess of energy, which is dissipated by erosion within the river channel. This may result in secondary impacts, for example, damage to engineered structures. This implies that physical damage has to be repaired and measures to prevent damage have to be adopted, which in turn means incurring a financial loss.

1.2.3 Impact on Sandwinning

Potential financial loss and expense arising from the impacts of fluvial channel and beach erosion resulting from decreased sediment availability, is further exacerbated by the practice of sandwinning - a major economic activity occurring below Inanda Dam. This precipitates a number of secondary impacts, not least of which is the implication it has for the ecology (Allan, 1991). Boswell (1991) documents the existence of at least seven significant sandwinning operations between Inanda Dam and the Mgeni estuary, of which three are legal operations. Noting that the dam serves as an efficient trap for sediment, it can be reasonably assumed that the supply of sediment available for sandwinning, below the Inanda dam, will diminish. This however, is with the exception of the sediment yield generated in the catchment of the Mgeni river below Inanda dam. It is expected with the decrease of sediment availability within the fluvial channel, that is the section of river designated for sand mining, that mining could take place on the flood plains.

Mining of the floodplain may produce negative geomorphological and ecological consequences. Ecological impacts on the area and its significance are discussed in section 1.2.1. In fluvial systems, channel banks and flood plains that are permeable have the capacity for water storage. In cases of flood, water will move from the channels to the banks for storage. If the flood wave is of sufficient magnitude, water will move across and be stored on the flood plain adjacent to the channel, thereby attenuating the flood wave by reducing the flood peak and velocity of the wave (Gustard, 1992). Mining of the floodplain will reduce this capacity.

In a study on bedload sediments of the Mgeni River below Inanda Dam, by Garland (1998), the following points were noted regarding the impact of dam construction on sedimentology and sandwinning below Inanda Dam. In addition to the aforementioned predictions made by Garland (1998), based on the assumption that the total Lower Mgeni catchment produces sediment at the same rate as the catchment above the Inanda Dam, the Lower Mgeni could yield approximately 600 000 tons per annum, of which bedload constitutes between 72 000 to 119 000 tons per annum. Citing Forbes *et.al.* (1982) according to Garland (1998), in 1982 approximately 810 000 tons of material was being extracted from the Lower Mgeni. In 1997 combined extraction of sediment was reduced to approximately 253 000 tons per annum. Sustainable and a "safe yield" of sediment need to be estimated for the Lower Mgeni. This study will focus on determining the sediment yield for the study area, it will be extrapolated to the rest of the Lower Mgeni, thereby contributing to sustainable sandwinning in the Lower Mgeni.

It is generally accepted that strict regulation ought to be introduced and enforced to ensure more effective control over sandwinning activity (Allan, 1991). This will aid in minimising the negative impact of sandwinning on the environment. Ideally therefore, in order to maintain a sustainable yield, the volume of sediment removed must be equal to or be less than the sediment yield being generated by the Lower Mgeni catchment. Seeing that sediment yield can be modelled per subcatchment, further consideration should be given to the location of sandwinning operations. Further, sandwinning at particular locations, and the institution of control measures, for example, a "quota" on volume of sediment extracted, may be considered and applied to particular operations in order to determine feasibility in terms sustainable yield.

A "complete" interpretation and understanding of the existing current hydrological status is therefore critical for the appropriate management of resources and the process of informed decision-making.

1.3 OBJECTIVES

Taking into account the potential impact of dam construction on catchment hydrology in general, and streamflow and sediment yield in particular, together with its concomitant effect on geomorphological, ecological and other processes, an estimation of current streamflow and sediment yield for the delimited study catchment becomes imperative.

The principal objectives of this study is to estimate streamflow and sediment yield of the Lower Mgeni study catchment. This involves the selection of an appropriate hydrological model to simulate catchment hydrology, which includes streamflow and sediment yield production. The selection of the hydrological model is discussed in the following chapter.

Overall aims of this study include contributing towards the completion of the distributed hydrological modelling system (Tarboton and Schulze, 1992; Kienzle *et.al.*, 1997) for the entire Mgeni catchment and testing the sediment yield component of the *ACRU* model in an application below the Inanda Dam. Therefore, the primary task is to set up and run the model for the delimited study catchment. This aspect of the study involves setting up an input database for each distributed subcatchment within the catchment; utilising the processes and techniques that are used to translate data into hydrological information; "running" the hydrological model which in turn "drives" the system and simulates the catchment hydrology; and finally assessing the capacity of the model to simulate sediment yield realistically.

It is the intention of this study to contribute to a more informed understanding on the processes and their resultant outputs occurring within the entire catchment. This would be achieved by providing relevant catchment information so that effective and holistic planning, development and management may be realised.

CHAPTER 2: SELECTION AND DESCRIPTION OF THE *ACRU* MODEL

Taking into account the potential impacts of the construction and operation of Inanda dam, and the principle objectives of this study, as noted in Chapter 1, the *ACRU* modelling system was selected for application. The *ACRU* model was chosen on the basis this model was applied to the Mgeni catchment upstream of Inanda dam. Based on existing research and studies, it was evident the *ACRU* model is capable of fulfilling the objectives of this study, which ultimately is to determine the magnitude of runoff, streamflow and sediment yield below Inanda dam. Further, it is logical to utilise the same model that has been applied to the Mgeni catchment, thereby contributing to the completion of the modelling of the entire Mgeni catchment, especially that part of the Mgeni catchment below Inanda dam.

The hydrological modelling system *ACRU*, which has its name from the Agricultural Catchments Research Unit in the Department of Agricultural Engineering, University of Natal, Pietermaritzburg, was initiated by Schulze (1975), who conducted an evapotranspiration-based study. Since then the model has been subject to subsequent developments with contributions made by other researchers and graduate students to its present day status of an internationally recognised modelling system (Schulze, Angus and George, 1989; Tarboton and Schulze, 1992). The *ACRU* model has been developed as a physical-conceptual, non-parameter fitting/optimising, multi-purpose, daily time step based on a daily multi-layer soil water budgeting model. It has been designed as a multi-level model with the capacity to operate in either lumped or semi-distributed mode (Tarboton and Schulze, 1992).

This chapter provides some considerations for hydrological model selection, and a summary of the concepts and structure of *ACRU* model, with particular reference to streamflow and sediment yield estimation.

2.1 HYDROLOGICAL MODELLING AND MODEL SELECTION

Hydrological modelling can be appropriately acknowledged as a sufficiently equipped resource base to serve as an effective tool in providing prerequisite data necessary for the sound management of water resources. Information thus acquired through the process of observation and study can be effectively applied to areas that require planning and management. Modelling used in water resources engineering and management can be broadly classified into two categories,

1) physically based/deterministic models, or
2) statistical/stochastic models.

The differences between them are briefly discussed below.

2.1.1 Deterministic versus stochastic modelling

Broadly speaking, according to Ward and Robinson (1990: 286-287), runoff models may be regarded as *deterministic* or *stochastic*, deterministic models simulate the physical processes operating in the catchment to transform precipitation into runoff, whereas stochastic (probabilistic) models take into consideration the chance occurrence or probability distribution of the hydrological variables. It is further stated that models may also be described as *conceptual* or *empirical* depending on how much consideration is given to the physical processes acting on the input variables to produce the output of runoff. Since the model utilised in this study is a mental representation of hydrological processes, it is a conceptual model. According to Krumbein and Graybill (1968), conceptual models are formalised further as a scale model, a deterministic model, or a statistical model. The model employed in this study represents the physically- based/ deterministic approach. Deterministic models introduce variables to quantify the factors affecting erosion, transport and deposition; these parameters can be derived empirically or calibrated using curve fitting techniques (Onstad, 1984). The term stochastic model is essentially synonymous with statistical model. Stochastic modelling is in some cases developed from deterministic relationships (Onstad, 1984), for example, the relation between sediment yield and rainfall is used to develop distribution functions. Sediment yield is therefore determined by using rainfall as an input parameter in conjunction with the predetermined distribution functions. The two models differ in that the deterministic model has no random components, so that the course of a phenomenon, in this study the hydrological process, is determined exactly at any fixed point in time (Krumbein and Graybill, 1968).

Deterministic modelling has been chosen primarily because there is no need for a long period of daily streamflow records, which is essential to the stochastic approach. Noting the lack of good quality or valid records in South Africa, there is a general paucity of data for long periods of streamflow. Shorter periods of record would require extrapolation, for the estimation of the magnitudes of floods for a return period that is greater than the length of streamflow record, this situation is highly unsatisfactory (Schulze, 1987). No catchment remains static, and neither are most catchments insulated from human-induced changes , which alter hydrological response. This, according to Schulze (1987), would imply that the use of historical records of streamflow for the prediction of "future states of extrapolation", are fundamentally flawed.

Deterministic modelling has a number of advantages over stochastic modelling. Deterministic models can be adjusted and modified to reflect the dynamic nature of a catchment (Angus,1987). Although this capability is not utilised in this study, it is valuable because once the initial input data is set up, it is relatively easy and cost effective to simulate "What if?" scenarios, accommodating thus for changes occurring within catchment.

Deterministic/physically-based models can be classified as either lumped or distributed models. The essential difference between the two types of models, according to Angus (1987), is the level of discretization to which the catchment is subjected.

2.1.2 Distributed versus lumped modelling

In lumped modelling, the catchment is regarded as a single unit, irrespective of the size of the catchment. The input factors namely climatic, soil and vegetation are subsequently averaged. This yields a single value for the input variables that have been selected to represent the entire catchment. In a distributed model, however, the catchment is divided into a number of subcatchments. Each subcatchment is treated as a single unit, having its' own individual hydrological response. The responses of the different units are assimilated and integrated to simulate the hydrological response for the entire catchment under consideration. The climate, soil and vegetation variables derived from the catchment are determined for each unit and are representative of those individual units. Ultimately, the modelling is made more accurate by reflecting the spatial heterogeneity that occurs within the catchment. Distributed modelling is, therefore, more versatile than its lumped counterpart, as it is more accurately representative of the entire catchment and its ability to evaluate the effects of land use changes on catchment hydrology.

The hydrological model selected for this study is the *ACRU* hydrological model, and the simulation is conducted in the distributed mode.

Further detailed description and information of the *ACRU* model may be obtained in Schulze (1989a), Tarboton and Schulze (1992) and Schulze (1995). *ACRU* is designed to facilitate refinement and further development on a continuous basis (Tarboton and Schulze,1992). The version utilised in this study is ***ACRU*-3.27**. This chapter describes the concepts and structure of the *ACRU* model; and subsequently, the modelling of streamflow and sediment yield.

2.2 *ACRU* CONCEPTS AND STRUCTURE

The *ACRU* model is designed to be physical-conceptual. It is conceptual in the sense that it conceives of a one-dimensional system in which the important processes and interactions are idealised and included in discrete time units. It is physical, for example, the ability of the soil to store and transmit water is represented explicitly and vegetative water consumption is simulated realistically, using variables, which would be observable, if the hydrological system met the idealisations made (Schulze, 1989b and Schulze, 1995) .

The *ACRU* model is a multi-purpose model (see Figure 2.1) and the following variables may be simulated: runoff elements (for example, stormflow, baseflow, peak discharge at daily, monthly or annual level), sediment yield from a catchment (daily, monthly or annual), soil water status and total evaporation. Other outputs include reservoir analysis, irrigation water demand, irrigation water supply, effects of land cover and use changes, and seasonal crop yields. Risk analysis can be conducted on some of the components (Schulze, 1989b); Tarboton and Schulze, 1992).

The model uses daily time intervals as the basic time step. Data input as monthly values (for example, temperature) are transformed to daily values internally by Fourier Analysis (Schulze, 1989b; Tarboton and Schulze, 1992). *ACRU* has also been designed as a multi-level model with either multiple options or alternative pathways available in many of its routines, depending on the level of sophistication of available input information and the type of output required (Schulze, 1989b; Tarboton and Schulze, 1992).

Although *ACRU* can operate as a point or a lumped catchment model, it is utilised in this study in the distributed mode. In the distributed mode, subcatchments are discretized, with streamflow taking place in a predetermined scheme within the total catchment area under consideration, and each subcatchment can generate individually requested and different output (Tarboton and Schulze, 1992). The *ACRU* model also has the capacity to simulate changes in land cover and use, and this includes gradual or abrupt changes. This dynamic input option facilitates the modelling of hydrological response of catchments to changing land use and management (Schulze, 1989b; Tarboton and Schulze, 1992).

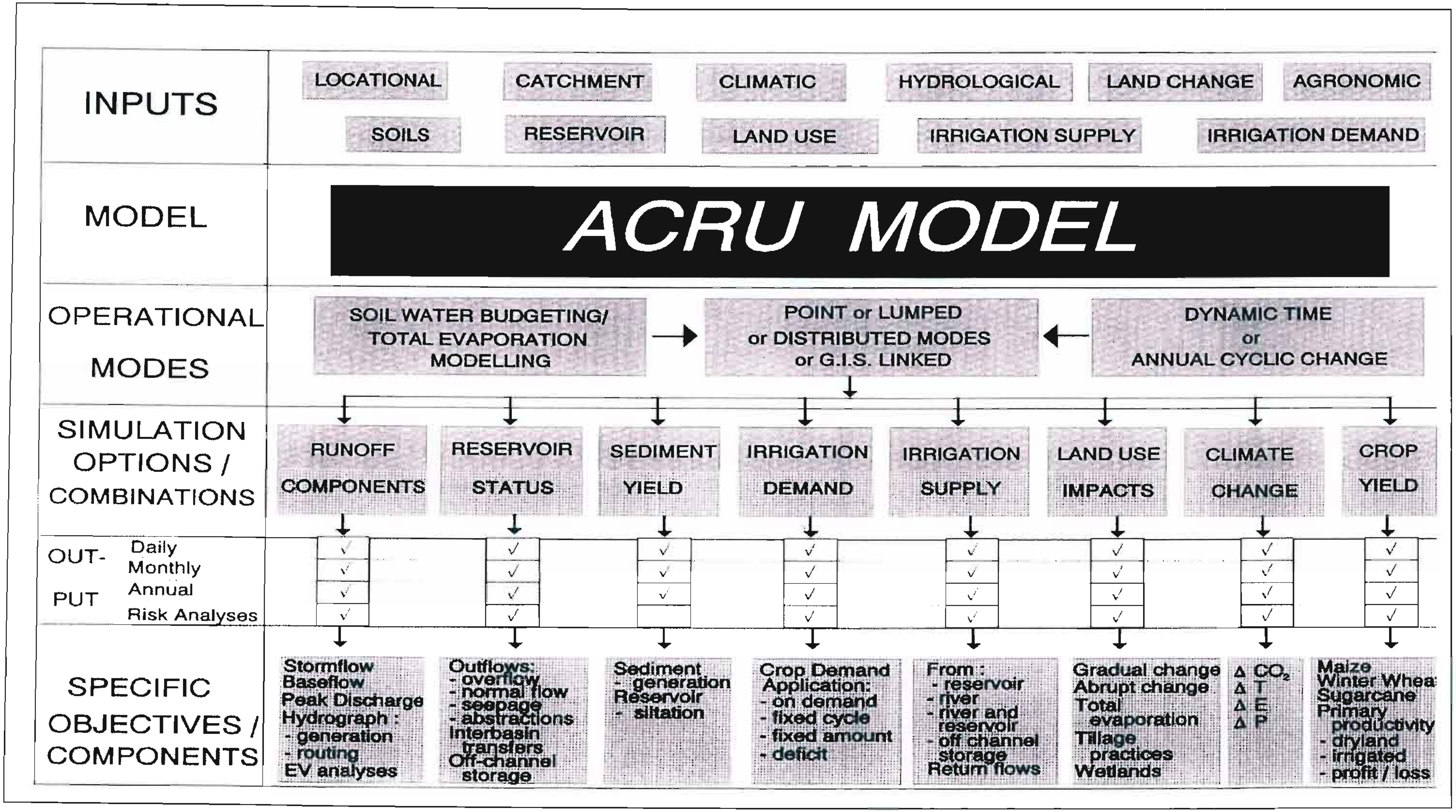


FIGURE 2.1: The *ACRU* agrohydrological modelling system: Schulze (1995)

The *ACRU* model is described by George *et.al.* (1989) and Tarboton and Schulze (1992) as a menu-driven, user-friendly model with an interactive Menubuilder. The *ACRU* Menubuilder prompts the user for input information through unambiguous questions. It has the capacity to perform internal checks for realistic input values, and a Decision Support System, which assists in the rapid input of complex soils/land cover information. Therefore, the *ACRU* Menubuilder may be described as being structured along the lines of an expert system. The concepts of the *ACRU* model are illustrated in Figure 2.1.

The *ACRU* model is designed for daily multi-layer soil water budgeting by the partitioning and distribution of soil water as depicted in Figure 2.2. Rainfall not abstracted as interception or as stormflow, infiltrates the soil surface where it either percolates, and is redistributed to be stored in a number of soil layers, or it is "lost" through total evaporation or drainage below the root zone (Schulze, Angus and George, 1989; Tarboton and Schulze, 1992). Kienzle (pers. comm., 1994) notes that the rainfall percolating below the root zone is not "lost", but rather it contributes to baseflow. The generation of stormflow, according to Tarboton and Schulze (1992), is based on the premise that, after initial abstractions, the runoff produced from rainfall is a function of soil water deficit from a critical response depth of the soil.

Although the objective of this analysis is to estimate streamflow and sediment yield from the study catchment, it is necessary to consider the estimation of stormflow as it is usually a significant contributor to streamflow in times of precipitation. Stormflow is also significant as it is instrumental in the detachment, entrainment and transport of sediment particles, hence contributing to sediment yield.

2.3 STREAMFLOW SIMULATION

As depicted by Figure 2.2, the simulated streamflow comprises baseflow and stormflow, with the stormflow component consisting of a quickflow response (that is, stormflow released into the stream on the day of the rainfall event) and a delayed stormflow response (Schulze, 1989c). The estimation of stormflow volume is based on the SCS equation (USDA-SCS, 1972),

$$Q = \frac{(P - I_a)}{(P - I_a) + S} \qquad \text{for } P > I_a \qquad \textbf{Eqn. 2.1}$$

where

Q = estimation of stormflow volume (mm),

P = daily rainfall (mm),

I_a = initial abstractions, and

S = the potential maximum retention of the soil (mm).

The generation of stormflow is based on the principle that, following initial abstractions, the runoff potential is a function of the soil moisture (Schulze, 1989c and Schulze, 1995). Modification of the SCS equation, by Schulze (1989c) and (1995a), for use in the *ACRU* model has resulted in a number of conceptual differences. They include the following:

(1) Rainfall intercepted by the vegetation is deducted separately from the total rainfall amount prior to being applied to Equation 2.1 and is therefore not part of the initial abstractions in the SCS equation.

(2) The coefficient of initial abstraction can vary from month to month, dependent on vegetation, site and management characteristics.

(3) The potential maximum retention of the soil, S, is calculated as a soil water deficit antecedent to rainfall event by multi-layer soil water budgeting, and hence the SCS curve number concept is not considered at all.

(4) The critical response soil depth for which the moisture deficit is taken into account, can be varied to take into consideration different runoff producing mechanisms. As an example, for a catchment with predominantly short vegetation, which is shallow-rooted, a soil water deficit equivalent to topsoil-horizon depth may be more representative of the runoff mechanism. On the other hand, for a catchment with tall, dense vegetation cover with deeper roots, and thus a relatively higher infiltratibility, the critical depth of soil water may be deeper than the topsoil-horizon, and therefore must be taken into account.

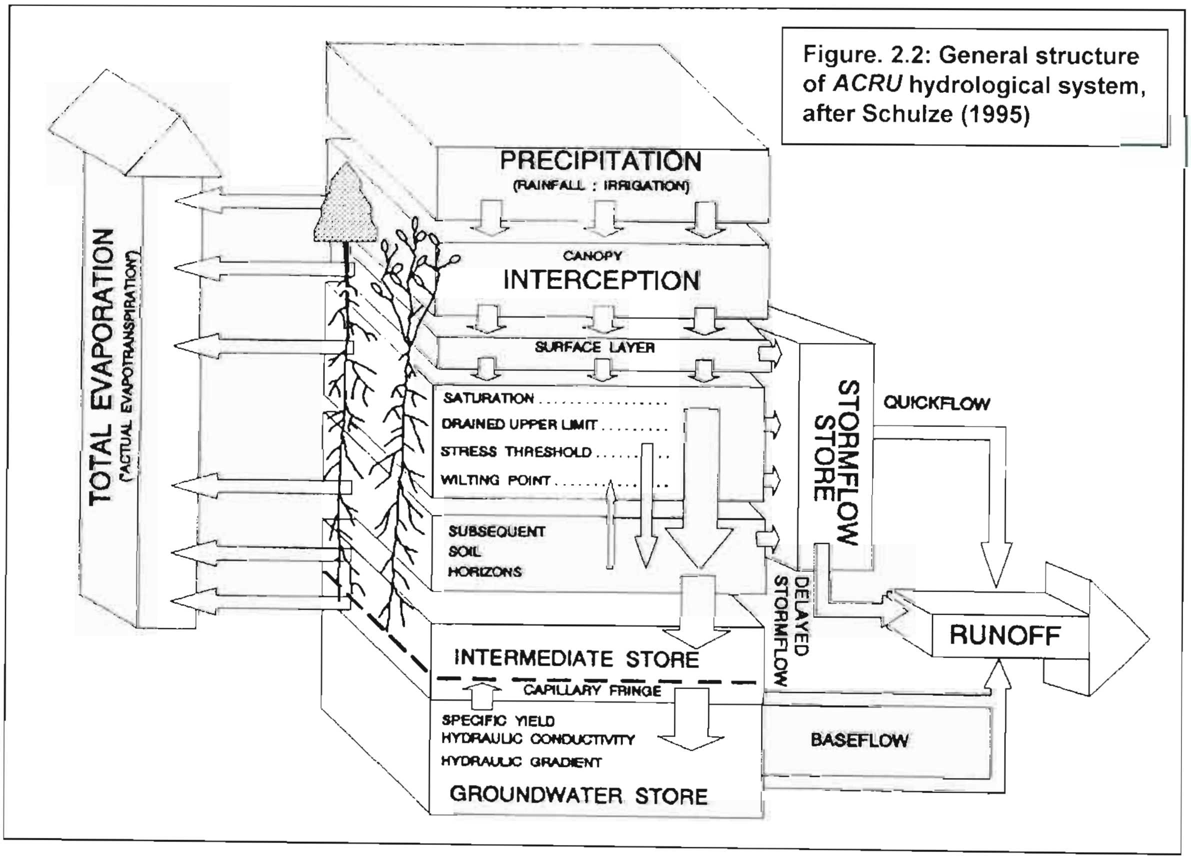


Figure. 2.2: General structure of *ACRU* hydrological system, after Schulze (1995)

(5) The *ACRU* model also incorporates a coefficient of stormflow, which takes into account any lagged response of stormflow that may be caused by soil properties or catchment characteristics, including catchment size and gradient, and vegetation properties.

The baseflow component of streamflow is derived from the groundwater store, which is recharged by drainage from the lower active soil horizons (Tarboton and Schulze, 1992). Baseflow contributes to streamflow as depicted in Figure 2.2. In the *ACRU* model, baseflow generation is controlled by two coefficients. The first relates to the drainage rate of water out of the lowest subsoil horizon store into the intermediate groundwater store when its soil water content exceeds field capacity. This response rate is a function of soil texture, and suggested values are given in Schulze *et.al.* (1989). The second response coefficient concerns the baseflow release of water from the intermediate/groundwater store into the stream. Schulze (1989c) suggests and discusses possible values, and notes that although baseflow "release" is expected to perform as a constant, experience has shown that baseflow release "decay" is not constant.

2.4 PEAK DISCHARGE SIMULATION

In order to determine sediment yield using the *ACRU* model, one has to also determine peak discharge (Schulze and George, 1989). Schmidt and Schulze (1984) observe that peak discharge, especially in small catchments, is closely related to runoff volume and the accurate estimation of antecedent soil water condition.

2.4.1 Estimation of peak discharge

The estimation of peak discharge in the *ACRU* model is based on the SCS equation (USDA-SCS, 1972), and, assuming a single triangular hydrograph, the equation for peak discharge (q_p) is:

$$q_p = \frac{0.2083\ A\ Q}{D/2 + L} \qquad \textbf{Eqn. 2.2}$$

Where
q_p = peak discharge (m^3s^{-1})
Q = runoff depth (mm)
A = catchment area (km^2)
L = catchment lag time (h) and
D = effective storm duration (h).

The simulation of peak discharge according to Schmidt and Schulze (1989) may be summarised as follows:

"In the *ACRU* model peak discharge refers to the highest instantaneous rate of runoff occurring during a given day from the total hydrograph. It is therefore comprised of the peak discharge in m^3s^{-1} calculated from the day's generated stormflow, as given by Equation 2.2, superimposed on the mean baseflow for the day in m^3s^{-1} and carry over for the day of mean quickflow from the previous day's stormflow, also in m^3s^{-1}."

2.4.2 Estimation of catchment lag time

Three possible options, to determine catchment lag time for use in *ACRU*, are discussed and described in Schmidt and Schulze (1989); catchment lag time may be calculated by one of the following options available in *ACRU*:

(1) using the catchment time of concentration,
(2) using the original SCS equation, or
(3) the Schmidt/Schulze equation.

(1) The **time of concentration** is the time it takes for runoff to travel from the hydraulically most distant part of the catchment (i.e. point of longest water travel time) to the point of reference (Schmidt and Schulze, 1987a). Lag may be calculated using the equation 2.3 (USDA, 1972):

(2)

$$L = 0.6\ T_c \qquad \textbf{Eqn. 2.3}$$

Time of concentration may be calculated by adding the flow travel times. The travel time in each flow reach is determined by dividing the reach length (in m) by flow velocity as determined from uniform flow equations (e.g. Manning's equation) for full flow conditions. Time of concentration (T_c) may be estimated using the following equation:

$$T_c = \sum_{i=1}^{n} \frac{H_{li}}{V_i \times 3600} \qquad \textbf{Eqn 2.4}$$

where H_{li} = hydraulic length of reach i (m)
v_i = flow velocity in reach i ($m.s^{-1}$), and
n = number of reaches.

In the absence of a clearly defined "hydraulically most distant" point, as is generally the case for catchments which do not have a well developed drainage system, one of the following empirical equations may be utilised to determine catchment lag time.

(2) **The SCS Lag Equation**:

$$L = H_l^{0.8}(S' + 25.4)^{0.7} / 7\,069\ S_{\%}^{0.5} \qquad \textbf{Eqn. 2.5}$$

where L = catchment lag time (h),

H_l = hydraulic length of catchment along the main channel (m),

$S_{\%}$ = average catchment slope (%), and

$$S' = \frac{25\,400}{CNII} - 254$$

with, CNII = retardance factor approximated by the runoff Curve Number for average catchment antecedence wetness. The values for CNII are defined in Schmidt and Schulze (1987b). The values for various land use/land treatment classes, hydrological soil groups and runoff potentials are noted in Schmidt and Schulze (1987b). The hydraulic length (H_l) is calculated as the length of the main stream to the furthest catchment divide measured on a contour map. In the absence of a contour map, H_l may be determined by

$$H_l = 1738\ A^{0.6}$$

where A = catchment area (km^2)

(3) **The Schmidt-Schulze Lag Equation**

The equation developed by Schmidt and Schulze (1984) is given as

$$L = \frac{A^{0.35} MAP^{1.1}}{41.67\ S_{\%}^{0.3} I_{30}^{0.87}} \qquad \textbf{Eqn.2.6}$$

where

L = catchment lag time (h)

A = catchment area (km^2)

MAP = mean annual precipitation (mm)

$S_{\%}$ = average catchment slope, and

I_{30} = 2-year return period 30-minute rainfall intensity (mm.h^{-1}).

Mean catchment slope may be determined from the following equation

$$S_{\%} = \frac{M\,N \times 10^{-4}}{A}$$

where

M = total length of all the contour lines within the catchment (m), according to the scale of the map,

N = contour interval (m), and

A = catchment area (km^2).

The 2-year period 30-minute rainfall intensity (I_{30}) is related to the typical rainfall patterns occurring in that region. In South Africa, this may be approximated by multiplying the 2-year return period one-day rainfall depth, after Schmidt and Schulze (1987a), presented in Figure 2.3, by an intensity multiplication factor given in Table 2.1 for the various rainfall zones (see Figure 2.4) as delimited in Weddepohl (1988).

Table 2.1 Intensity multiplication factor

	Rainfall Distribution Zone			
	1	2	3	4
Multiplication Factor	0.430	0.664	0.974	1.236

In the estimation of catchment lag time, it is found, in the opinion of both Schmidt and Schulze (1989) and Schulze and George (1989), that the time of concentration method should be used if flow velocity can be calculated for most reaches making up the flow path; and if this is not possible then one of the empirical equations described can be utilised. It is the experience of Schmidt and Schulze (1989) that preference should be given to the Schmidt-Schulze lag equation in southern Africa, especially in "natural" catchments. The SCS lag equation is superior in arid conditions with limited vegetation cover and shallow soils, where it has been found to give better estimates.

2.5 SEDIMENT YIELD SIMULATION

Sediment yield is defined according The Encyclopaedic Dictionary of Physical Geography, (1991), as the total mass of particulate material reaching the outlet of a drainage basin. Values of sediment yield are commonly evaluated on an annual basis (t $year^{-1}$) and may be expressed as specific yields or yields per unit area (t km^{-2} $year^{-1}$). Soil erosion and the problems related to it, such as loss of soil productivity and detrimental effects caused by deposition of sediment in reservoirs with subsequent decrease in storage capacity has been a matter of concern for hydrologists and agricultural engineers. In South Africa, the sediment load carried by rivers is estimated to be between 100 - 150 million tonnes (Rooseboom, 1975). Soil erosion, in the opinion of Schmidt (1989), is a serious problem, caused by either one or a combination of arid climatic conditions, intense thundershower activity with inherent high rainfall erosivity, shallow erodible soils, and limited vegetation cover and poor conservation management techniques.

A number of sediment yield prediction methods are available, and have been used for various purposes. These methods can be broadly grouped into five categories (Onstad, 1984):

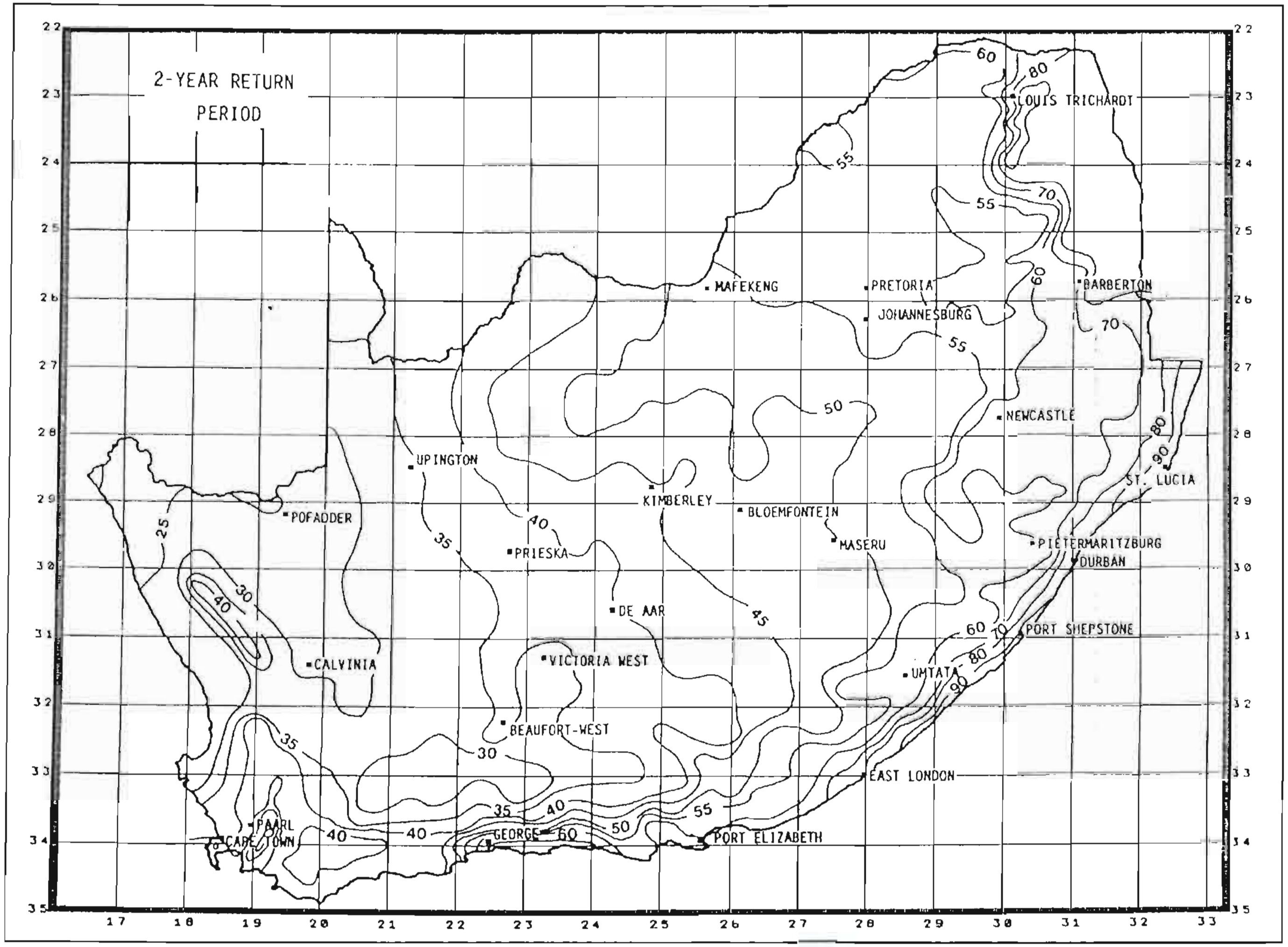


Figure 2.3: Expected maximum one-day rainfall in southern Africa for 2-year return period, after Schmidt and Schulze (1987a)

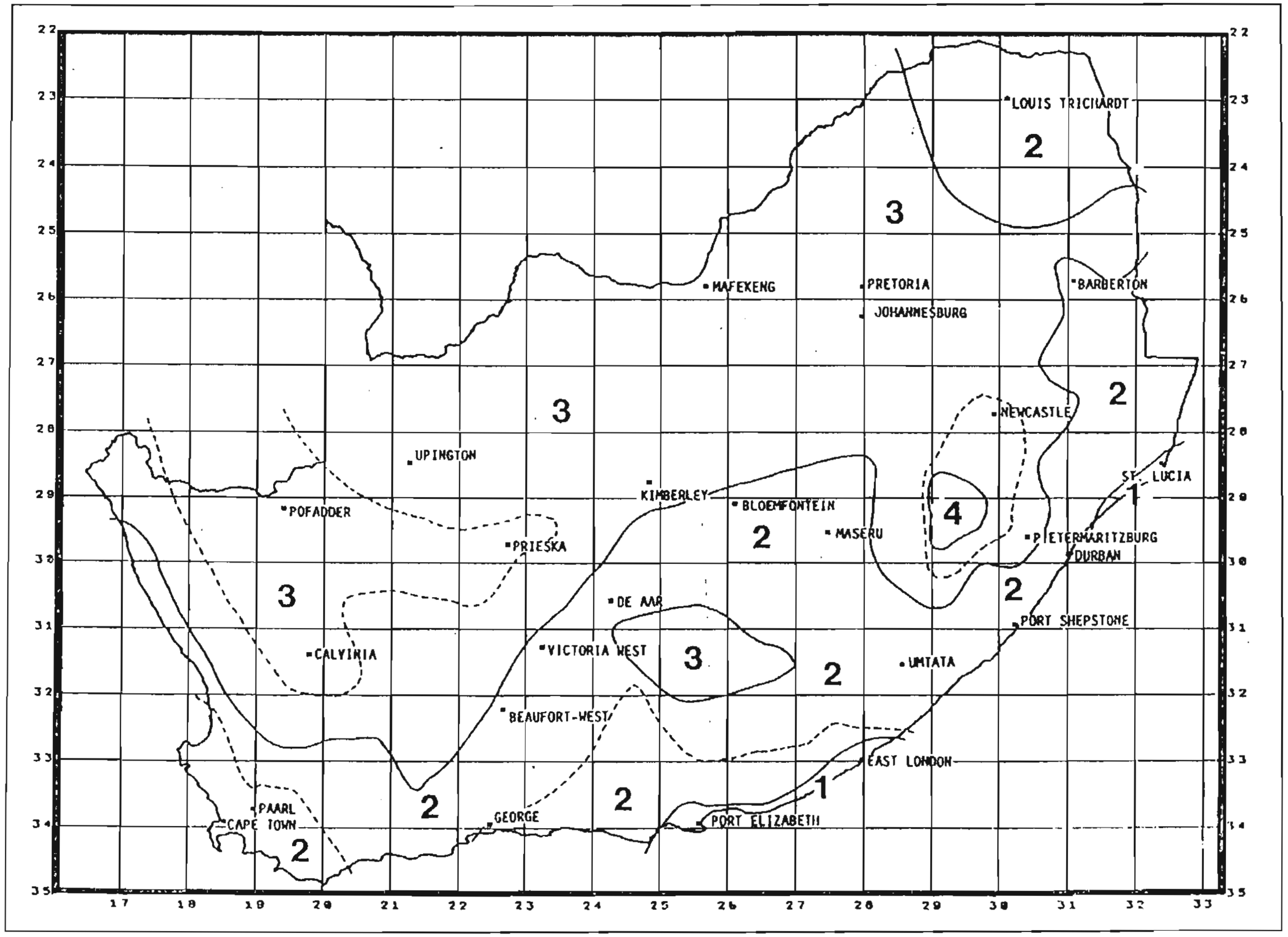


Figure 2.4: Regionalisation of rainfall distribution in southern African, after Weddepohl (1988)

(1) sediment delivery ratio procedures;
(2) sediment rating curves;
(3) statistical equations;
(4) deterministic models including empirical parametric approaches and those using time-variant interactions of physical processes, and
(5) stochastic approaches.

The modelling of sediment yield, in this study, utilises a physically-based/deterministic approach. Although complex deterministic models, representing erosion and sediment transport processes, exist, their practical value is limited. This is due to the requirements of the input parameters, which can only be met for research catchments. Deterministic models use parameters to quantify the factors affecting erosion, transport and deposition; these parameters may be derived empirically or calibrated applying curve fitting techniques (Onstad, 1984). An example of an empirical model is the Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978). This method has been utilised extensively and the equation forms the basis for many other empirical equations, including the Modified USLE (Williams, 1975) and Revised USLE (Renard *et.al.*, 1991) The practical application of the USLE and MUSLE equations are founded on the fact that the components of the equation have been researched extensively for southern African conditions (Schmidt, 1989).

The USLE method permits the estimation of long-term annual soil loss. The equation was developed empirically from a large database, and although the component factors are physical attributes, they represent statistical and not strictly physical interrelationships. The USLE equation given as:

$$A = RKLSCP \qquad \textbf{Eqn. 2.7}$$

where

A = computed long term average soil loss per unit area ($t.ha^{-1}.annum^{-1}$)
R = an index of rainfall erosivity ($J.mm.1000^{-1}.m^{-2}.h^{-1}$)
K = soil erodibility factor (dimensionless)
LS = slope length and gradient factor (dimensionless)
C = cover and management factor (dimensionless)
P = support practice factor (dimensionless)

The USLE has not been designed to determine soil loss estimates on an individual storm basis. Williams (1975) developed a model to predict storm sediment yield for basins up to 2600km^2. In this model the rainfall erosivity factor is replaced with a runoff factor. This modification, according to

Williams and Berndt (1977), allows for the prediction of sediment yield directly, thus eliminating the need for sediment delivery ratios. They observed that although stormflow runoff volume and peak discharge were correlated, the detachment process is related to stormflow runoff volume, whilst sediment transport is associated with peak discharge. This equation is termed the Modified Universal Soil Loss Equation (MUSLE) and is expressed as:

$$Y_{sd} = 11.8(Q.q_p)^{0.56}KLSCP \qquad \textbf{Eqn. 2.8}$$

where

Y_{sd} = sediment yield for an individual event (t)

Q = storm runoff volume for the event (m^3), and

q_p = peak discharge for the event ($m^3.s^{-1}$)

K = soil erodibility factor ($t.h.N^{-1}.ha^{-1}$).

The other factors K, LS, C and P are taken directly from Equation 2.7, and are identical as outlined in the USLE. The method of estimation of Q (storm flow volume) and q_p (peak discharge), for use in the *ACRU* model utilised in this study, is described in Equations 2.1 and 2.2 respectively. The description and method of estimation for the other factors utilised in *ACRU* is discussed under the relevant sections in the following chapter.

CHAPTER THREE: APPLICATION OF *ACRU* TO THE LOWER MGENI STUDY CATCHMENT

3.1 INTRODUCTION

The distributed version of the *ACRU* model was selected to model the Mgeni catchment (Tarboton and Schulze, 1992) and is utilised in this study. The distributed version of the *ACRU* model, according to Tarboton and Schulze (1992), has the ability to take into consideration the spatial heterogeneity of catchment characteristics, thus providing more accurate representation of catchment variables, allowing for better simulation of catchment hydrology.

3.1.1 Catchment discretization

The *ACRU* model makes use of cell-type discretization to subdivide the catchment, where each cell represents a subcatchment. These subdivisions are an attempt to achieve relatively homogeneous subcatchments based on climatic and physiographic factors. Cell boundaries were defined by utilising large-scale orthophotos and topographical maps. Although catchments are disaggregated in order to define "homogeneous" units, discretization in the Mgeni catchment is ultimately dependent on daily rainfall estimation. It would be obviously futile to define cells smaller than that for which rainfall could be estimated accurately; consequently therefore, according to Tarboton and Schulze (1992), subcatchment delimitation occurred according to physiographic boundaries, and by taking into account the distribution of raingauges in the Mgeni catchment, altitude, land cover and soils. In total four subcatchments were delimited for the study area and are shown in Figure 3.1.

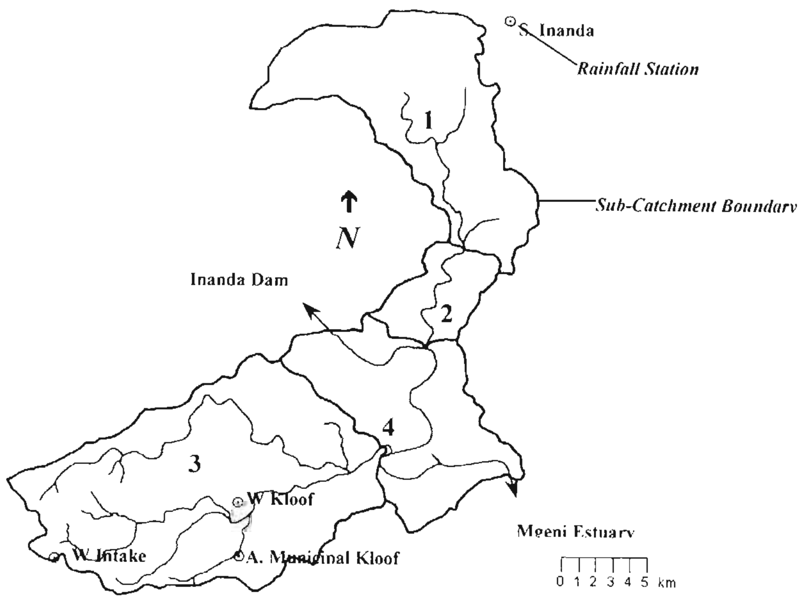


Figure 3.1 Subcatchments of the Lower Mgeni study area

Initially, however, the working group for the Mgeni Project from the Department of Agricultural Engineering at University of Natal-Pietermaritzburg created delimitations for three subcatchments only. Catchments 1 and 2 were originally delimited as one catchment, but due to the marked physiographic difference between them it was subsequently divided by the author into two separate subcatchments. The process of delineating cell boundaries is essentially subjective and dependent on the particular purpose of the modelling exercise (Angus, 1987; Schulze, Angus and George, 1989).

3.1.2 Operation in the distributed mode

Cell models, according to Schulze, Angus and George (1989), may be described as being semi-distributed models in that the catchment is demarcated as an assembly of interconnected units of area. Each unit is represented as a cell in the model, where each cell is a lumped representation of that area, that is, in terms of its catchment characteristics. The interconnected layout of the cells within the study area is depicted in Figure 3.2. Two types of cells may be identified in Figure 3.2, namely, exterior cells and interior cells. An exterior cell may be described as having a part of its subcatchment boundary as part of the main catchment boundary. It is also assumed that outflow from exterior cells is independent of all the other cells. An interior cell, on the other hand, may have one or more cells upstream of it and, therefore, outflow for interior cells have to include contributions from upstream cells that have been determined previously.

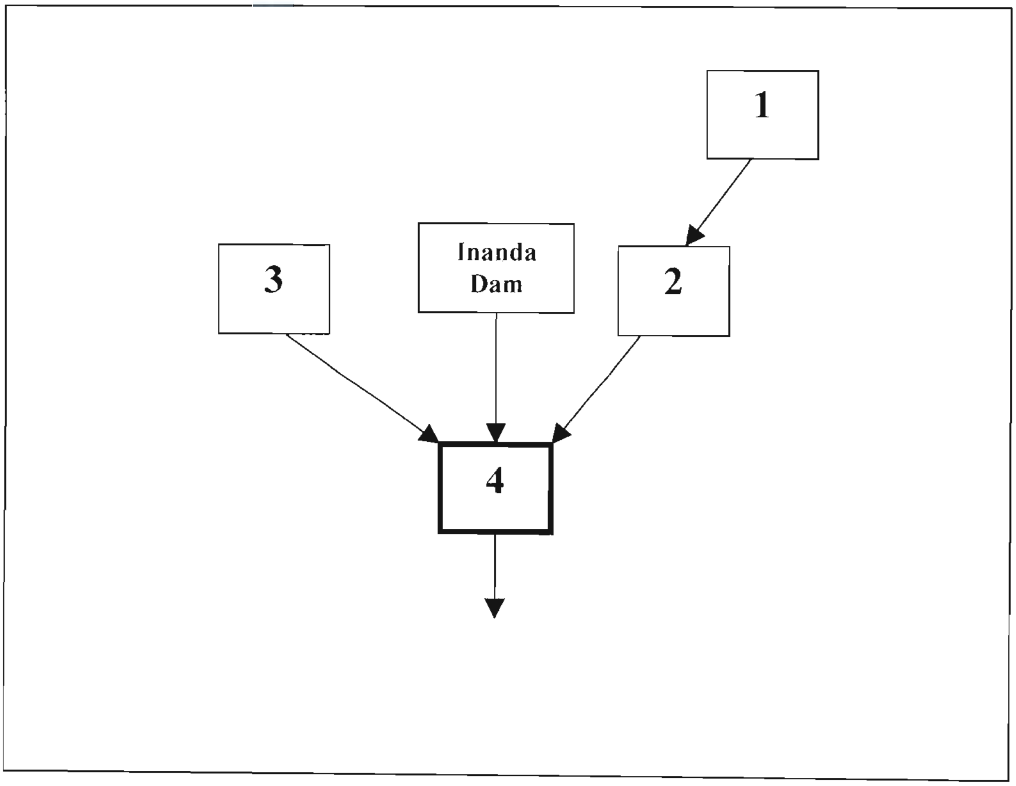


Figure 3.2 Layout of cells for the Lower Mgeni

It is important that the sequence of cells is analysed correctly. Within *ACRU* this is accomplished by using a simple numbering system to the subcatchment layout (Figures 3.1 and 3.2). Each subcatchment is allocated a number greater than the upstream cell preceding it, that is, the cells immediately upstream and downstream of the cell being considered, have to be specified. The *ACRU* model analyses each subcatchment in ascending numerical order, thus effectively ensuring that outflow information from upstream catchments is always available when analysing any internal subcatchments downstream (Angus, 1987; Schulze, Angus and George, 1989). This information is conveyed to the model by means of a menu containing input information for subcatchment layout. That extracted section of the menu containing information on the layout of the study catchment is presented in Figure 3.3.

Subcatchment configuration information (if ICELL=1)			
ICELLN	IDSTRM	PRTOUT	Subcatchment Number
1	2	0	1
2	4	0	2
3	4	0	3
4	5	0	4

Figure 3.3 Menu depicting subcatchment configuration information

Although only four subcatchments have been delimited for this study catchment, the layout of the interconnecting cells may be changed. If the basic rule of allocating a number greater than a number allocated for any subcatchment upstream of itself is followed, the model will represent cell outflows correctly.

3.1.3 Inter-Subcatchment Runoff

The lumped version of the *ACRU* model's soil moisture budgeting routine is performed on a point scale with all units expressed in millimetres (mm) (Angus, 1987). Therefore, streamflow comprising stormflow and baseflow is also expressed in mm. In order for outflow from upstream cells to be taken into account in the downstream cells, the stream flow depth estimated by the model has to be converted to a volume (m^3) because the area of each subcatchment may vary (Schulze, Angus and George, 1989).

The presence or absence and the identity of the upstream cell is determined by interrogation of the menu. The method of directing streamflow between subcatchments applied to the study catchment, described in Angus (1987) and Schulze, Angus and George (1989), is depicted in Figure 3.4.

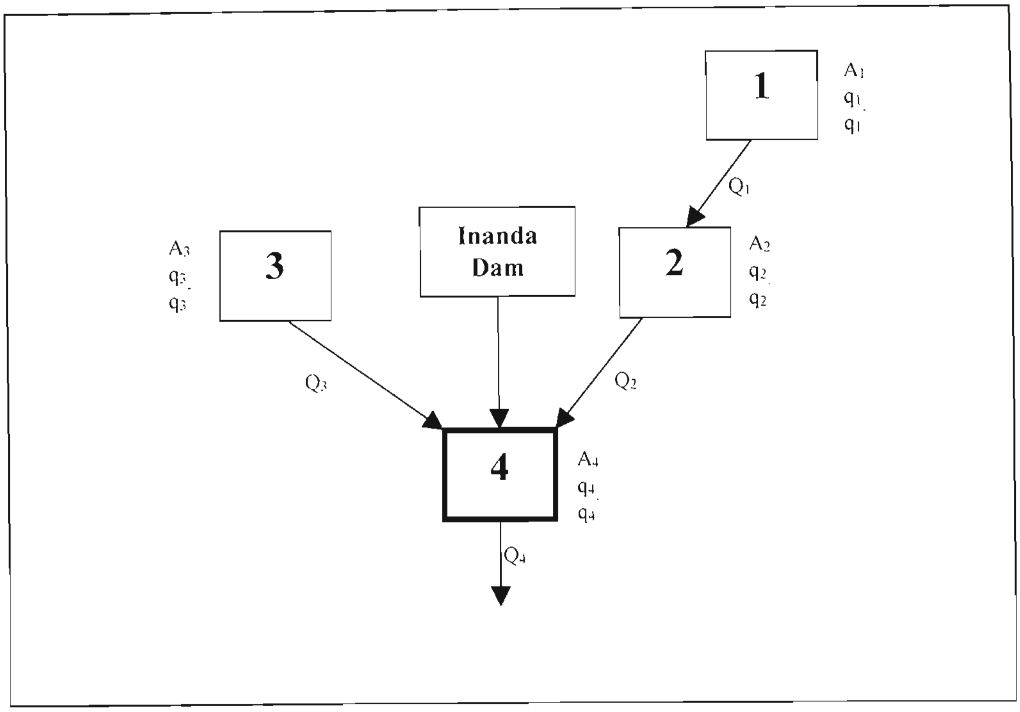


Figure 3.4: Method of directing streamflow to downstream cells for the Lower Mgeni

where

A_i = area of Cell i (km^2),
q_i = streamflow depth generated in Cell i (mm)
q_i' = equivalent depth of streamflow distributed over the entire portion of the subcatchment upstream of Cell i, and
Q_i = total volume of streamflow leaving Cell i (m^3)

Daily streamflow depths (q_i) are calculated for each cell, and should upstream cells exist then q_i is converted to a volume by multiplying by the catchment area A_i. This value is added to the upstream streamflow volumes and becomes outflow Q_i from the cell. Q_i may also be expressed as an equivalent depth of streamflow (q_i') over the entire catchment upstream of the outlet of the cell.

Equivalent streamflow depth, according to Angus (1987), is a useful method for expressing streamflow, as this enables identification of high and low streamflow producing regions within the catchment. Given that rainfall is also expressed in mm, this method permits the determination of the proportion of rainfall that becomes streamflow, that is, the runoff coefficient.

3.2 DATA AND INFORMATION REQUIREMENTS FOR *ACRU* STREAMFLOW SIMULATION

Distributed modelling makes high demands on input because each subcatchment modelled requires an individual and separate set of input variables. This is due to the highly variable nature of catchment physiography, land uses and soils for the study area. In order to model the hydrology of the Mgeni catchment, large amounts of different types of data were collected and transformed into hydrological information and used to generate modelling inputs (Tarboton and Schulze, 1992).

Input variables required by the *ACRU* model are presented in Figure 2.1. In addition, some of the input variables, as elaborated by Tarboton and Schulze (1992), are noted below:

(1) Locational and catchment: These include system layout, catchment names, areas, geographical location and mean elevation.

(2) Climatic: Rainfall, A-pan equivalent potential evaporation or variables to estimate evaporation including, *inter alia*, maximum and minimum temperatures, temperature lapse rates, wind speed and day length.

(3) Hydrological: This category comprises streamflow data from gauging weirs, hydrological response rates, catchment hydraulic length and catchment response time.

(4) Soils: Hydrological properties of soils are considered, including horizon depths, soil water properties of each horizon and soil water redistribution rates between horizons.

(5) Land cover and change: Crop coefficients, leaf area indices, interception loss rates, root distribution, impervious areas and changes of these variables both seasonally and historically are included.

(6) Reservoir: These inputs comprise capacities, surface area, wall length, normal flow, seepage, area: capacity relationships, drafts and inflows.

(7) Irrigation: Information on irrigated soils and crops include area irrigated, mode of scheduling, months in which irrigation water is applied, conveyance losses and water source.

This section describes the methodology applied and various problems experienced in the process of acquiring the input parameters noted above. While the most salient points relevant to the input variables utilised in this study are described, for further detail the reader is referred to Schulze *et.al.* (1989), Tarboton and Schulze (1992); Schulze (1995) and Smithers and Schulze (1995), where relevant background theory and method for acquiring input data and information is discussed and described in detail. It should also be pointed out that these methods were modified, as was necessary for the purposes of this study, and that problems in obtaining certain input data were encountered. These difficulties will be noted under the relevant subsections.

In order to facilitate input for *ACRU*, a menubuilder incorporating Decision Support Systems has been developed by Lynch (1993). The *ACRU* Menubuilder, as described in George *et.al.* (1989), is a user-friendly interactive program to "build" the menu by setting up the input data file. This is accomplished by prompting the user for input information, whereby the user is guided through various options, which are subsequently converted by the Menubuilder to the input menu which instructs *ACRU* on input values, computational options and output requests. It contains a HELP facility and is also able to perform internal checks for realistic input values, displaying either warning or error messages. Additional features utilised in this study will be described under the relevant sections. This section which presents the input of information into the *ACRU* Menubuilder based on the method outlined by Schulze and George (1989). Information, where necessary, will be presented in either the text or alternatively in the relevant appendices.

3.2.1 Mode of simulation

Initially, it is necessary to specify the mode of simulation, that is, whether the model is to operate in point/lumped or distributed mode (ICELL). This will determine whether information on catchment configuration needs to be obtained and how the information in the menu is to be interpreted by the programme. In this study **ICELL = YES** (operate in distributed catchment mode).

3.2.2 Distributed model specifications

When the model is being operated in distributed mode, there is a need to note the total number of subcatchments (**ISUBNO = 4**), for the purpose of subsequent formatting. In some instances, there may be a need to assess hydrological changes within a particular catchment. This would usually involve the time-consuming task of a rerun of all subcatchments. This problem is overcome by allocating **MINSUB = 1**, which is the most upstream catchment and **MAXSUB = 4** which is the subcatchment furthest downstream, within which changes are effected or the impacts of changes are experienced. Hypothetically, if more subcatchments had been delimited, only the subcatchments under consideration will be modelled.

3.2.3 Information on subcatchment configuration

That portion of the menu depicting information on the layout of cells in the study catchment is presented in Figure 3.3. It refers to the catchment illustrated in Figures 3.1 and 3.2. This input gives an overview of the flow pathway of water from one subcatchment to the next. For each individual catchment (**ICELLN**) there is need to specify into which downstream subcatchment its water will flow (**IDSTRM**) and which subcatchment(s) immediately upstream flow(s) into it (**IUSTRM**).

3.2.4 Locational information

The heading is self explanatory and includes: (1) **AREA**: Area of the subcatchment (km^2); (2) **ELEV**:

Average altitude (m) above mean sea level of the subcatchment; (3) **ALAT**: Latitude of the centre of the subcatchment (degrees and minutes of degrees); (4) **ALONG**: Longitude of the centre of the subcatchment (degrees and minutes of degrees); (5) **IHEMI**: Indicates whether the subcatchment is in the southern or northern hemisphere; and (6) **IQUAD**: Indicates whether the subcatchment is east or west of Greenwich. The locational information of the four study subcatchments is depicted in Figure 3.5.

Locational information						
CLAREA	ELEV	ALAT	ALONG	IHEMI	IQUAD	
39.85	404.0	29.65	30.90	2	1	1
9.36	231.0	29.70	30.90	2	1	2
67.53	499.0	29.73	30.90	2	1	3
30.41	250.0	29.77	30.83	2	1	4

Figure 3.5 Extract from distributed *ACRU* menu with locational information of cells

3.2.5 Input data file organisation

DNAMIC indicates whether dynamic file(s) is to be used or not, and because none were used in this study the entry would therefore be **DNAMIC = NO**. **IRAINF** indicates the rainfall data input file that is relevant to a specific subcatchment. In this study subcatchments 1 and 2 used the Inanda rainfall file and subcatchments 3 and 4 utilised the Kloof rainfall file.

3.2.6 Length of record for simulation

This input determines the period of simulation run, for which **IYSTRT = 1990** would be the first year and **IYREND = 1998** would be the last year for which the rainfall/hydrometeorological data series is to be considered in a simulation run. This input becomes useful when data sets are particularly long. Where test runs need to be conducted for the period of a few years, this allows for checking input and output prior to committing extensive runs.

3.2.7 Simulation and printout options

This section makes provision for the option of selecting a daily (**WRIDY = YES**) or monthly (**WRIMO = YES**) summary of the soil water budget/hydrological response for the subcatchment. It should be noted that although both these options were selected they cannot be conducted simultaneously in a single run. The two options above represent the most commonly requested options available in *ACRU*.

The option selected is based on the analysis being undertaken and the level of detail required in the interpretation of results. In addition to this, depending on other specifications for a particular simulation run, there are different versions of the daily and monthly summary printouts that are selected internally within *ACRU*.

3.2.8 Output options

In this section, due to the nature of this study, only the **SUMMRY** option could be used. This option provides a summary of monthly means, standard deviations and coefficients of variation, as well as frequency analysis (at defined percentile levels) for selected variables, as noted in Schulze and George (1989). It has been noted that this is a very useful risk analysis and method for obtaining an overview and insight into the variability of the results. Due to the simulation period, in this study the statistics are utilised, because the period of simulation exceeds five years, and as such is considered to be statistically meaningful. In terms of the stated objectives of this study, the monthly summary statistics is deemed to be adequate and utilised in this study.

3.2.9 Rainfall

In hydrological modelling accurate rainfall estimation remains the single most important variable, as it is a fundamental requirement for successful modelling. According to Schulze, Dent and Schäfer (1989), rainfall-runoff models are especially sensitive to rainfall input, whereby errors in estimation will be exacerbated in runoff simulations. Since the modelling is being conducted in the distributed mode, it is necessary to estimate rainfall accurately for each subcatchment. Rainfall data from point measurements for the Mgeni catchment and the two methods utilised to estimate representative rainfall for each discretized subcatchment is discussed in Tarboton and Schulze (1992). The process of acquiring the rainfall data and the method used to estimate representative rainfall for the delineated subcatchments of this study, will be described subsequently in subsection 3.2.9.3.

3.2.9.1 Rainfall data acquisition

The data search was initiated at the Computing Centre for Water Research (CCWR), University of Natal Pietermaritzburg. The CCWR has collated on a comprehensive scale for southern Africa daily rainfall, temperature and pan evaporation data as well as other climatic data such as relative humidity, windrun, solar radiation fluxes and sunshine duration. The data compiled by the CCWR is obtained from the following sources: South African Weather Bureau, Department of Agricultural Development, Department of Environment Affairs, South African Sugar Association, Provincial Parks Boards, organised agriculture, municipalities, mines and private individuals (Dent and George, 1989). A description of process in obtaining the rainfall data utilised in this study follows.

Normally rainfall and other climatic data are extracted from the databases at the CCWR. The procedure to extract daily climate data for a given station or region from CCWR collated data files is accomplished by running programme **EXCLIM** which is stored on an account named **POOL**, which is accessible to all CCWR users. The EXCLIM programme is menu driven and completely self-explanatory. In the event of difficulties, user consultants are available to assist. Output from data extraction is written to the user's account.

The first stage of data extraction involves delimiting the area of interest for this study, and this is accomplished by delimiting the study area using the latitude and longitude co-ordinates of the northwest and southeast corners as reference points. This creates a rectangular area, and all rainfall stations located within this area are listed, that is, the rainfall station number, name of the station, co-ordinates of the station and the period of recorded data. Information with respect to rainfall station data factors, as noted above for the study catchment, is depicted in Table 3.1, and the location of the rainfall stations is illustrated in Figure 3.1.

When this study was initiated in 1991, it is evident from Table 3.1 that the information available at CCWR was inadequate for this study, because the data required for the period of simulation, that is, January 1990 to December 1993, was not available. This implied that the data had to be obtained by different means. This process will be described.

Table 3.1 Lower Mgeni rainfall station information

Number	Name	Latitude	Longitude	Period
0240757	S. Inanda	29^{0} $37''$ E	30^{0} $56''$ W	1951 - 1990
0240586	W. Kloof	29^{0} $46''$ E	30^{0} $50''$ W	1932 - 1990
0240564	W. Intake	29^{0} $47''$ E	30^{0} $46''$ W	1923 - 1990
0240587	A. M. Kloof	29^{0} $47''$ E	30^{0} $50''$ W	1959 - 1989

The areal distribution of rainfall stations within the study catchment as illustrated in Figure 3.1 is clearly inadequate due to a concentration of three rainfall stations, namely, Kloof, Intake and Municipal Kloof within Subcatchment 3, whilst Subcatchments 1, 2 and 4 on the other hand have no rainfall stations. This in effect means that Subcatchments 1, 2 and 4 have no direct rainfall measurement within them, and therefore accurate representative estimation of rainfall had to be determined through other means. Although found outside Subcatchment 1, the Inanda rainfall station is located close to the northeastern boundary and is utilised in this study. The main reason for the use of the Inanda rainfall station is the areal variability of rainfall within the catchment, and the fact that no other rainfall station is located in the catchment north of the Mgeni river. Given the differences in physiography and the location of the study catchment effectively being divided into two parts namely, the northern (Subcatchment 1 and 2), and the southern (Subcatchment 3), while the major portion of

Subcatchment 4 lies in the southern part, it becomes essential to take into account the local climatological differences so that accurate representation of rainfall for the different subcatchments can be arrived at.

Taking into account the points noted above, the Kloof and the Inanda rainfall stations were selected for use in this simulation. Although three stations are located within the Subcatchment 1, the Kloof rainfall data was utilised for the reasons given below. Firstly, the Municipal Kloof station, operated by the Department of Agricultural Development, was disregarded due to difficulties experienced in trying to obtain new data or updating existing databases (R. De Vos, pers. comm., 1994). The updating of data for the Kloof and Intake stations was accomplished by accessing the data from the computer mainframe of the South African Weather Bureau (R. De Vos, pers. comm., 1994), and was subsequently reformatted in accordance with an *ACRU* format (R. Nundlall, pers. comm., 1994). In considering these two sets of data for determining rainfall for the southern part of the catchment, the Intake data was found to be incomplete for the last four months of 1993 and therefore the Kloof station was selected. Due to the paucity of raingauges in the northern section of the catchment, the Inanda station was chosen on the basis that it is the only rainfall station in that vicinity (Figure 3.1). As noted in Table 3.1 the rainfall data available for the Inanda station, operated by the South African Sugar Association, was incomplete in terms of the period for which the simulation is being conducted. In order to have the existing database (CCWR) updated, the data required to do so was accessed from the South African Sugar Experiment Station (SASEX), based at Mount Edgecombe on the Kwazulu Natal north coast. The data was obtained and prepared by the Department of Biometrics, SASEX, by accessing the data from the mainframe of the South African Sugar Association (SASA) and then prepared and copied onto a computer diskette. This data was manipulated and converted into the *ACRU* format. CCWR user consultant (R. Nundlall, pers. comm.) completed the update and acquisition of the rainfall data of the selected stations.

3.2.9.2 Rainfall estimation method for the Lower Mgeni catchment

Spatial variation in rainfall, errors in calculating areal averages and their effect on simulated runoff, and associated problems have been considered by many researchers. In an overview of this research, by Schulze, Dent and Schäfer (1989), it is observed that lumped models perform as well as a semi-distributed model when rainfall input is relatively uniform spatially; however, the semi-distributed model was superior when rainfall was areally heterogeneous. It is also noted that use of a single rainfall record as a lumped input can at best predict the peak discharge of a catchment, with a standard error in the order of twenty percent. Further, the use of non-representative set of raingauges can also result in poor runoff predictions. The spatial distribution of rainfall is influenced quite significantly by the physiographic characteristics of the catchment. Subdivision of the study area into subcatchments is based primarily on physiographic differences, and bearing in mind the points noted above, it is of critical importance to adopt an appropriate method of rainfall estimation for the different subcatchments of the Lower Mgeni.

Tarboton and Schulze (1992) describe two possible methods of rainfall estimation, namely:

(1) Estimation of interpolated rainfall surfaces, and

(2) Driver station rainfall estimation.

The author initially used a method very similar to the driver station rainfall estimation method to estimate rainfall; however, upon detailed examination and analysis of the technique described in Tarboton and Schulze (1992), their method was found to be more appropriate for application to this study catchment. The method used initially to estimate rainfall for each subcatchment is as follows:

(1) The mean annual precipitation, monthly average rainfall and altitude according to the one minute by one minute cell division grid, covering the entire catchment, was extracted from the CCWR data base, this information was transferred onto a map overlay depicting the catchment.

(2) Mean annual precipitation, averaged monthly rainfall data and altitude for the Inanda and Kloof rainfall stations were also extracted at the CCWR.

(3) Using simple calculation the average altitude and mean annual rainfall was determined for each subcatchment, using these values, a single 1 minute x 1 minute cell's rainfall was selected to be representative of that particular catchment.

(4) By using the average monthly rainfall data of the Inanda and Kloof rainfall stations (driver stations - source of rainfall data), and the mean monthly precipitation values of the selected cell (as determined above) of each subcatchment, the appropriate correction factors were determined and applied to this simulation.

The correction factor referred to above is determined by considering the difference in the values of average monthly rainfall between each subcatchment and the average monthly rainfall of it's respective driver station. This difference is accommodated by determining and applying a correction factor (expressed as a ratio), for example, if the rainfall (driver) station records a value of 100mm, whilst the hypothetical subcatchment being considered has a monthly average of 80mm, then taking note of the fact that rainfall for the subcatchment is lower than that of the driver station, the correction factor will be 0.8. Alternatively, if the subcatchment value was higher, example, 120mm, then the correction factor will be 1.2. Thus the use of correction factors enables more accurate representation of subcatchment rainfall, which permits better simulation of catchment hydrology. This method was utilised for the *ACRU* simulations conducted initially.

Although the method described above was found to be adequate for the purposes of this study (S.A. Lorentz, pers. comm., 1994), the author selected the method outlined in Tarboton and Schulze (1992) described as "Driver station rainfall estimation". It is the opinion of the writer that this method is superior to the one noted above. A description and application of the method used in this study follows.

3.2.9.3 Driver station rainfall estimation

Estimation of daily rainfall for each subcatchment, using the driver station method, was conducted according to the following steps as outlined by Tarboton and Schulze (1992, p20-21):

(1) A driver station was selected for each subcatchment according to the following criteria:

- it had to be as close as possible to, or within, the subcatchment,
- the difference between driver station mean annual rainfall and subcatchment rainfall had to be acceptably small,
- its altitude was representative of the subcatchment's mean altitude,
- it had a long continuous record with a minimum of missing or suspect data, and
- where data was missing the next best driver station, according to the above criteria, was used to estimate the missing rainfall.

(2) Median monthly rainfalls for each selected driver station were extracted from the CCWR database.

(3) Median monthly rainfalls for (1'x1') grid points (Dent, Lynch and Schulze, 1988) within each subcatchment were extracted from the CCWR database and averaged to obtain spatially representative subcatchment median monthly rainfalls.

(4) Daily rainfall was estimated for each subcatchment, by calculating weighted ratios between the subcatchment median rainfall and driver station median rainfall for a respective month for each driver station used, in order to estimate rainfall for a particular subcatchment. The weighted ratio was calculated according to the following equation:

$$R_w = P.R_m + R_a.(1 - P) \qquad \textbf{Eqn 3.1}$$

where,

R_w = weighted ratio for a respective month,

P = subcatchment median monthly rainfall as a proportion of subcatchment median annual rainfall,

R_m = ratio of subcatchment's median monthly rainfall to the driver station's median monthly rainfall,

R_a = ratio of subcatchment's median annual rainfall to the driver station's median annual rainfall.

The advantage, as described by Tarboton and Schulze (1992), for using a weighted ratio (R_w) rather than a simple annual ratio (R_a) or a simple monthly ratio (R_m), is that it places more weight on the annual ratio when the month has low rainfall and at the same time still allows monthly variation, in subcatchment to driver station median rainfall, to exert an influence. This influence, according to them, is greater in months with high rainfall and lower in months with low rainfall, thereby avoiding abnormally high ratios that could occur in low rainfall months (winter) if a simple monthly ratio were used.

Table 3.2 Driver station derived subcatchment correction factors

Monthly rainfall adjustment factors, CORPPT(i) (if PPTCOR ne = 0)												
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	
.84	.84	.82	.85	.89	1.04	1.06	.93	.92	.88	.84	.85	1
.79	.79	.80	.82	.83	.90	.91	.87	.87	.81	.81	.81	2
.84	.85	.81	.84	.82	.81	.85	.93	.83	.88	.86	.86	3
.79	.81	.79	.85	.85	.83	.81	.94	.83	.84	.82	.81	4

Taking into consideration the points noted in Tarboton and Schulze (1992), the "Driver station rainfall estimation" method was selected and applied to this study. The median monthly rainfall (driver stations) and the subcatchment factors are presented in Table 3.2. According to Tarboton and Schulze (1992) the weighted ratio determined should be limited to a minimum of 0.8 and a maximum of 1.2.

3.2.9.4 Rainfall data control variables

This section for input into the *ACRU* Menubuilder determines how the rainfall is interrogated by *ACRU* in a simulation. The first option (**PPTCOR**) refers to the adjustment to driver station rainfall in order to represent subcatchment areal rainfall. Three options are available:

0 = no correction to be applied,
1 = adjustment to be applied by multiplication of a factor **CORPPT(1)**,
2 = adjustment by addition or subtraction of a constant value because of a systematic error in raingauge recording **CORPPT(1)**.

The option selected is 1, that is, the adjustment is applied by multiplication of a factor, which is determined by using the "Driver station rainfall estimation" method as presented in Table 3.2.

3.2.10 Potential evaporation

3.2.10.1 Potential evaporation - some background

The accurate estimation of daily or monthly potential evaporation (E_p) is vital for hydrological modelling. This is particularly so for simulations performed in a region such as southern Africa, where generally an estimated ninety one percent of mean annual rainfall is returned to the atmosphere by evaporative losses, as against a global average of 65-70% (Whitmore, 1971). Many different methods of estimating potential evaporation exist and these include: lysimeters, complex physically based equations, evaporation pans and simple surrogates based often on single variables such as temperature. These methods provide different results under different climatic conditions. For the region of Southern Africa, A-pan evaporation has been selected as the reference potential evaporation (Schulze and Maharaj, 1991).

Class-A evaporation pan information has been accepted and used widely as a reasonably reliable and inexpensive representation of the potential evaporation process. The problem with utilising A-pan evaporation data, in general, and the study catchment, in particular, is the poor spatial distribution and absence of A-pan stations. The problem is compounded when this data has to be interpolated for unmeasured locations, especially where physiographic factors may be different from the location of the A-pan station. It is, therefore, necessary to use surrogates of A-pan evaporation. A number of equations have been developed to estimate the equivalent daily A-pan potential evaporation. The methods available in *ACRU* (Schulze, 1989d) include the physically based (Penman, 1948) and the temperature-based (Thornthwaite, 1948; Blaney and Criddle, 1950; Linacre, 1977; Linacre, 1984) equations. These methods are presented in Schulze (1989d), to which readers are referred to for further detail.

In their study, Clemence and Schulze (1982), evaluated temperature-based equations for the estimation of potential evaporation. They found, from the lysimeter studies undertaken under diverse South African climatic conditions and a variety of crops, that the equation proposed by Linacre (1977) proved to be superior to the others. It was also observed that the difference in efficiency, for estimating potential evaporation using either A-pan information or the Linacre (1977) equation, was minimal. The option to utilise the Linacre (1977) was enhanced further by the development of generalised "wind regions" (see Figure 3.6), which have been delimited by Dent, Schulze and Angus (1988). This development has provided predetermined wind factor values assigned to these regions, which have been built into the *ACRU* Menubuilder. Although the Linacre (1984) equation marks an improvement in the estimation of potential evaporation, the Linacre (1977) equation is recommended (Schulze and George, 1989) owing to the improved estimation of E_p, and was therefore selected.

The basic input required for Linacre's equation is monthly maximum and minimum temperatures.

Since this information is available at the Pinetown station, which was monitored for the period of 1960 to 1968, these averaged mean monthly maximum and minimum temperatures were utilised in the initial simulation. More representative temperature data, however, is available at the CCWR. This temperature information is the result of a study conducted by Schulze, Maharaj and Lynch (1989). In this study the southern African subcontinent was divided into 11 temperature lapse rate regions, depicted in Figure 3.7. For each region and month, stepwise multiple regression equations of mean, maximum and minimum temperatures were developed using the variables of altitude, latitude, longitude, distance from coast and physiographic index. Mean, maximum and minimum temperature, on a month by month basis, at a 1'x1' cell resolution, stored as gridded images covering South Africa is available at the CCWR. The monthly maximum and minimum temperatures are presented in Table 3.3 and Table 3.4 respectively. Conversion of monthly values to daily values is conducted internally within *ACRU* through Fourier analysis.

Table 3.3 ***ACRU* mean monthly maximum temperatures (^{0}C)**

Monthly means of daily max temperature, TMAX(i)												
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	
26.1	26.6	26.9	24.5	23.9	22.3	22.1	23.1	23.4	23.1	23.9	25.8	1
26.1	26.6	26.9	24.5	23.9	22.3	22.1	23.1	23.4	23.1	23.9	25.8	2
26.1	26.6	26.9	24.5	23.9	23.3	22.1	23.1	23.4	23.1	23.9	25.8	3
26.1	26.6	26.9	24.5	23.9	22.3	22.1	23.1	23.4	23.1	23.9	25.8	4

Although the calculation is conducted within the programme, the Linacre (1977) equation is presented. The equation was modified for use in South Africa (Dent, Schulze and Angus, 1988) where it was decided to adjust the equation by employing two significantly physical variables, namely, day length and windspeed.

Table 3.4 ***ACRU* mean monthly minimum temperatures (^{0}C)**

Monthly means of daily min temperature, TMIN(i)												
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	
18.5	18.7	18.1	15.9	13.0	11.1	10.8	12.3	14.0	15.0	16.4	17.6	1
18.5	18.7	18.1	15.9	13.0	11.1	10.8	12.3	14.0	15.0	16.4	17.6	2
18.5	18.7	18.1	15.9	13.0	11.1	10.8	12.3	14.0	15.0	16.4	17.6	3
18.5	18.7	18.1	15.9	13.0	11.1	10.8	12.3	14.0	15.0	16.4	17.6	4

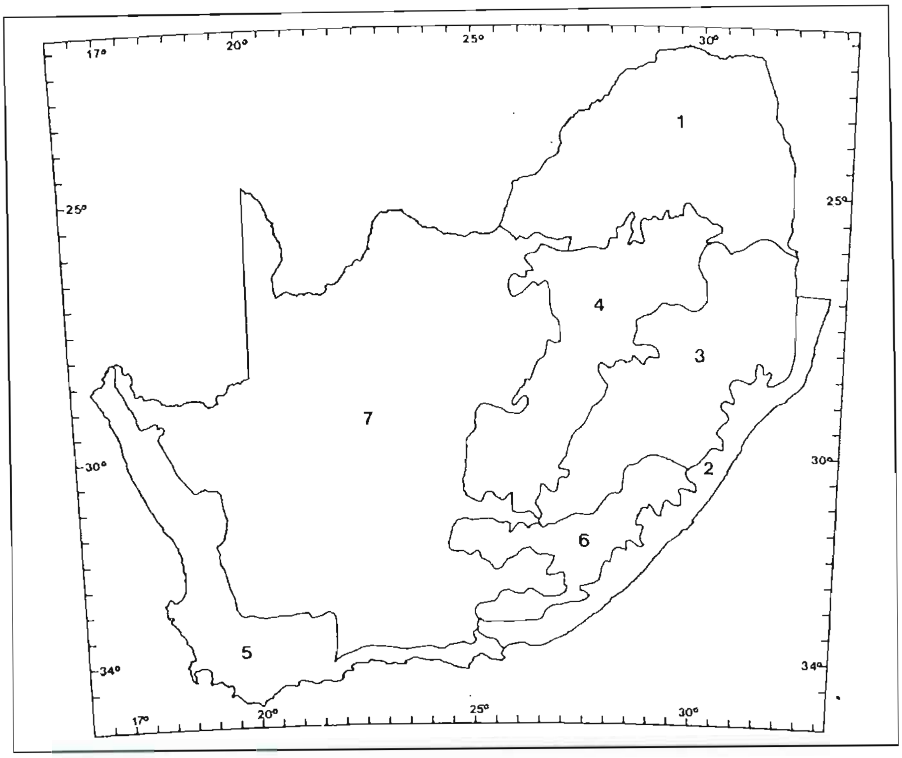


Figure 3.6 **Delimitation of major wind regions in southern Africa, after Dent, Schulze and Angus (1988)**

The Linacre (1977) equation is expressed as:

$$E_p = \frac{D_l\,(700T_m)/(100-\Phi) + u_1(T_a - T_d)}{(80 - T_a)} \qquad \textbf{Eqn 3.2}$$

where D_l = daylight hours/12

T_m = $T_a + 0.006A_m$, with

T_a = mean air temperature (^{0}C) = $(T_{max}+T_{min})/2$

A_m = altitude (m)

Φ = latitude (degrees) and

u_1 = windfactor

$(T_a\text{-}T_d)$ = difference between air and dew point temperature, approximated by = $0.0023A_m + 0.37T_a + 0.53R_m + 0.35R_{hc} - 10.9$ in ^{0}C $(T_a\text{-}T_d) > 4\ ^0$C in which

R_m = the mean daily or monthly range of temperature (^{0}C) and

R_{hc} = the difference between the mean temperature of the hottest and coldest months of the year (^{0}C)

3.2.10.2 *ACRU* - Potential evaporation control variables

The first variable (**EQPET**), specifying the method that was utilised to derive daily A-pan potential evaporation, has to be chosen. Among a number of options available, option 1, namely, the Linacre (1977) method was selected. The following variable refers to the type of temperature data (**TEMP**) available. In this study monthly means of daily maximum and minimum temperatures were used. The next variable considered is the wind coefficient for the Linacre (1977) potential evaporation equation (**LINWIN**). In southern Africa the coefficient is input by selecting a wind region number from the wind regions depicted in Figure 3.6, as delineated by Dent, Schulze and Angus (1988). **Wind region 2** (see Figure 3.6) was selected because the catchment under consideration for this study lies within this region.

The variable **TELEV** notes the altitude of the temperature station. This information is used to determine temperature: altitude correction (using regional lapse rates) to account for the subcatchment temperature. Lastly the variables to be taken into account are **XMAXLR** and **XMINLR**, which refer to minimum and maximum mean regional lapse rates (^{0}C .1000m^{-1}) respectively. These regional lapse rates have been determined by Schulze and Maharaj (1989) and the delineated regions are shown in Figure 3.7 (M. Maharaj, pers. comm., 1994). Lapse rate region 2 was selected for the *ACRU* simulation, as the study catchment lies within it, and the relevant mean maximum and minimum lapse rates were input.

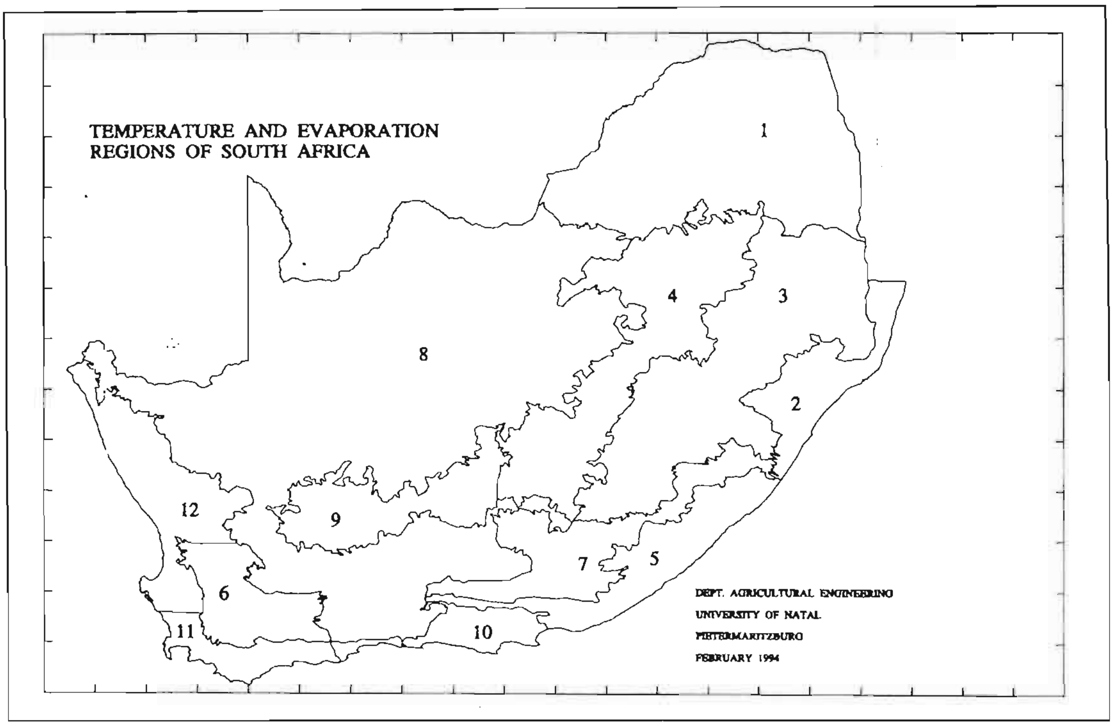


Figure 3.7: Regional lapse rates, after Schulze and Maharaj (1989)

3.2.11 Land cover

3.2.11.1 Theoretical background

The term "Land Cover", includes natural vegetation cover, land use (for agriculture and forestry) and urban land cover. Land cover processes with respect to hydrological modelling may be distinguished (Schulze, George and Angus, 1989) into two functional group processes, namely, above ground and below ground processes. The following factors, according to Schulze, George and Angus (1989) should be considered important:

(1) above ground factors concerned with
  - interception losses,
  - consumptive water use,
  - shading of soil, thereby separating total evaporation into soil evaporation and plant transpiration,
  - erosion protection (by plant/litter),
  - impervious areas, and

(2) below ground factors concerned with
  - plant root distribution,
  - root water uptake, and
  - the onset of stress and reduction rate of root water uptake and transpiration.

Taking into account these factors, the Department of Agricultural Engineering at the University of Natal commissioned the Institute of Natural Resources (INR) to provide data and information on the Mgeni catchment land cover. The INR was requested to undertake a land cover survey to classify and map land cover in the Mgeni catchment into different hydrological response classes (Tarboton and Schulze, 1992). For details on the INR land cover classification, the reader is referred to Bromley (1989a, 1989b) and Tarboton and Schulze (1992). Land cover information for the study catchment was extracted from the Mgeni catchment Geographical Information System. This information is depicted in a map (see Figure 3.8).

The INR land cover classes were grouped into 7 main groups. These main groups were divided into subgroups, which formed the 22 land cover classes as designated by the INR. The information of land cover classes and subcatchment proportional cover of the Lower Mgeni study subcatchments, together with the capacity of the LC programme (Lynch, 1993), determine hydrological land cover information to be used in the *ACRU* Menubuilder.

The LC programme allows the user to do area weighting based on the land cover information for each subcatchment. This is a stand-alone programme and the information that has been input is saved on a data file. Furthermore, this output file will contain land cover information before the area weighting is done and as well as the final information once the area weighting has been completed. Although the output file could be imported into the *ACRU* menu by using the ILCOVER (programme to import area weighted land cover information into the *ACRU* menu), in this study the output file was printed and the values for the different hydrological land cover variables were "manually" input into the *ACRU* menu.

The LC programme extracts the information of the different land cover classes within the subcatchment and allocates the appropriate hydrological land cover variables' (interception loss **VEGINT**, leaf area index **ELAIM**, crop coefficient **CAY**, and water extraction **ROOTA**). LC programme. Area weighting, the subsequent step, of the different hydrological land cover classes and their respective values of the variables, is then applied. The results of this procedure, that is, the values of the subcatchment's vegetation variables after area weighting, shown in Table 3.5, is typed directly into the *ACRU* menu. The following extracted values (Table 3.5), from the *ACRU* menu displays the input variable values utilised in this simulation.

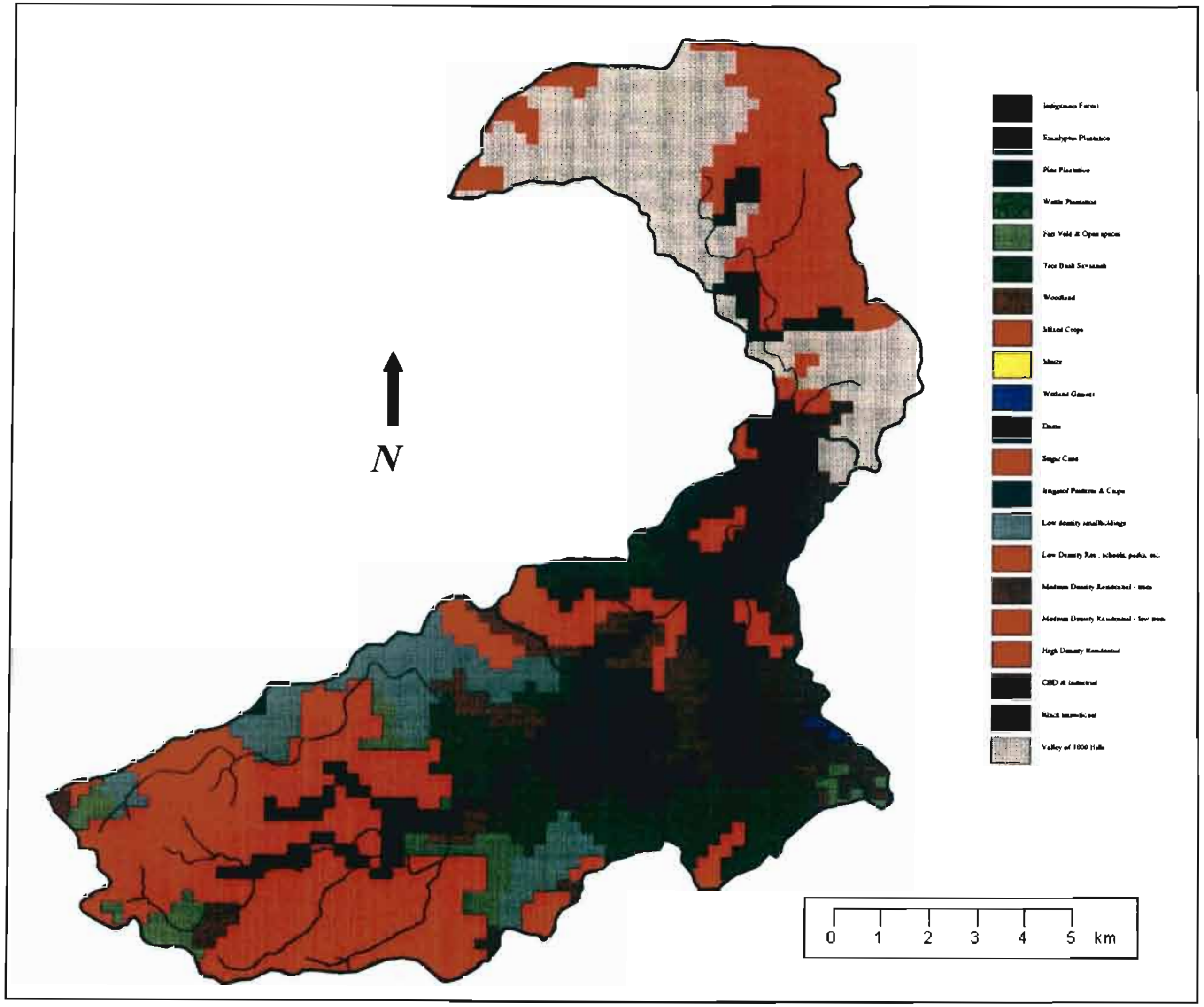


Figure 3.8: Land cover of the Lower Mgeni

Reference has already been made to the hydrological land cover variables of interception loss, leaf area index, crop coefficient and water extraction. These variables will be explained briefly and some important concepts noted in order to give further clarity. Interception, as noted in Schulze, George and Angus (1989) and Tarboton and Schulze (1992), is the process by which precipitation is "caught" by the land cover, stored temporarily as interception storage and then evaporated. Interception loss is the portion of precipitation, which after interception does not reach the ground, because, having being retained, it is either absorbed by aerial portions of the vegetation or returned to the atmosphere by evaporation. Tarboton and Schulze (1992) note that in the case of forests, water is evaporated at rates well in excess of available net radiation and potential evaporation. Hence, an enhanced wet canopy evaporation rate (E_w) has been incorporated into *ACRU* for simulation under forest cover. For detail on interception loss values, the reader is referred to the *ACRU* User Manual (Schulze and George, 1989).

Tarboton and Schulze (1992, p41) define the leaf area index (LAI) "as the planimetric area of the plant leaves relative to the soil surface area. It is a determinant of the consumptive water use by plants as well as of shading of the soil, protection of the soil from erosive raindrop impact and interception". There are different methods to calculate LAI. The method used in this study is described in the next section.

Crop coefficient (CAY) is described in Tarboton and Schulze (1992, p41) as follows:
"The CAY controls the maximum transpiration through a crop. Transpiration from the land cover is equivalent to the product of the reference evaporation (A-pan) and CAY for that day, when the plant is not subjected to stress. A separate variable for each land cover controls the soil water content at which the plant becomes stressed, whereafter transpiration is reduced below the maximum value."

In the *ACRU* model, soil water extraction takes place simultaneously from both soil horizons and in proportion to the assumed active rooting masses within the respective horizons (Schulze, George and Angus, 1989). ROOTA describes the fraction of active root mass in the topsoil horizon. Typical values of ROOTA have been incorporated into the Decision Support System of *ACRU*. Tarboton and Schulze (1992, pp41) state "on the premise that `roots look for water, water does not look for roots', there is a subroutine within *ACRU* whereby if the subsoil horizon is not stressed, but the topsoil horizon is, the subsoil's contribution to total evaporation is enhanced beyond that computed for its root mass fraction; similarly, if the subsoil horizon is stressed but the topsoil horizon is not, the topsoil's contribution is enhanced."

Table 3.5 **Menu depicting vegetation variable information**

Monthly mean of crop coefficients, CAY(i)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
.75	.75	.75	.68	.61	.55	.55	.55	.67	.71	.75	.75	1
.71	.71	.69	.59	.40	.32	.32	.32	.41	.58	.64	.71	2
.79	.78	.72	.65	.56	.50	.49	.49	.57	.65	.72	.76	3
.76	.76	.73	.63	.47	.40	.37	.37	.47	.62	.70	.75	4

Interception loss per rainday, VEGINT(i)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
1.67	1.67	1.67	1.67	1.49	1.48	1.48	1.48	1.66	1.66	1.67	1.67	1
1.52	1.52	1.52	1.51	1.44	1.38	1.38	1.38	1.39	1.43	1.48	1.52	2
1.60	1.60	1.51	1.41	1.34	1.28	1.28	1.28	1.30	1.35	1.47	1.57	3
1.72	1.72	1.72	1.60	1.49	1.37	1.37	1.37	1.32	1.53	1.63	1.72	4

Fraction of active root system in topsoil horizon, ROOTA(i)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
.78	.78	.78	.79	.84	.84	.84	.84	.78	.78	.78	.78	1
.85	.85	.85	.89	.91	.91	.91	.91	.88	.88	.86	.85	2
.79	.79	.81	.88	.92	.92	.92	.92	.88	.87	.81	.80	3
.83	.83	.83	.90	.91	.91	.91	.91	.89	.86	.84	.83	4

3.2.11.2 Incorporation of impervious land cover into *ACRU*

A significant portion of the study catchment under consideration may be classified as urban. It is, therefore, important to take into account the impervious land cover when simulating catchment hydrology. According to Tarboton and Schulze (1992), runoff from an impervious area is segregated into a portion that contributes directly to streamflow, and that portion which flows onto a pervious area.

In their view, impervious areas may be distinguished as:

(1) directly adjacent to a water course, stormwater drain or channel, in which case runoff from the impervious areas contributes directly to streamflow (adjunct impervious areas), or

(2) disjunct from a watercourse, where runoff from the impervious area flows onto a pervious area and contributes to the soil water budget of the pervious area (disjunct impervious areas).

This concept is accomplished in *ACRU* by, first, inputting into the Menubuilder that fraction of urban area of the catchment contributing directly to stream flow, and is, therefore, an adjunct impervious area (**ADJIMP**), and, second, that fraction of the catchment contributing directly to the soil water budget of pervious areas (**DISIMP**). It is expected in impervious areas that a certain amount of the precipitation is intercepted and stored, thereby not contributing to runoff, this fraction is input in the *ACRU* Menubuilder as the variable STOIMP (mm). Table 3.6, modified in collaboration with S.W. Kienzle (pers. comm., 1994), presents suggested default values of ADJIMP and DISIMP for different urban land covers. Default interception storage is assumed to be 1 mm for all the urban land covers used in *ACRU* (Tarboton and Schulze, 1992).

It should be noted in the process of determining ADJIMP and DISIMP, that these factors are calculated in terms of being impervious fractions of the entire catchment. The procedure to determine ADJIMP and DISIMP involves simple area weighting of the ADJIMP and DISIMP default values. The STOIMP of 1mm is assumed for the study. The ADJIMP and DISIMP factors utilised for the subcatchments of this study is presented in Table 3.7.

Table 3.6 Urban land cover classes used in *ACRU* and their default values, modified after Tarboton and Schulze (1992)

LAND COVER	% IMPERVIOUS	ADJIMP	DISIMP
CBD & Industrial	67.5	0.50	0.175
Res.- High	65.0	0.50	0.150
Res.- Medium	40.0	0.25	0.150
Res.- Low	20.0	0.05	0.150
Rural-Urban	20.0	0.00	0.20
Res.- Park	05.0	0.00	0.050

Table 3.7 Subcatchment ADJIMP and DISIMP factors

Streamflow simulation control variables							
QFRESP	COFRU	SMDDEP	IRUN	ADJIMP	DISIMP	STOIMP	
.30	.012	.00	1	.008	.009	1.00	1
.30	.012	.00	1	.040	.131	1.00	2
.30	.012	.00	1	.097	.182	1.00	3
.30	.012	.00	1	.075	.083	1.00	4

3.2.11.3 Catchment land cover information

The variable **LCOVER** offers the option of selecting whether vegetation information is input manually or whether defaults values are to be used in the simulation. Since the variables required for input for this simulation are determined using the LC programme, "actual" values were manually input into the Menubuilder; since this is the case, it is not necessary to examine all the options available for catchment land cover information variables. This input data for the respective subcatchments of the study area is presented in Table 3.5. The reader is referred to Schulze and George (1989) for further detail of options available in *ACRU*.

3.2.12 Soils

Soil is the medium in which many hydrological processes operate, and because of its capacity to absorb, retain and release, that is, redistribute water, spatial and vertical information on soils is essential for hydrological modelling. Soil information pertinent to hydrological modelling is, however, not always readily available in the detail or type of data required, therefore, it may have to be derived or implied from non-hydrologically based classification. This section focuses on some of the theoretical background and the procedures and decisions followed to input soil information into the *ACRU* model.

3.2.12.1 Soils input required for the *ACRU* modelling system

Tarboton and Schulze (1992) note that there are noticeable differences in the "rates and lags of hydrological processes within a catchment and between catchments as a consequence of hydrological processes associated with different soil properties", and the following soil information is identified as the minimum requirements for hydrological modelling using the *ACRU* modelling system:

(1) depths of top- and subsoil horizons (m)

(2) soil water retention at wilting point for top- and subsoil horizons (m.m^{-1})

(3) soil water retention at field capacity for top- and subsoil horizons (m.m^{-1})

(4) soil water retention at saturation (porosity) for top- and subsoil horizons, values of which may be perturbed by tillage practices, (m.m^{-1})

(5) daily fractions of redistribution of soil's water from top- and subsoil horizons when the topsoil water content is above field capacity

(6) daily fractions of redistribution of soil water from subsoil out of the active root zone when the subsoil's water content is above field capacity and

(7) information on changes of clay distribution within the soil profile, which, by implication of the above, must be gleaned from soil texture classes, clay percentages and sequences of soil horizons within soil series.

The significance of the soils information required above is explained in Schulze (1989e) and Tarboton and Schulze (1992), to which the reader is referred to. It is also noted that *ACRU* operates for general use with two `active' horizons in which rooting development occurs, and ,therefore, soil water extraction occurs through evaporation and transpiration.

3.2.12.2 Source of soil information

The former Soil and Irrigation Research Institute (SIRI) of the State Department of Agricultural Development remains the prime source of soils information in southern Africa. SIRI, now the Institute for Soil, Climate and Water (ISCW) is involved in carrying out a national Land Type survey which aims to delineate Land Types at 1:250 000 scale (with field work at 1:50 000), to define each Land Type and analyse soil profiles within the Land Type (SIRI, 1987). Unpublished Land Type field maps at a scale of 1:50 000 covering the Mgeni catchment, including the study area, were made available for the Mgeni Project and were subsequently digitised by the Department of Agricultural Engineering (DAE), (Tarboton and Schulze, 1992). The 226 Land Types found within the Mgeni catchment were grouped into similar Land Types (Tarboton and Schulze, 1992); Figure 3.9 depicts the Land Type distribution in the Lower Mgeni study catchment. In addition to the Land Type maps, SIRI made the computerised inventories for each Land Type within the Mgeni catchment available to the DAE for inclusion in the Mgeni information base (Tarboton and Schulze, 1992).

The Land Type series, although not intended as a hydrological data inventory, has been found to have excellent potential for hydrological decision making, as for example in the case of hydrological information determined for use in the *ACRU* model. Although not useful in its original format, the Land Type information can be "translated" into *ACRU* variables.

3.2.12.3 "Translation" of Land Type information for application in *ACRU* for the Lower Mgeni catchment

The hydrological input information for this hydrological simulation is determined by utilising the interactive soils Decision Support System (DSS) that is incorporated into the *ACRU* modelling system. The DSS is linked to Land Type inventories by a suite of computer programmes which facilitate a "translation" of the Land Type inventory information into hydrologically useful variables (Tarboton and

Schulze, 1992). Land Type information can be translated at the level of:

(1) individual soil series of a terrain unit within a Land Type, or of

(2) averaged values of individual Land Types, or at the level of

(3) a defined catchment, which is made up of various percentages (adding to 100%) of a number of Land Types delimited within it.

For the Mgeni catchment the GIS was used to combine the subcatchment boundaries and spatial soils information to obtain a summary of Land Types and their relative proportions within each subcatchment. This information is illustrated in Figure 3.9 and the proportional distribution is noted in Appendix 1. These values for the 4 subcatchments in the study area were entered (G.P. Jewitt, pers. comm., 1994) into the soil DSS to obtain a translation of the Land Type information into hydrological soil variables required by the *ACRU* modelling system.

Under the soil input section of the Menubuilder, selection of the **PEDINF** refers to the decision as to whether the hydrologically relevant information can be considered adequate or not. In this study the **YES** option was chosen as the input data (Table 3.9), because necessary hydrologically relevant information was generated using the soil DSS, making "adequate" information available. Although the hydrological soil input information is generated by entering the Land Type information into the soils DSS, some important procedures are followed and assumptions are made, to produce the input variables. These include: clay distribution model and class, PO, FC for top- and subsoil, WP for top- and subsoil and saturated response fractions are assigned to each Land Type series. The relevant tables and suggested input values utilised to obtain these variables are described in Schulze (1989e), Schulze *et.al.* (1989) and Tarboton and Schulze (1992).

When the "adequate" soil information option is selected, the variables and values tabulated in Table 3.8 are required as input. The procedure to determine this data for each individual catchment is initiated by identifying the numbers of soil groups present, and thus the need to obtain a weighted average of the estimated values. Using the soils DSS, the following topsoil variables are determined: permanent wilting point (WP1), field capacity (FC1), and saturation (that is, porosity, PO1) for each soil group, and the proportional percentage soils group cover. This procedure is repeated for the subsoil, thus determining values for WP2, FC2 and PO2. The soils DSS component of the *ACRU* Menubuilder performs all area weighting automatically, producing the output of values of the variables noted above. The hydrological soil information generated by the DSS for the 4 study subcatchments is presented in Table 3.8.

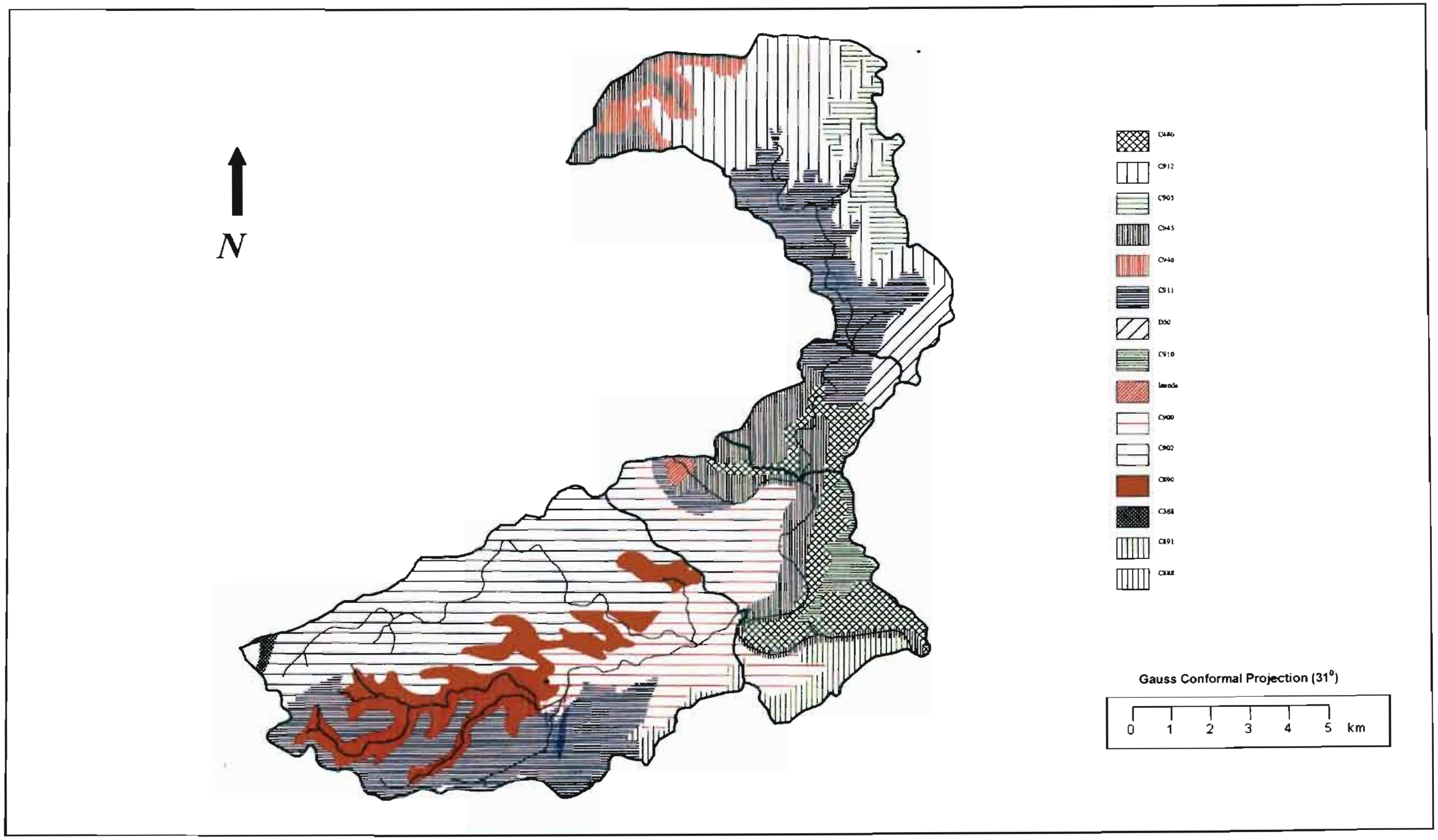


Figure 3.9: Land Type distribution in the Lower Mgeni

Table 3.8 Hydrological soil input data generated by the soil DSS for *ACRU*

Soils information (II) (if PEDINF=1)										
DEPAHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO2	ABRESP	BFRESP	
.17	.35	.124	.128	.227	.243	.442	.432	.39	.28	1
.20	.41	.127	.140	.229	.256	.430	.426	.39	.28	2
.21	.42	.112	.125	.213	.239	.451	.435	.46	.32	3
.18	.37	.113	.109	.213	.219	.447	.428	.45	.29	4

where, DEPHO, DEPBHO = Depths of top- and subsoil horizons (mm)

WP1, WP2 = Soil water content at permanent wilting point (m.m^{-1}) for top- and subsoil horizons

FC1, FC2 = Soil water content at field capacity (m.m^{-1}) for top- and subsoil horizons

PO1, PO2 = Soil water content at porosity (m.m^{-1}) for top- and subsoil horizons

ABRESP, BFRESP = Redistribution fractions of "excess" water (per day), top- and subsoil and subsoil to drainage

3.2.13 Streamflow simulation control variables

The theoretical background relevant to this section is already discussed in Section 2.2 "Streamflow simulation". Therefore, this section shall only describe the streamflow simulation variables selected and, where necessary, additional explanation will be provided. The streamflow simulation in the *ACRU* model is based on linking the principles of the SCS technique with a two-layer soil water budget to generate stormflow (Schulze and George, 1989). It is also noted that for any given (total daily rainfall) event the quickflow fraction is only a portion of the generated stormflow that contributes to streamflow. The quickflow fraction is represented by the variable **QFRESP**, and the other portion of flow is the baseflow component. Generally, some of the rainfall contributes to an intermediate groundwater store; a fraction of this water is released, becoming baseflow on that particular day. The coefficient of baseflow response is represented as **COFRU** in *ACRU* and typical values, according to Schulze and George (1989), would range from 0.02 to 0.05. The next variable considered is **SMDDEP**, representing the effective depth of the soil (m) assumed to be contributing to stormflow production; the option to use the default value of the depth of the A horizon was selected. Choosing between whether baseflow is to be included or excluded from the runoff simulation statistics (**IRUN**) is the next selection; in this simulation the baseflow is included. The following input factor to be determined is the portion of the catchment comprised of impervious areas (**ADJIMP**). The method to calculate **ADJIMP** is outlined in Section 3.2.11.2. The final variable considered relevant to this simulation is **COIAM(I)**. This factor represents a monthly coefficient that estimates "the rainfall abstracted by interception, surface storage and infiltration before runoff commences".

3.2.14 Peak discharge control variables

Peak discharge simulation is required in order to estimate sediment yield. It is estimated by means of a modified SCS equation. Peak discharge is discussed in Section 2.3 and the methods utilised to estimate peak discharge (Equation 2.2) and determine catchment lag time (Equation 2.6) are outlined. The procedure and reasons for selecting the relevant equations is also described. This section of the study presents the peak discharge control variables selected as input for *ACRU*'s simulation. **PEAK** refers to whether peak discharge is to be estimated or not. As mentioned, it is necessary to simulate (**YES**) because it is fundamental to estimating sediment yield using the MUSLE equation in *ACRU* model. If the **YES** option is selected further information is required and is noted below. Another significant variable that had to be selected is the method to calculate catchment lag time (**LAG**). From the three options available, the Schmidt-Schulze method (**OPTION 2**) was used in this study. In order to use the Schmidt-Schulze equation the following information had to also be provided: (1) **SLOPE** - average subcatchment slope; (2) **XI30** - 2-year return period 30-minute rainfall intensity in mm.h^{-1}; and (3) **XMAP** - mean annual precipitation (mm) over the subcatchment. The input information required is presented in Table 3.9.

3.2.15 Sediment yield variables for use in 'MUSLE'

The Modified Universal Soil Loss Equation (MUSLE) is used to estimate sediment yield in the *ACRU* model, and is given as:

$$Y_{sd} = 8.93(Q.q_p)^{0.56}KLSCP \qquad \textbf{Eqn. 3.3}$$

where

8.93 = runoff erosivity constant

0.56 = runoff erosivity exponent

Y_{sd} = sediment yield for an individual event (tonne)

Q = storm runoff volume for the event (m^3), and

q_p = peak discharge for the event (m^3.s^{-1})

K = soil erodibility factor(dimensionless)

LS = slope length and gradient factor(dimensionless)

C = cover and management factor(dimensionless)

P = support practice factor(dimensionless)

Table 3.9 **Peak discharge input requirements for the Lower Mgeni subcatchments**

Peak discharge control variables (if PEAK=1)		
LAG	SLOPE	
2	14.1	1
2	15.6	2
2	13.0	3
2	254	4
Peak discharge control variables (if PEAK=1 and LAG=2)		
XI30		
56.44	1	
56.44	2	
56.44	3	
56.44	4	

Having selected this option (**MUSLE = 1**) there are several factors used to characterise the state of the catchment in terms of: its runoff energy (namely, runoff erosivity constant, 8.93, and exponent, 0.56), its inherent soil loss potential (namely, the soil erodibility factors **SOIFAC1** and **SOIFAC2**), the slope length (**ELFACT**), the support practice (**PFACT**) and the cover factor (**COVER*(I)***) (Lorentz and Schulze, 1995). This part of the dissertation reports on the methods followed to determine the variables of the MUSLE. The storm runoff volume (**Q**) and peak discharge ($\mathbf{q_p}$) for the event are calculated internally within *ACRU*. The techniques utilised to estimate these variables is described in sections 2.2 and 2.3 respectively.

3.3.15.1 The soil erodibility factor (K)

The soil erodibility factor, one of the required inputs into *ACRU*, is the K-factor values of each subcatchment within the study catchment. K (*ACRU* variable = **SOIFAC**), is calculated by means of a modified spreadsheet programme (S.A. Lorentz, pers. comm., 1994). An example of Land Type information for Land Type c911 is given in Appendix 2.

The following variables had to be determined as input requirements of the spreadsheet programme. The basic information is taken directly from the computerized Land Type inventory. However, some calculation is involved in estimating certain input variables. Land Type series, soil series, soil horizon depth, soil texture and the number and proportional percentage of cover of the terrain units present, is assumed directly from the computerised Land Type inventories. The percentage clay is taken as the mean of the range (clay content) that is given in the computerised inventories. Using this averaged value of clay content and the soil texture, with the aid of a Soil Texture Chart (Figure 3.10), after Macvicar *et.al.*, 1977) the percentage silt content is estimated. Upon input of this information the spreadsheet automatically calculates the total percentage of sand, which is further segregated into silt plus very fine sand and coarse sand fractions (see Appendix 2).

Thereafter, the factors of organic matter content, the structure code and permeability code had to be determined. The procedures followed to estimate these variables is as described below:

(1) Organic matter content: The values for organic content of the soil series present was estimated with the assistance of S.W. Kienzle (pers. comm., 1994). The organic content value ranges from 0.5% to 4% and a value of 2% is assumed to be the default value. As a general rule one may assume the darker the soil, the higher the organic matter content. In assigning organic matter content values, the following broad categories were assumed: soils that are light in colour and have no roots present are allocated a value of 0.5%; light soils with roots assume a value of 1%; and if the soil is darker the value may be increased to between 2-3%. In summary, organic content values were estimated from photographs of soil profile (Macvicar, *et. al.*, 1977) and the estimated values verified and adjusted.

(2) Structure Code: Soil structure is an essential factor in calculating soil erodibility. The method of determining structure was established in consultation with S.W. Kienzle (pers. comm., 1994). The structure code is given as noted in Table 3.10.

Table 3.10 Structure codes utilised in this study

CLAY CONTENT	% COMPOSITION	CODE
Low	< 7%	1/2
Medium	> 7% < 25%	3
High	> 25%	4

Clay content is significant in determining the structure code. Broadly, if the clay content is low (< 7%) the code would be 1 or 2; and if the clay content is high (> 25%) the code would be 4; and if the clay content is medium (in between the values allocated for the low and high

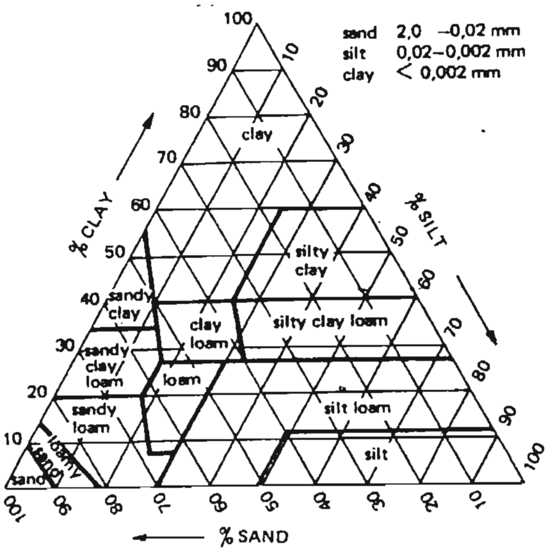


Figure 3.11 Soil texture chart, after Macvicar *et.al.*, 1977

categories) then it would fall in the structure code 3. In addition to considering clay content, the structure of the soil is determined by viewing the soil profile photographs (Macvicar, *et. al.*, 1977). The structure may be described as very fine granular, fine granular, medium or coarse granular or blocky/platy or massive, and the appropriate structure code is selected (see Table 3.11).

(3) Permeability code: The first step is to determine the SCS Grouping of each relevant soil series This accomplished according to the hydrological information by soil form and series for southern Africa, Schulze and George, 1989, which is based on the soil erodibility nomograph developed by Wischmeier *et.al.*,1971). Using the information in Table 3.11, the permeability code was selected and entered into the spreadsheet programme.

This section outlines the variables required and the method employed to determine K-factors used in *ACRU*. Each subcatchment is made up of different Land Type series, which in turn comprise a number of terrain units that occur at "fixed" proportional percentage cover. Further, each terrain unit is made up of soil series that occur in a "fixed" combination and proportion (see Table 3.11, percentage area). One of the primary sources of information are the SIRI computerised inventories for each Land Type within the Lower Mgeni study catchment, which has been incorporated into the Mgeni information base, and is available at the Department of Agricultural Engineering, University of Natal,

Table 3.11 **Permeability codes utilised, modified after Schulze and George, 1989**

SCS GROUPING	CODE
D	6.0
C/D	5.0
C	4.0
B/C	3.5
B	3.0
A/B	2.0
A	1.0

An example of the computerised SIRI Land Type inventory is depicted in Appendix 2. Some of the information utilised in the spreadsheet programme is extracted from the computerised Land Type inventories. The K-factor values of the different soil series has to be calculated in order to determine terrain unit K-factors. To this end the spreadsheet programme is written in a format to include a component that utilises an area weighting procedure for the K-factors of the soil series found within that terrain unit. Hence, the first step towards determining the subcatchment's K-factor is the calculation of individual K-factor values for each soil series. Once the required information is provided, the spreadsheet programme calculates the K-factors of each soil series, and, utilising the area-weighting component of the programme, the K-factor of the terrain units under consideration is determined.

Once the K-factor of the different Land Type series found in the Lower Mgeni subcatchments has been calculated, area weighting of the proportional Land Type series cover of each subcatchment (see Appendix 1) is conducted, and hence the K-factor values were determined for the 4 subcatchments of the study area.

Renard *et.al.* (1991) report that significant variability in K-factor values is caused by antecedent soil water conditions and by seasonal variations in the value of soil erosion determinant properties. This concern is noted in Lorentz and Schulze (1995), where a method is outlined to specify the required K_{max} and K_{min} values. In their research Renard *et.al.* (1991) report that the ratio of dry period to wet period K-factors (K_{max}/K_{min}) varies between three and seven. Therefore, it is necessary to employ a method that takes into account variation in K-factor value.

The K_{max} and K_{min} values (**SOIFAC1**, **SOIFAC2**) are determined by first estimating a nominal K-factor, K_{nom}, as described in the preceding part of this section. This is taken as the average K-factor which together with an estimate of the K_{max}/K_{min} ratio, is used to determine the K_{max} and K_{min} values (Lorentz and Schulze, 1995); and is calculated as follows:

$$K_{min} = 2K_{nom}/1+r_k$$

$$K_{max} = K_{min}.r_k$$

where r_k = estimate of K_{max}/K_{min} ratio - based on information of the average and monthly variation of rainfall erosivity.

The method noted above was not utilised in this study. Instead, the values for K_{max} and K_{min} were estimated with the assistance of S.A. Lorentz (pers.comm., 1994). The method involved making the assumption that the previously calculated K-factor, K_{nom}, (Appendix 2) is K_{max}. K_{min} was determined by dividing the K_{max} value by five ($K_{max}/ 5 = K_{min}$). The calculated values for K_{max} and K_{min} for the subcatchments are displayed in Table 3.12.

In evaluating the results of the "final" simulation run (S.A.. Lorentz, pers. comm., 1994), sediment yield values were found to be exceedingly high and therefore unacceptable. As a result, the process that followed entailed investigating that aspect of concern in order to rectify the problem. Initially, subcatchment C-factors were examined as a possible cause to problem. These C-factor values were recalculated based on certain modified landuse C-factors, using the RUSLE method. Although the results produced showed a decrease in sediment yield, these results were found to be unacceptably high. This was then followed by an investigation into the K-factor. Adjustment to the K-factor involved substituting the single K-factor with K-maximum and K-minimum (see Section 3.15.1). Although the outcome of this modification showed a reduction in sediment yield values by approximately half, the values still exceeded realistic expected values of the study catchment. Based on the view that the model may be flawed, an intense examination of the sediment yield and related components of the model, followed. After a week of systematic examination of the model, it was discovered that a part of the programme was incorrectly written (S.A. Lorentz, pers. comm. 1994). Correctly written the programme should calculate daily K-factors based on daily antecedent moisture conditions (AMC). The model however was utilising the single highest AMC value to estimate daily K-factors, thereby producing unacceptably high sediment yield values. On correction of this problem, the subsequent results of sediment yield results reflected more realistic values. These results compare favourably with expected values of sediment yield for the study area.

3.2.15.2 The slope length factor (ELFACT)

Although slope length factors have been calculated, using the method outlined in Schulze (1989b) and S.W. Kienzle (pers. comm., 1994), these were rejected in favour of the procedure noted in Lorentz and Schulze (1995). *ACRU* input variable **ELFACT** is the length steepness factor, LS, which comprises a slope length factor, L, and a slope steepness factor, S. Slope length and gradient are important because these factors effect the rate of soil erosion. Slope length is defined as the distance from the point of origin of overland flow to the point where gradient decreases sufficiently to allow deposition, or where the runoff enters a well defined natural or constructed channel (Schmidt, 1989). This section describes the procedure to obtain the length-steepness factor (ELFACT).

The gradient values utilised in this study were extracted from the Mgeni database available at the DAE (S.W. Kienzle, pers. comm., 1994). These values are tabulated in Table 3.12. Based on these data, the following step is the calculation of the slope length and slope length factor.

Table 3.12 Subcatchment K_{max} and K_{min} - factor information

Sediment yield variables (if MUSLE=1 and PEAK=1)								
SOIFAC1	**SOIFAC2**	ELFACT	PFACT	ICOVRD	SEDIST	ALPHA	BETA	
.38	.07	1.97	1.00	0	.30	8.93	0.56	1
.41	.08	2.06	1.00	0	.30	8.93	0.56	2
.40	.08	2.01	1.00	0	.30	8.93	0.56	3
.46	.09	1.66	1.00	0	.30	8.93	0.56	4

Slope length was estimated by the following equations (Lorentz and Schulze, 1995):

$$(\lambda_l) = -3.0S_{\%} + 100 \qquad \text{for } S_{\%} < 25\% \qquad \textbf{Eqn. 3.4}$$

and

$$(\lambda_l) = 25 \qquad \text{for } S_{\%} > 25\% \qquad \textbf{Eqn. 3.5}$$

where

$S_{\%}$ = slope gradient in percent

Having determined the slope length, the slope length factor is calculated using the following equations.

$$L = [\lambda_l/22.1]m \qquad \textbf{Eqn. 3.6}$$

where

22.1 = the RUSLE unit plot length in metre and

m = a variable slope length exponent, related to ratio, β, or rill to interill erosion by

$$m = \beta_r/1+\beta_r \qquad \textbf{Eqn. 3.7}$$

where

$$\beta_r = \sin\Phi/0.0896[3.0(\sin\Phi)^{0.8} + 0.56 \qquad \textbf{Eqn. 3.8}$$

where

Φ = the slope angle in degrees

The next stage of the procedure is to calculate slope steepness factor, S, by means of the following equations.

$$S = 3.0(\sin\Phi)^{0.8} + 0.56 \qquad \textbf{Eqn. 3.9}$$

The slope length and steepness factor, LS (**ELFACT**), for each subcatchment is calculated by the simple multiplication of the slope length factor, L, and the slope steepness factor, S.

$$ELFACT = L \times S \qquad \textbf{Eqn. 3.10}$$

The factors calculated above indicate the method to determine slope length factor, and is tabulated in Table 3.13.

Table 3.13 Subcatchment slope length and steepness factor (ELFACT) information

Catch.	Slope %	λ_l	Slope ^{0}	β_r	m	L	S	SL
1	14.1	57.7	8.026	1.319	0.5325	1.667	1.181	1.9690
2	15.6	53.2	8.867	1.396	0.5826	1.668	1.232	2.0550
3	13.0	61.0	7.407	1.259	0.5573	1.761	1.143	2.0130
4	25.4	25.0	14.239	1.786	0.6410	1.082	1.537	1.663

3.2.15.3 The cover and management factor

The Cover and Management factor, C (*ACRU* variable **COVER**), according to Schmidt (1989), is probably the most important factor in the MUSLE equation. This is primarily due to the fact that humans have the most influence on C factor, that is, in terms of conservation practice. C-factors had to be determined for the twenty land cover classes identified in the study catchment. Each land use practice may be comprised of a further number of land use practices that occur in "fixed" percentages.

It is therefore necessary in certain cases of C-factor calculation to utilise a proportional weighting function to generate a representative C-factor of that particular land use. The various land uses and their respective land use C-factor components that were utilised in this study is presented in Appendix 3, and the broad land covers are disaggregated into their component land covers. C-factor values for the cultivated crops were obtained at the DAE (S.W. Kienzle, pers. comm., 1994). The COVER factor values for uncultivated land, that include permanent pasture, veld and woodland and undisturbed forestland, is extracted from Tables 3.14 and 3.15 (Lorentz and Schulze, 1995). The C-factor estimates for the urban land use classes, noted in Appendix 3, were determined in consultation with S.W. Kienzle and S.A. Lorentz (pers. comm., 1994).

The range in listed C-values are caused by the ranges in the specified litter covers and by variations in effective canopy heights

The C-factors were estimated by the method outlined above. An alternative method utilising the procedure outlined for the calculation of C-factor for RUSLE is suggested by Lorentz (pers.comm., 1994). Unfortunately, most of the input variables required for this method of estimation were not available for virtually all the landuses. Although this is a superior method for determining C-factors, it

Table 3.14 C-factor for undisturbed forest land

Percent of area covered by canopy of trees and undergrowth	Percent of area covered by litter at least 50mm deep	Cover Factor
100 – 75	100 – 90	.0001 - .0001
70 – 45	85 – 75	.002 - .004
40 – 20	70 – 40	.003 - .009

Table 3.15 C-factor for permanent pasture, veld and woodland, Schulze (1989)

Vegetative canopy		Cover that contacts the soil surface						
			Percent ground cover					
Type and height	Percent cover	Type	0	20	40	60	80	95-
No appreciable canopy	25	G	0.45	0.2	0.1	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Grassland or short brush with average drop fall height of 0.5m	25	G	0.36	0.17	0.09	0.038	0.013	0.003
		W	0.36	0.2	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.17	0.1	0.06	0.032	0.011	0.003
		W	0.17	0.12	0.09	0.068	0.038	0.011
Appreciable brush or bushes, with average drop fall height of 2m	25	G	0.4	0.18	0.09	0.068	0.038	0.011
		W	0.4	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.4	0.011
Trees, but no appreciable low brush. Average drop fall height of 4m	25	G	0.42	0.19	0.1	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.4	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.2	0.13	0.084	0.041	0.011

was found to be unsuitable due to the lack of required data. However, original C-factors were modified by calculating a new C-factor value for grass (0.0008), based on the "RUSLE" method. The assumptions that the "pasture" and "undifferentiated open space" land uses be assigned the same C-factor as that of grass, also contributed to the modification of the subcatchment C-factors. These modifications adjusted the subcatchment C-factor values utilised in the study. The C-factor information relevant to the 4 subcatchments of the study area is presented in Table 3.16.

Table 3.16: Subcatchment CP-Factors

CATCHMENT 1 (105)	**CP-FACTOR**	**%LANDTYPE**	**CP-CATCH**
Indigenous forest	0.0010	5.33	0.0001
CBD & Industrial	0.0002	1.13	0.0000
Valley of 1000 hills	0.0704	53.23	0.0375
Sugar cane	0.1500	33.50	0.0503
Undifferentiated cropping	0.1503	1.91	0.0029
Low density residential - gardens	0.1769	4.24	0.0075
Rural urban transition	0.2006	0.63	0.0013
		99.97	**0.0994**
CATCHMENT 2 (146)	**CP-FACTOR**	**%LANDTYPE**	
Indigenous forest	0.0010	13.78	0.0001
CBD & Industrial	0.0002	7.95	0.0000
Tree bush savannah	0.0146	2.22	0.0003
Valley of 1000 hills	0.0704	7.16	0.0050
Undifferentiated cropping	0.1503	10.27	0.0154
Rural urban transition	0.2006	58.62	0.1176
		100.00	**0.1385**
CATCHMENT 3 (137)	**CP-FACTOR**	**%LANDTYPE**	
Mixture undifferentiated forest	0.0010	0.70	0.0000
Indigenous forest	0.0010	8.01	0.0001
High density residential	0.0572	1.08	0.0006
Medium density residential - few trees	0.0538	36.31	0.0195
Woodland	0.0562	1.36	0.0008
Medium density residential - trees	0.0608	9.59	0.0058
Tree bush savannah	0.0146	3.16	0.0005
Parks, sportsfields, etc	0.0955	0.81	0.0008
Grassland	0.0043	2.41	0.0001
Undifferentiated open space	0.0008	4.06	0.0000
Sugar cane	0.1500	14.40	0.0216
Low density smallholdings	0.1303	11.51	0.0150
Undifferentiated cropping	0.1503	0.02	0.0000
Rural urban transition	0.2006	6.27	0.0126
		99.69	**0.0774**

3.2.15.4 Support practice factor

As a general rule, in the case of pasture, veld, bush and forest land uses, the protection provided for the soil does not vary significantly throughout the year and residual effects are not marked. The P-factor of 1 (*ACRU* variable **PFACT**) is generally assumed for uncultivated lands. Since the land use of the subcatchments under consideration is primarily uncultivated and there are no conservation practices, a P-factor of 1 is assumed in this study.

CHAPTER 4: RESULTS AND VALIDATION

The hydrological modelling system for the Lower Mgeni catchment was set up to enable simulation from 1990 to 1998, after the Inanda dam became operational in 1989. The *ACRU* hydrological model is capable of simulating many different hydrological variables and performing different functions. For the purpose of this study, streamflow and sediment yield are considered. Although the *ACRU* model simulates on a daily time step only, the monthly statistics are reported. The estimated rainfall, simulated runoff and sediment yield results, and selected statistics of the Lower Mgeni catchment are presented and discussed in this chapter. The Lower Mgeni is comprised of subcatchments 1 to 4, with a cumulative catchment area of 147.15 km^2.

While simulation of streamflow is conducted in the distributed mode, modelling of catchment sediment yield cannot as yet be performed in this mode. This implies that the total streamflow results from subcatchment 4 represents streamflow production of the entire study catchment, while simulated runoff reflects subcatchment runoff. However, the investigation of sediment yield results of the Lower Mgeni catchment necessitates, that the results of the subcatchments be considered individually, as if each subcatchment was modelled separately and independently of the other catchments.

4.1 RESULTS AND VALIDATION OF SIMULATED RAINFALL OF THE LOWER MGENI

4.1.1 Rainfall Results

Rainfall, the driving mechanism in any hydrological simulation, remains the single most important variable in hydrological modelling. As such it is imperative that estimation of rainfall for the subcatchments are accurate. The method used to determine rainfall for the individual subcatchments within the Lower Mgeni, is described in Section 3.2.1. The rainfall of the individual subcatchments and that for the total Lower Mgeni catchment for the duration of the simulation period, are presented and described respectively.

A summary of the descriptive statistics of subcatchment rainfall (Table 4.1), permits a comparison of rainfall between the 4 subcatchments and a description of the rainfall characteristics for the Lower Mgeni. It is evident from Table 4.1 and Figures 4.1 (Comparison of mean monthly rainfall); 4.2 (Minimum monthly rainfall); and 4.3 (Maximum monthly rainfall) that there is no significant variation in rainfall between the subcatchments. In the comparison between mean monthly rainfall with respect to mean, minimum and maximum values, it is noted that the values are generally higher for Subcatchment 1 as compared to Subcatchment 2, and a similar trend was observed when comparing Subcatchment 3 to Subcatchment 4 respectively. A possible explanation for the difference may lie in the fact that subcatchments 1 and 2, and subcatchments 3 and 4 have different rainfall driver stations and different monthly precipitation correction factors. However, it is also evident that there is no

Table 4.1 **Descriptive statistics of monthly rainfall (mm)**

Mean	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
Catch1	109.6	68.2	95.6	32.0	14.9	11.3	33.8	17.4	32.1	94.5	77.5	117.0	703.9
Catch2	99.7	61.6	87.8	30.3	14.0	11.3	33.8	16.5	29.4	86.9	71.3	106.9	649.6
Catch3	111.2	80.7	104.3	33.9	11.6	12.4	21.9	16.1	36.1	109.9	77.4	130.9	746.2
Catch4	98.8	72.5	94.5	30.9	10.3	11.3	18.2	14.6	32.2	98.8	71.1	117.8	671.0
Lower Mgeni	107.5	74.4	98.9	32.5	12.4	11.8	25.1	16.2	33.8	102.0	75.7	122.9	713.1
Minimium	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
Catch1	51.6	13.1	31.3	12.6	0.0	0.4	0.0	0.0	6.6	60.7	40.7	24.3	422.0
Catch2	46.9	11.9	28.7	12.0	0.0	0.4	0.0	0.0	6.1	55.8	37.4	22.2	387.6
Catch3	63.0	19.8	31.9	5.9	0.2	0.2	1.2	1.3	6.5	68.7	33.9	46.4	387.3
Catch4	56.0	17.7	28.9	5.4	0.2	0.2	1.0	1.2	5.8	61.8	31.2	41.8	348.4
Lower Mgeni	57.4	17.1	30.9	8.0	0.1	0.3	0.8	0.8	6.4	64.3	35.4	37.9	388.7
Maximium	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
Catch1	213.70	145.10	176.70	81.20	50.30	35.00	121.80	54.30	100.20	120.30	163.90	306.20	868.40
Catch2	194.50	131.20	162.10	77.00	47.10	35.00	121.80	51.50	91.80	110.50	150.80	279.70	801.90
Catch3	161.10	162.30	191.30	105.60	33.60	42.60	91.20	49.30	98.50	126.40	194.90	319.60	1010.70
Catch4	143.20	145.90	173.40	96.40	29.90	38.60	76.00	44.70	87.90	113.60	178.90	287.60	912.00
Lower Mgeni	173.8	152.3	181.8	95.3	38.2	39.2	98.3	49.8	96.3	121.1	180.4	306.8	938.5

significant difference with respect to mean rainfall between these subcatchments, and this does not, therefore, account for the difference. A possible explanation for the difference is related to the differences in elevation of the subcatchments. It is noted that subcatchments 1 and 3 (upper catchment reaches) are significantly higher than subcatchments 2 and 4 (river valley). A further explanation may be related to the dominant aspect for each subcatchment. Aspect is predominantly southwest in subcatchments 1 and 2, and mainly northeast in subcatchments 3 and 4. This difference may relate also to the major weather patterns, for example, some of the rainfall for Durban is frontal, which is of a 'tropical-temperate trough type'. Given the advance of a depression and westerly trough in phase with the diurnal heating cycle over Kwazulu Natal, warm, moist north easterly winds, driven by the sea breeze, plain-mountain circulation and gradient wind, circulation advances against a cooler, maritime south-westerly airstream is advected northward behind the trough. As such, when the weather system moves mainly from west to east, subcatchments 1 and 2 are expected to experience more rainfall than subcatchments 3 and 4, as the latter subcatchments are within a "localised rain-shadow", due to the dominant aspect and topography of that area. The descriptive statistics emphasise the similarity in rainfall between the subcatchments. Diab and Preston-Whyte (1991) have identified four major synoptically forced rainfall-producing systems (tropical-temperate trough; westerly wave; ridging high; east coast low) and four minor systems (high-pressure; easterly flow; mid-latitude cyclone; tropical cyclone) as dominating and influencing rainfall in Kwazulu Natal. It is therefore important to understand the effects of the interaction between synoptic weather systems and local physiographic conditions on the spatial distribution of rainfall.

Figure 4.1, which depicts mean monthly rainfall for the simulation period for each subcatchment and the mean for the total catchment, indicates that rainfall over the entire Lower Mgeni is fairly uniform. Mean monthly rainfall for the total catchment, for the simulation period from January 1990 to December 1998, was determined by the process of area weighting. It is according to the size of each subcatchment and their respective estimated rainfall values. The differences between the subcatchment mean monthly rainfall values versus the mean monthly rainfall for the total study catchment (Lower Mgeni), were calculated from these data and are presented in Figure 4.2.

Based on data extracted from the CCWR, long-term mean monthly rainfall was estimated using driver station rainfall data and monthly correction factors determined for the subcatchments. This allows for a comparison between the rainfall trend during the simulation period and long term rainfall trends. The Inanda (1951-1990) and Kloof (1932-1990) rainfall stations' data and the previously calculated subcatchment correction factors, were used to determine the long-term mean monthly rainfall for the four subcatchments. These values were subsequently added according to the areal proportion of each subcatchment. In comparing total catchment mean monthly rainfall for the simulation period, against the long-term trends, it is observed that rainfall from January to July is consistently lower. This trend, is reversed for the latter part of the year, that is, from August to December, with the exception

Figure. 4.1: Mean monthly rainfall

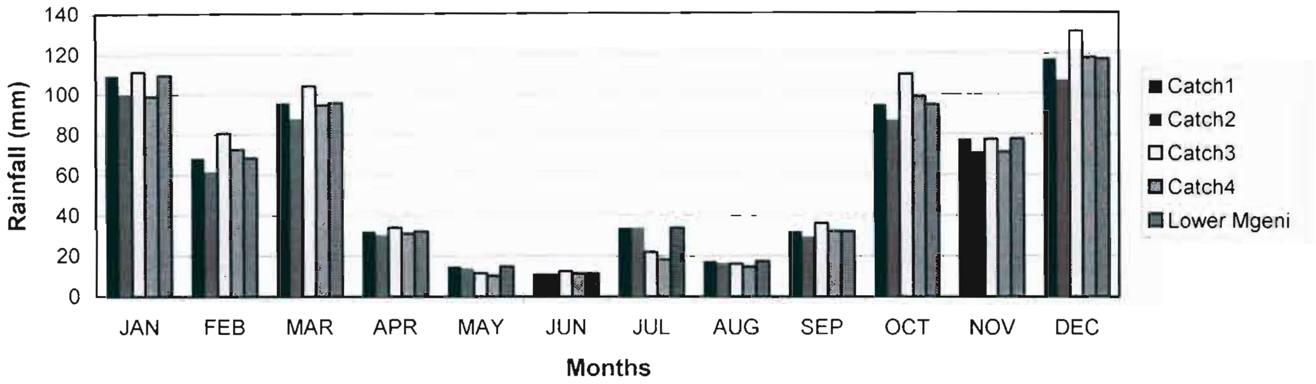


Figure. 4.2: Mean monthly rainfall for subcatchment vs Lower Mgeni

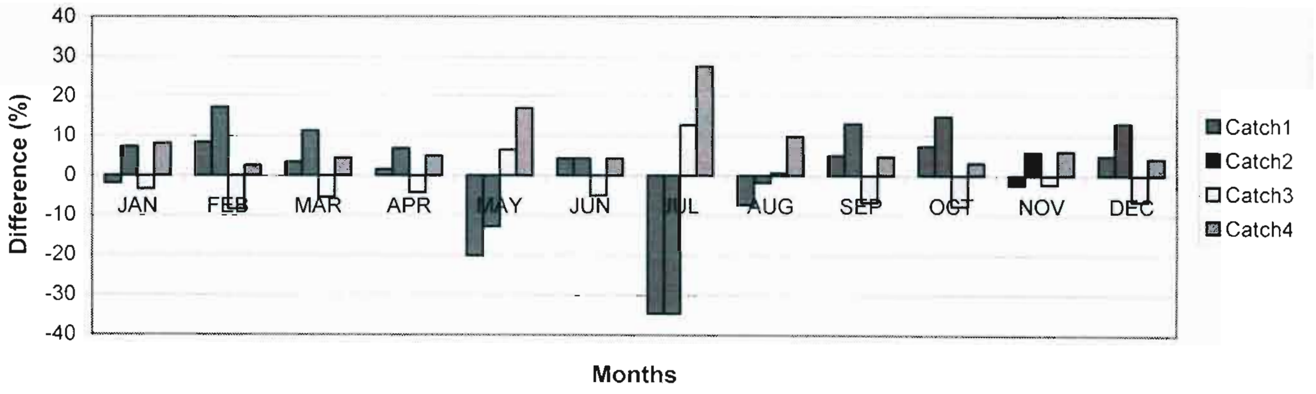
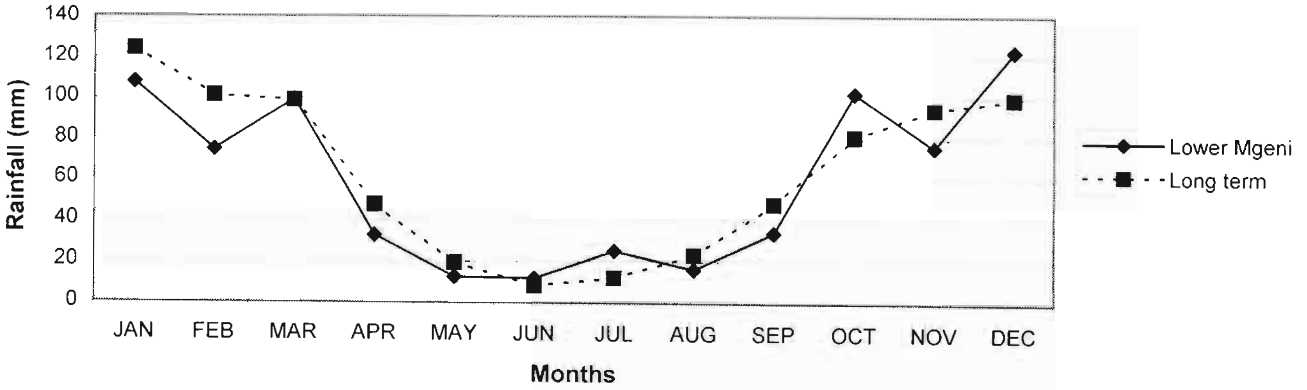


Figure. 4.3: Simulated vs. long term mean monthly rainfall



of November (Figure 4.3). It may be argued that the rainfall for the duration of the simulation is representative. Figures 4.1 and 4.3 distinguishes the relatively "drier" months from the "wetter" months, for both the simulation period and the long term trend, with a "dry season" occurring from April to August, and relatively high rainfall for the remaining months, which is a typical summer rainfall regimen.

4.1.2 Rainfall Validation

The techniques utilised to estimate rainfall is discussed at length in Section 3.2.9. However, existing research evidence will be advanced to support the validity of the rainfall estimation. Distributed hydrological modelling using a daily time step requires an accurate estimation of daily rainfall for each subcatchment. Spatial variation in rainfall, errors in calculating areal averages and its effect on simulated runoff, and associated problems have been considered by many researchers. In an overview of this research, (Schulze, Dent and Schäfer, 1989), it is observed that lumped models perform as well as a semi-distributed model when rainfall input is relatively uniform spatially; however, the semi-distributed model was superior when rainfall was spatially heterogeneous. It is also noted that use of a single rainfall record as a lumped input can at best predict the peak discharge of a catchment with a standard error in the order of 20%. Further, the use of non-representative set of raingauges can also result in poor runoff predictions. Because the spatial distribution of rainfall is influenced quite significantly by the physiographic characteristics of the catchment, the subdivision of the Lower Mgeni study area into subcatchments is based primarily on physiographic differences.

The advantage, as described by Tarboton and Schulze (1992), for using a weighted ratio (R_w, see Equation 3.1) rather than a simple annual ratio (R_a) or a simple monthly ratio (R_m), is that it places more weight on the annual ratio when the month has low rainfall and at the same time still allows monthly variation, in subcatchment to driver station median rainfall, to exert an influence. This influence, according to them, is greater in months with high rainfall and lower in months with low rainfall, thereby avoiding abnormally high ratios that could occur in low rainfall months (winter) if a simple monthly ratio was used.

Results of the application of the method outlined in Tarboton and Schulze (1992) indicate that use of the driver station rainfall estimation method was more accurate and superior in estimating rainfall for individual subcatchments that did not have any rainfall stations located within them. They conclude that the use of catchment daily rainfall values determined by the driver station method, in comparing observed to simulated streamflow, produced better results than using the interpolated surface technique of rainfall estimation.

The WR90 study, commissioned by the Water Research Commission, provides a compendium of data and information for water resources planning and development (Midgley *et.al.*, 1994a;b;c). As part of this study, mean annual precipitation (MAP) for quaternary catchment U20M was determined as 926 mm/a. In a separate study BKS (1994), considering a number of rainfall gauges in this area, estimated rainfall to range from 791.55 to 922.6 mm/a and 832.2 to 1085.4 mm/a for the Inanda Dam and Mgeni Mouth, respectively. These estimates compare reasonably with the simulated MAP of the Lower Mgeni subcatchments, which ranges from 649.6 to 746.2 mm/a and a MAP of 713.1mm/a for the total study catchment.

This subsection presents information on rainfall within the Lower Mgeni catchment. A summary and description of the rainfall characteristics, and the validation of the results, are reported. This section permits the identification of broad monthly rainfall trends, thereby allowing the development of appropriate proactive water resource planning and management strategies.

4.2 RESULTS AND VALIDATION OF SIMULATED STREAMFLOW OF THE LOWER MGENI

4.2.1 Hydrology Results

The previous section describes the rainfall characteristics of the Lower Mgeni, and this section will discuss the results of runoff and streamflow production. Given that the production of streamflow is a synthesis of the various hydrological processes occurring within a catchment, "accurate" estimation of streamflow is an indication that the model is simulating the hydrological processes of a catchment realistically. The value of simulating the hydrology of the Lower Mgeni catchment is to be able to assess the probability of receiving certain water yields at points of interest in the catchment. The estimation of streamflow production of the Lower Mgeni catchment is one of the major objectives of this study. Runoff and streamflow was simulated for all the subcatchments of the delineated Lower Mgeni study catchment over a 9-year period from 1990 to 1998.

4.2.1.1 Simulated Runoff

Summary monthly statistics characterising simulated runoff of all the subcatchments within the study area, and the total catchment is tabulated in Table 4.2, permitting the assessment of runoff and a comparison of the differences between the subcatchments. This table is essential to any investigation of runoff produced within the study catchment. It is clear from Table 4.2, as depicted in Figure 4.4.1; 4.4.2;and 4.4.3, that there is no significant variation in runoff production trends between the delimited subcatchments, with respect to monthly mean, minimum and maximum simulated runoff. As the simulated runoff is measured in mm, which is a representative unit of measurement, it facilitates comparison between the subcatchments. In addition to this, values for the Lower Mgeni were determined by areal weighting. The variation in runoff production between the subcatchments is evident in Figure 4.5. It is clearly shown in the illustration that the runoff production for subcatchment 3 generally exceeds the total study catchment mean, with the only exception being the month of July where the runoff is less than the Lower Mgeni mean. In Subcatchments 2 and 4, the runoff production is consistently lower than that of the study catchment mean. These simulated runoff results correlate

Table 4.2 **Subcatchment monthly summary statistics of simulated runoff (mm)**

Month		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	Catch1	25.5	13.8	18.2	4.4	2.8	1.5	8.8	1.5	3.8	9.7	4.9	23.4	118.2
	Catch2	26.2	15.1	19.9	5.9	3.7	2.4	10.5	2.4	4.3	11.9	7.1	25.0	134.5
	Catch3	27.0	20.7	27.2	12.1	5.3	4.6	6.9	2.7	5.8	21.1	12.6	38.0	183.9
	Catch4	18.6	13.7	19.0	6.9	1.9	2.2	3.9	1.3	3.9	16.1	9.1	31.4	127.9
Minimium	Catch1	1.1	0.2	0.8	0.2	0.0	0.0	0.0	0.0	0.1	1.8	0.4	0.3	29.6
	Catch2	2.2	0.8	1.8	0.8	0.0	0.0	0.0	0.1	0.4	3.7	1.4	1.0	36.1
	Catch3	6.4	4.0	4.0	0.4	0.4	0.0	0.3	0.5	1.3	8.9	2.2	5.3	42.5
	Catch4	4.0	1.6	1.8	0.2	0.0	0.0	0.0	0.2	0.8	6.0	1.4	2.6	22.4
Maximium	Catch1	94.0	52.6	59.3	18.7	9.1	5.1	56.2	5.0	25.0	26.0	15.7	101.6	272.7
	Catch2	92.4	55.6	60.2	19.4	11.0	7.6	62.3	7.1	24.5	30.8	20.6	98.1	301.9
	Catch3	67.0	77.5	52.9	43.4	13.3	16.3	34.7	5.9	24.0	37.0	39.9	137.3	299.7
	Catch4	44.1	54.3	43.6	32.5	6.0	10.0	22.3	3.1	19.1	31.8	32.1	133.5	244.8
Runcoff.(%)	Catch1	23.3	20.2	19.0	13.8	18.8	13.3	26.0	8.6	11.8	10.3	6.3	20.0	16.8
	Catch2	26.3	24.5	22.7	19.5	26.4	21.2	31.1	14.5	14.6	13.7	10.0	23.4	20.7
	Catch3	24.3	25.7	26.1	35.7	45.7	37.1	31.5	16.8	16.1	19.2	16.3	29.0	24.6
	Catch4	18.8	18.9	20.1	22.3	18.4	19.5	21.4	8.9	12.1	16.3	12.8	26.7	19.1
	Lower Mgeni	23.1	22.9	22.9	26.2	30.7	26.3	27.9	13.0	14.2	16.1	12.4	25.9	21.2

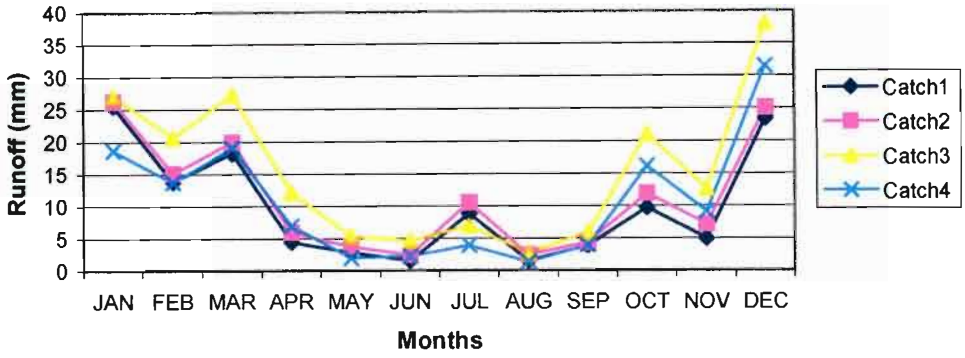


Figure 4.4.1: Mean simulated runoff

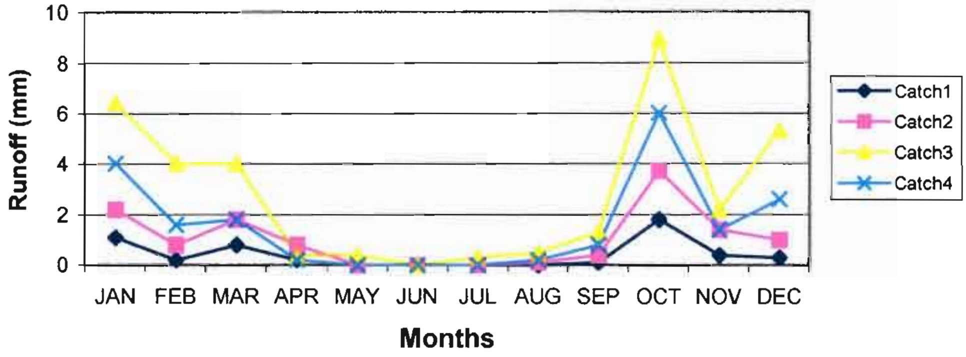


Figure. 4.4.2: Minimum simulated runoff

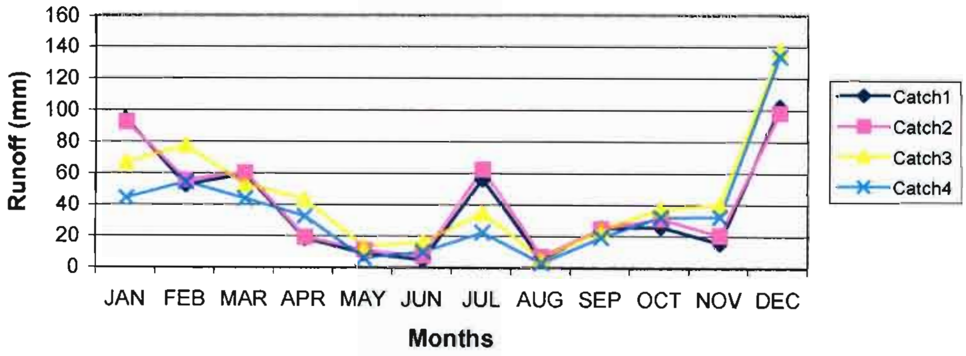
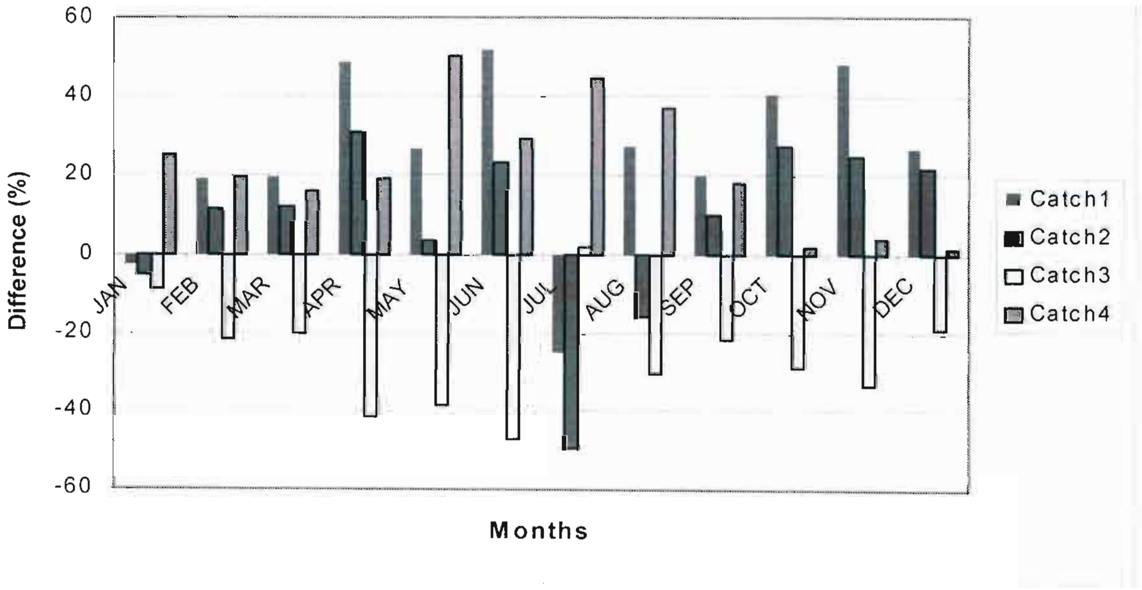


Figure 4.4.3: Maximum simulated runoff

to the rainfall trends, thereby demonstrating a strong relationship between rainfall and runoff production. It should be noted that these ("effective") rainfall values take into account vegetation interception, demonstrating a relationship between vegetation cover and runoff production. It is the opinion of the author that one of the primary reasons for a significantly higher runoff production for Subcatchment 3 is related to landuse/cover. Landcover that comprises more impervious areas contributes directly to increased runoff and streamflow production. In the *ACRU* model, the "ADJIMP" variable, represents that fraction of the urban area of the catchment contributing directly to runoff and streamflow. In comparing subcatchments, the ADJIMP value for Subcatchment 3 is between 129 and 1 213% higher than that of the other subcatchments, providing an explanation for the greater runoff production of Subcatchment 3.

Figure 4.5: Differences in subcatchment runoff production



Runoff and streamflow is a result of all the interacting hydrological processes in a catchment, notwithstanding the importance of the other variables such as vegetation/landuse; soil; slope;and other variables. It is the opinion of the author that the primary reasons for the significant difference between the subcatchments, may be attributed to the variation in rainfall, and the impact of land cover.

4.2.1.2 Simulated Streamflow

Given that the modelling is performed in the distributed mode, in order to analyse total streamflow production of the Lower Mgeni catchment, it is only necessary to consider the streamflow (**cellout**) output from subcatchment 4. This component of the model takes into account upstream contributions of runoff and streamflow from the other upstream subcatchments, thereby providing cumulative streamflow values for the subcatchment under consideration.

With the objective of developing a planning and management strategy for water resources of the Lower Mgeni, with specific emphasis on maintaining minimum streamflow demands, monthly streamflow was calculated to identify trends. The calculations are based on the total streamflow produced by the total study catchment, which is the **cellout** output of Subcatchment 4. Monthly streamflow, with respect to mean, minimum, and maximum mean monthly streamflow, were determined for the simulation period under consideration, and is represented in Figures 4.6.1-4.6.3. While Figures 4.6.1-4.6.3 displays monthly streamflow as a gross volume (m^3), the flowrates (m^3s^{-1}) were determined for the same streamflow aspects noted above, and are depicted in Figures 4.7.1-4.7.3.

Streamflow is directly related to precipitation, and the above figure therefore reflects the same trend as that of rainfall (Figure 4.5). Once again, a season of "low" flow with a monthly flowrate ranging fom1155m^3s^{-1} to 2735m^3s^{-1}, from April to September, is identified and distinguished from the period of "high" flowrate ranging from approximately 483m^3s^{-1} to 1747m^3s^{-1} for the remaining months of the year. The mean monthly flowrate per annum is approximately 706m^3s^{-1}. Although the months of February and October have higher than expected monthly values, it is observed that this does not concur with the long-term rainfall trend. It must be noted that the simulation period is, in relative terms, short, and is influenced by extreme high and low rainfall events, and "wet and dry rainfall cycles". Therefore caution should be exercised when using the mean monthly trends as a guide for the development of planning and management strategies that involve these values. However, it does give an indication of expected streamflow and therefore provides estimated values which may be considered for the above mentioned purposes. This information will be extremely important to the maintenance of desired ecological and geomorphological conditions. As noted above, Figures 4.6.1-4.6.3 depict the mean monthly streamflow produced for the total Lower Mgeni study catchment. The mean annual volume is 22 278.5 million m^3, exceeding the annual volume required to maintain riverine and estuarine ecology, which according to DWAF (1990) is 18.5 million m^3.

4.2.1.3 Runoff coefficient

This subsection of the results of streamflow simulation, is a report on the runoff coefficients for the 4 subcatchments and the total study catchment. Runoff coefficient refers to the value obtained when the streamflow (mm) is divided by the rainfall (mm), and is expressed as a proportional percentage. Table 4.3 displays the runoff coefficients for the individual subcatchments and the total catchment, as reflected in Figure 4.8.

The figure below indicates the runoff coefficient values for the 4 subcatchments and the total Lower Mgeni study subcatchment for the period of simulation. The following trends were observed: for the period between August to November, the runoff coefficient is relatively low, as compared to the

Figure 4.6.1: Mean streamflow volume

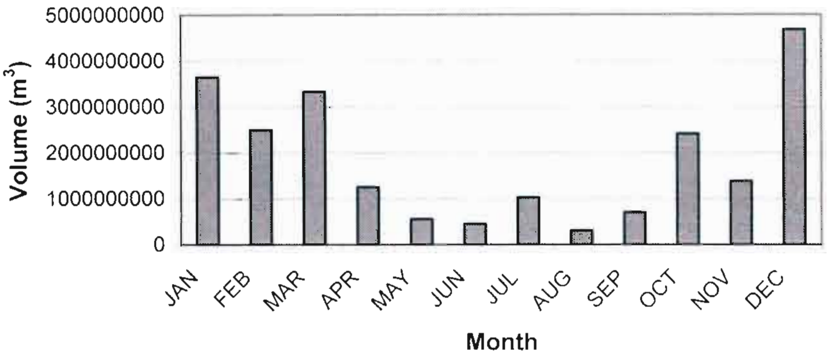


Figure 4.6.2: Minimum streamflow volume

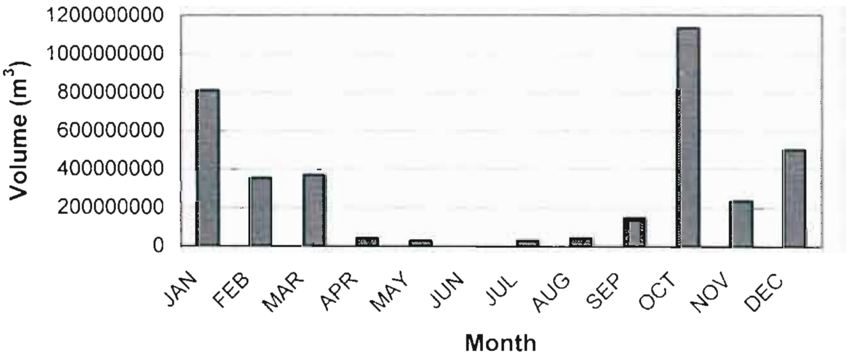


Figure 4.6.3: Maximum streamflow volume

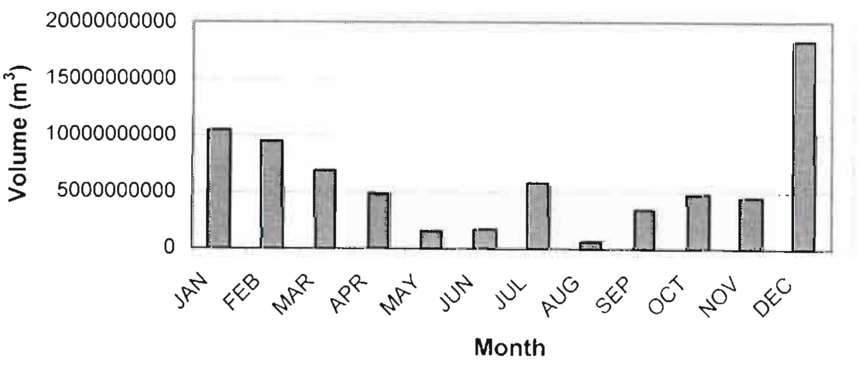


Figure 4.7.1: Mean streamflow flowrate

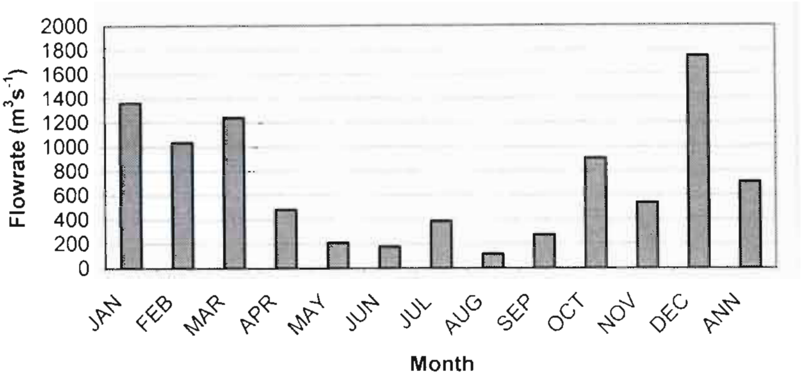


Figure 4.7.2: Minimum streamflow flowrate

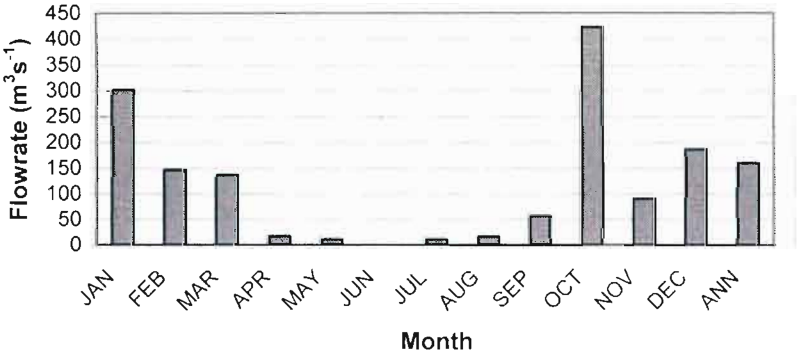


Figure. 4.7.3: Maximum streamflow flowrate

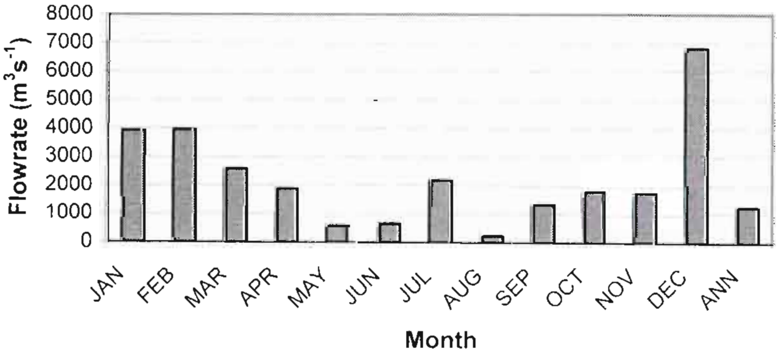
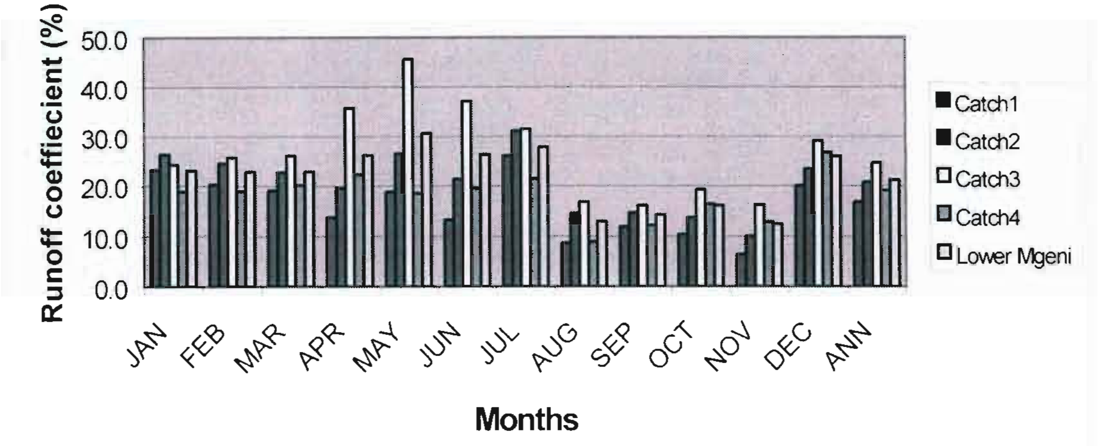


Figure 4.8: Subcatchment and Lower Mgeni runoff coefficients



remaining months when the runoff coefficient is close to or greater than 20%. This is explained by the expected lower antecedent moisture conditions (AMC), which is primarily related to seasonal rainfall patterns. The rainfall has to meet the moisture requirements of soil, prior to being available as either runoff or streamflow. Based on the subcatchment runoff coefficients, a runoff coefficient was determined for the Lower Mgeni (based on runoff versus rainfall) according to areal weighting, and was calculated at 21.1%. This value compares favourably with the runoff coefficient (streamflow versus rainfall) of 21.2% for the total study catchment of the Lower Mgeni.

In a study of six of the twelve Management Subcatchments Kienzle *et.al.* (1997), it was found that the runoff coefficients ranged from 13% to 25.8%. Kienzle, (pers. comm., 1994) was of the opinion that it could be as high as 30% in some areas within the Mgeni catchment. According to his experience and work on the Mgeni catchment he suggests that a runoff coefficient value of 20% should be expected in the lower Mgeni catchment. This evidence, as noted in Table 4.2, further supports the validity of the simulation of streamflow in this study.

4.2.2 Streamflow Validation

ACRU has been applied, and shown to simulate streamflow fairly realistically and accurately in a number of studies. Evidence to this effect is presented in Schulze (1989b), Tarboton and Schulze (1992), and Kienzle (pers. comm.,1994).

The study by Angus (1987) which is also reported in Schulze (1989b), was conducted in the Zululand research catchments, of the University of Zululand, situated on the North Coast of Kwazulu Natal.

One of the objectives of the research was to investigate the relative abilities of the distributed and lumped versions of the *ACRU* model, which also included the simulation of high and low flow regimes. It was found that in the case of low flow regimes the distributed model underestimated streamflow consistently. However, once the streamflow was in excess of a depth of 10mm the model performance improved. Using 1 136 observations, it was found that the model underestimated observed flows by 4%. Further investigation of the seasonal analysis of performance indicated that high flows in summer were more accurately predicted than low flows in winter.

Although five simulations within the Mgeni catchment are reported in Tarboton and Schulze (1992), only the results of three will be utilised:

(1) The simulation was conducted in Quaternary catchment U231 (Figure 1.1) comprising Subcatchments 1 to 6 in the upper Mgeni with a cumulative area of 293.17km^2, for a 16 year period. Results indicate that simulated streamflow was 11% less than observed streamflow for the simulation period. Good correlation between observed and simulated streamflow is shown by the high correlation coefficients for both daily and monthly simulations. According to the students' 't' statistical test, the correlation is significant at the 99.5 percentile level.

(2) A further study within the Mgeni catchment was investigated in Quaternary catchment U233 (Figure 1.1), comprising Subcatchments 17 to 23 with a cumulative area of 335.53km^2. In a simulation period of 5 years, it was found that total daily simulated streamflow matches closely with total daily observed streamflow, while monthly simulated streamflow over-simulates monthly flows by 10%. Correlation statistics of daily flows are poor, while monthly totals of daily flow display better statistics.

(3) The final simulation reported, comprising Subcatchments 62 to 65 with a cumulative area of 177.76km^2, is located upstream of Henley dam (Figure 1.1). In this case, observed streamflow is under-simulated by 14% for both daily and monthly totals of daily streamflow, over the period of 1970 to 1985. Under-simulation is attributed to the use of static existing land cover (Bromley, 1989a, 1989b). Once again, as in the former example, the monthly simulation statistics are better than their daily counterparts.

The examples noted above provides adequate evidence that the *ACRU* model is able to accurately simulate streamflow, but at the same time acknowledges that it is far from perfect. However, it does allow the simulation of ungauged catchments. The results produced will have to be used with caution, taking into account that the model tends to in some instances under-simulate, and in other cases it over-simulates.

A more recent study by Kienzle *et.al.* (1997), within the Mgeni catchment of six of the twelve Management Subcatchments, noted the following when comparing daily and monthly streamflow generated by *ACRU* to observed data. In each case, simulated streamflow totals were within 6% of observed values, with five subcatchments simulating to within 3% of observed data. For details, the reader is referred to Kienzle *et.al.* (1997).

In a study by Garland (1998) mean monthly daily maximum discharge values were calculated for the Lower Mgeni for the period 1990 – 1997. These values were converted to monthly values of streamflow and compared to the *ACRU* results of this study. It was observed that the trends were similar to the *ACRU* results. It was also noted, in the results reported, that the month of July had similarly higher than expected long term trends, as is the case in this study. It may be concluded that this is evidence of the impact of rainfall for the period being considered.

From these highly successful verification studies it may be concluded that the *ACRU* model can be used with confidence to simulate hydrology within the Mgeni catchment, and that the model can be expected to provide acceptably realistic simulation of hydrology and hydrological responses within the Lower Mgeni study catchment.

4.3 RESULTS AND VALIDATION OF SIMULATED SEDIMENT YIELD OF THE LOWER MGENI

4.3.1 Sediment Yield Results

Sediment yield estimation is the other major objective of this study. Seeing that simulation of sediment yield cannot operate in the distributed mode, the total sediment of the total catchment is calculated by simply totalling the sediment yield for the 4 subcatchments that comprise the total catchment. The summary descriptive statistics, characterising sediment production of the subcatchments within the study area and of the total Lower Mgeni catchment, is tabulated in Table 4.3. This table allows an examination of sediment production within the catchment, and therefore a comparison of the differences between the subcatchments. Further, the table presents information of sediment yield of the total catchment.

It is clear from the table above that there is significant variation of sediment yield between the subcatchments of the Lower Mgeni. Although the difference is attributable to the difference in catchment size, the sediment yield is affected by climatic factors and catchment soil, vegetation and hydrological characteristics; these variables, the method of calculation, and their respective values are discussed in Chapter 3. Although the table above indicates the differences of sediment yield production between catchments, comparison is not simply due to the difference in catchment sizes. This is overcome by determining the sediment yield rate. The catchment sediment yield rate (t km^{-2} a^{-1}) is obtained by dividing the mean total annual sediment yield (t a^{-1}) by the catchment area (km^{2}). The sediment yield rate per annum was calculated by dividing the total sediment yield of the Lower Mgeni catchment by the total area.

Table 4.3, which depicts subcatchment sediment yield rates for the duration of simulation, was calculated as described above and depicted in Figure 4.8 and Figure 4.9. The values indicate that Subcatchment 3 and 4 have the lowest sediment yield rates of 32.3 t km^{-2} a^{-1} and 32.6 t km^{-2} a^{-1}, respectively. Subcatchment 2 has the highest yield rate at the value of 617 t km^{-2} a^{-1}, while subcatchment 1 has a rate of 53.2 t km^{-2} a^{-1}. Annual sediment production in the Lower Mgeni subcatchment is 10 855.1 tons with respect to gross mass which results in a sediment yield rate of 73.8 t km^{-2} a^{-1}.

4.3.2 Sediment Yield Validation

There is a noticeable paucity of literature and information on sediment yield and sediment yield rates for smaller geographically defined catchments in Kwazulu Natal. However, there are a few relevant and notable publications on the subject.

In a more recent study by Kienzle *et.al.* (1997) sediment yield was simulated using the same model and methodology as this study. It was reported that mean annual simulated sediment yield ranges from 2 t km^{-2} a^{-1} to 629 t km^{-2} a^{-1} for the 137 *ACRU* subcatchments of the Mgeni Catchment above Inanda Dam. Kienzle *et.al.* (1997) also cites results of studies by Rooseboom *et.al.* (1992) and BKS (1994) for the Midmar Dam, Albert Falls Dam and Henley Dam catchments. Rooseboom *et.al.* (1992) observed results of 10 t km^{-2} a^{-1}; 31 t km^{-2} a^{-1}; and 46 t km^{-2} a^{-1}, and BKS (1994) noted the following rates of 9.67 t km^{-2} a^{-1}; 30.08 t km^{-2} a^{-1}; and 58.92 t km^{-2} a^{-1}, while the *ACRU* results (Kienzle *et.al.*, 1997) were 19.8 t km^{-2} a^{-1}; 37.2 t km^{-2} a^{-1};and 69.5 t km^{-2} a^{-1}, respectively, for the catchments under consideration. These sediment yield rates are within the same range of values produced by this study's Lower Mgeni study subcatchments (32.3 t km^{-2} a^{-1} to 53.2 t km^{-2} a^{-1}), with the exception of subcatchment 2 which has a rate of 587.7 t km^{-2} a^{-1}. According to Kienzle *et.al.* (1997), the highest sediment yield values were found in the highly eroded Valley of a Thousand Hills landcover; and areas where a high proportion of informal dwellings exist. In the case of subcatchment 2, it has a significant proportion of Valley of a Thousand Hills, and major portion of the subcatchment comprises the "Black Transitional" landcover, which includes extensive informal housing, therefore explaining the significantly higher sediment yield. This result compares well with the higher end of the sediment yield range (Kienzle *et.al.,* 1997) of approximately 600 t km^{-2} a^{-1}. In an attempt to compare possible sediment yield relationships between the Kienzle *et.al.* (1997) study and this study, the author considered similarities and variability of landuse, landtype, vegetation cover and soils. The following studies were utilised as sources of information: Tarboton and Schulze (1992), Midgley *et. al.* (1994) and Kienzle *et. al.* (1997). Only the soils and vegetation cover depicted any similarity, i.e. on a regional scale. Most the factors under consideration emphasised the differences between these catchments, rather than the

Table 4.3: Sediment yield rates for Subcatchments and the Lower Mgeni (t km^2 a^{-1})

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	RATE
Catch1	511.2	226.4	385.9	63.9	62.5	19.9	185.8	17.0	120.4	134.9	72.8	319.1	2119.8	53.2
Catch2	1295.5	526.5	976.3	212.6	118.6	56.4	595.0	46.9	295.9	344.0	189.1	843.8	5500.6	587.7
Catch3	268.5	229.0	418.9	163.5	17.4	34.6	90.2	10.2	93.0	232.8	119.8	505.1	2183.0	32.3
Catch4	122.4	106.4	191.8	69.0	7.0	14.1	32.6	4.5	42.0	110.2	63.9	287.8	1051.7	34.6
Lower Mgeni	2197.6	1088.3	1972.9	509.0	205.5	125.0	903.6	78.6	551.3	821.9	445.6	1955.8	10855.1	73.8

Figure 4.9: Subcatchment sediment yield (t a^{-1})

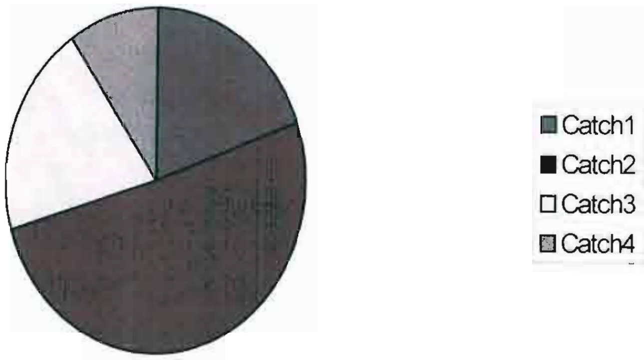
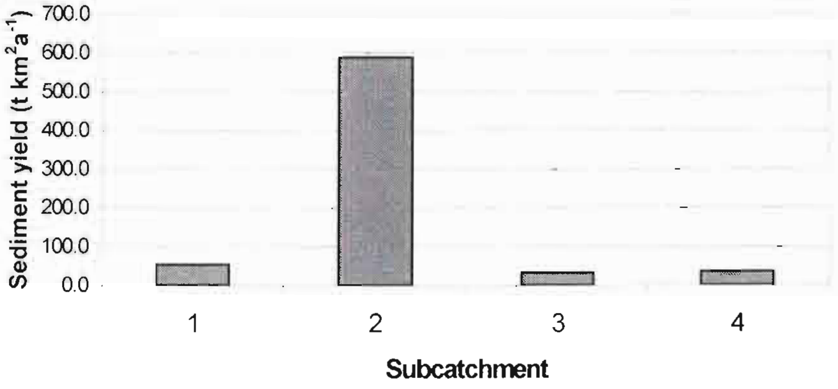


Figure 4.10: Subcatchment sediment yield rates



similarities, and unfortunately the information is depicted for different scales, thereby rendering any form of comparison and identification of sediment yield relationships and trends difficult.

In 1975 Rooseboom published a map of sediment production for South Africa. Rooseboom (1978) subsequently produced a soil erosion map in which volumetric reservoir sedimentation rates were used. Sediment yield for Mgeni was calculated at 374 t km^{-2} a^{-1}, and sediment yield of the Mlazi, which bounds the Mgeni to the south, was estimated at 439 t km^{-2} a^{-1}. The reason for citing the sediment yield for the Mlazi river is that it is one of the two rivers that had reservoirs which were surveyed as part of the study; and that the catchment characteristics of the Mlazi and Mgeni are similar, and therefore the sediment yields based on the surveying of the Shongweni dam on the Mlazi may be used to validate the sediment yield of the Lower Mgeni catchment. However, M^{c}Cormick *et.al.* (1992, p81), states several factors that suggest that the frequently cited fluvial sediment yields in Kwazulu Natal deduced from Rooseboom's data, are too high.

Sediment yield rates are determined by calculating sediment volumes from the observed decrease in reservoir storage volumes. In order to calculate the sediment yields of catchments, the sediment volumes have to be converted to annual sediment yields per unit catchment area. Sediment yield values used in the development of the new sediment yield map for southern Africa (Rooseboom *et.al.,* 1992) was partially derived from the reservoir re-surveys which are performed on a regular basis by the Department of Water Affairs and Forestry (DWAF). This, according to Rooseboom *et.al.* *(*1992), remains to be the most important source of sediment information currently available in South Africa. Re-surveys are undertaken at intervals depending on the importance of the reservoir and the sediment yield of its catchment. This listed information on reservoirs is published by the Department of Water Affairs. The most recent sediment yield rate cited for the Mlazi (Rooseboom *et.al.,* 1992) for the period of 1927 to 1987, with a catchment area of 750 km^{2}, is 231 t km^{-2} a^{-1}.

Rooseboom *et.al.* (1992, p51) describes a method to calculate sediment yield for an ungauged catchment. Statistical analysis was performed on a regional basis to overcome the variability in observed sediment yields. The method is based on a fundamental assumption that sediment availability is the determining factor in sediment yield processes across southern Africa. The method for estimating sediment yield for ungauged catchments was based on results of statistical analysis, which allowed confidence limits to be affixed to estimated yields (Rooseboom *et.al.*,1992). Unfortunately, the method developed cannot be applied to the Lower Mgeni catchment as the size of the catchment under consideration cannot be less than 200 km^{2}. Given that the total Lower Mgeni study catchment is only 147.15 km^{2}, the method was not suitable. However, as part of the study a sediment yield between 5 t km^{-2} a^{-1} to 723 t km^{-2} a^{-1}, for the region within which the study catchment is located, is reported.

Martin (1987) calculated sediment volumes in the northernmost Natal Valley, off the coast of Mozambique and Kwazulu Natal, using seismic reflection data and studies conducted by others. Martin (1987) concluded that 500 to 1000 metres of rock had eroded from the southeast African hinterland in the last 100 million years. Considering all terrigenous input as well as biogenic input, a total sediment yield of 322.5 tkm^{-2} was calculated for the east coast, averaged over the entire drainage basin. Martin (1987) noted that this figure of 322.5 tkm^{-2} could not be used as a measure of erosion because erosion in the field can be 10 to 20 times greater than fluvial sediments. The figure for sediment yield calculated by Martin (1987), while not based on any fluvial measurement, appears to be the most accurate (M^cCormick *et.al.,* 1992). Martin (1987) conceded that his figures for modern sedimentation may have been too high and that volumes of sediment in the Natal Valley/Mozambique depocentre were too low. However the figures Martin quotes compare favourably with yields made for other parts of the world (Stocking, 1984 and Walling, 1984). According to M^cCormick *et.al.* (1992), while Martin's (1987) study is by no means comprehensive and is only valid for the northern Kwazulu Natal Valley depocentre, it is based on sediment volumes measured from relatively accurate seismic reflection surveys and as such can be used for comparison in any future study. The study by Martin (1987) was reviewed to provide figures of sediment yield for the purpose of comparison and the validation of this study.

Le Roux (1990) cited a sediment yield between 50 t km^{-2} a^{-1} and 250 t km^{-2} a^{-1} for South Africa, based on measurements by Walling and Webb (1983). Le Roux's (1990) figures of sediment yield are much lower than those presented by Rooseboom (1978). The observation that the rate of soil erosion in South Africa is at least two to three times the rate of replacement by weathering is exceptionally high and cannot be sustained indefinitely (Le Roux, 1990). Le Roux (1990) tabulated information for only 27 dams with long records and unfortunately none of these are in Kwazulu Natal.

It is reasonable to assume, on the basis of the studies reported, that the sediment yield results of this study provides a realistic simulation of sediment yield for the Lower Mgeni catchment. The values of simulated sediment yield values for the subcatchments, the total catchment (73.8 t km^{-2} a^{-1}) and the annual rate compares most favourably with results reported in Kienzle *et.al.* (1997), which is described in detail above. Martin's (1987) value of 322.5 t km^{-2} a^{-1}, which in the opinion of M^cCormick *et.al.* (1992) appears to be the most accurate estimate of sediment yield for the east coast of southern Africa. The simulated total catchment value falls within the range 5 t km^{-2} a^{-1} to 723 t km^{-2} a^{-1}, which is cited for Region 4 (Rooseboom *et.al.,* 1992). Additional evidence that supports the findings of this study is found in the most recent re-survey of the Shongweni dam, which has a sediment yield value of 231 t km^{-2} a^{-1}. Based on the information noted in the various studies considered, it may be assumed that the simulation of sediment yield is "accurate" and realistic. It should be noted that it is difficult to compare this study's results to those noted above, with the exception of Kienzle *et.al.* (1997), as those studies represent long term trends over extensive areas, and do not take into account the geographical variation of the various factors that influence sediment yield within a catchment. Unlike *ACRU,* which is able to model on a subcatchment basis, taking into account geographical variation of the factors and variables that influence sediment yield, thereby providing more accurate estimates.

CHAPTER FIVE: CONCLUSION

The overall aims of this study were, firstly, to contribute to the completion of the development of the distributed hydrological modelling system for the Mgeni; and secondly, to test the sediment yield component of the model in an application in the Lower Mgeni. Specific objectives of the study entailed the simulation of hydrology, which focussed on simulated runoff and streamflow; and sediment yield responses of the subcatchments and the total study catchment of the Lower Mgeni, with respect to gross volumes and sediment yield rates produced.

5.1 OVERALL ACHIEVEMENTS

The first overall consideration and aim of this study, to set up and run the *ACRU* model for the delimited study catchment, namely, the Lower Mgeni catchment, was successfully accomplished. This aspect of the study involved firstly, the setting up of an input database for each distributed catchment within the catchment; secondly, the processes and techniques used to translate data into hydrological information; and finally the "running" of the hydrological model which in turn "drives" the system and simulates the catchment hydrology. This contributes towards the first aim of completing the modelling of the entire Mgeni catchment, including the Lower Mgeni.

The second overall aim, to test the sediment yield component of the model in an application, was particularly successful in achieving its objective. While the author was eventually able to "apply" the model successfully to the study catchment, a significant outcome of the research, in the initial stages of this study, was the identification of a serious error within the *ACRU* model and a subsequent modification of the model. The reader is referred to Section 3.3.15.1 for details.

5.2 STREAMFLOW AND SEDIMENT YIELD

Specific objectives of the study entailed the simulation of hydrology, which focussed on simulated runoff and streamflow; and sediment yield responses of the subcatchments and the total study catchment of the Lower Mgeni, with respect to gross volumes and sediment yield rates produced.

The application of the *ACRU* agrohydrological model to simulate streamflow from the Lower Mgeni study catchment, highlighted the usefulness of the model in these types of exercises. As observed in Section 4.2.2, strong relationships were found to exist between *ACRU* simulated values of streamflow and observed streamflow. However, in the application of the *ACRU* model it has also been demonstrated, in the examples cited, that the model does in some cases over-estimate as high as 14%, and under-estimate as low as 10%. In considering the application of *ACRU* in the Mgeni Catchment (Kienzle *et.al.*, 1997), however, the simulated streamflow was accurately modelled, when compared to the observed streamflow. This assertion is supported when considering the runoff coefficients of the subcatchments and the total Lower Mgeni study catchment. It was noted, these results were as expected for this area. Although the simulated streamflow may be used with confidence, it is imperative that the streamflow simulation of the Lower Mgeni is verified against observed data. If the results are verified then the simulated results may be applied with greater confidence, rather than treated merely as rough estimates. In order to monitor streamflow, one of two locations at the lower end of the study catchment, is recommended: namely, the old abandoned weir or the weir located at the Mgeni Water waterworks plant (J. Fitton, pers. comm., 1994). Another alternative would be the surveying of a stable cross-section of the river, and then monitor velocity of streamflow. With the subsequent application of a simple formula the rate of flow for the Lower Mgeni may be calculated. The methods thus outlined may be utilised to verify the simulated streamflow values.

Sediment yield trends generally followed the trends of streamflow for the individual subcatchments. This is attributed to the fact that soil erosion, an integral component of sediment yield, is related to the volume and rate of overland flow, which ultimately contributes to streamflow. On average, sediment yield ranged from approximately 1051.7 t a^{-1} to 5500.6 t a^{-1} for the subcatchments, and mean annual yield for the total Lower Mgeni catchment measured at 10855.1 t a^{-1}. These sediment yield rates are within the same range of values produced by this study's Lower Mgeni study subcatchments (32.3 t km^{-2} a^{-1} to 53.2 t km^{-2} a^{-1}), with the exception of subcatchment 2 which has a rate of 587.7 t km^{-2} a^{-1}. Although the results of sediment yield simulation cannot be verified, these sediment yield values have been validated by comparison to results obtained from other studies conducted in the region (Section 4.3.2). This permits the use of the simulated values as a realistic approximate of sediment yield within the study area. The difference between the sediment yield results of the simulation and other studies, is that the "model" for each rainfall event, which is subsequently totalled as monthly values, produces the results of this study. The results obtained by other studies are based on identifying the long-term trends of sediment yield for extremely large catchments. The advantage of the *ACRU* model is that it may be applied to a range of catchment sizes.

Needless to say the utilization of such a model has widespread benefits for a more integrated catchment approach to the processes of planning and development. The *ACRU* model can serve as a reliable information resource base in terms of hydrological information, and can be effectively appropriated for planning and development ends. The *ACRU* model can provide a comprehensive set of information which may be utilized to inform decision-making concerning management and planning strategies to facilitate in the process of development. Pertaining to its usefulness in this regard, the dynamic input option of the *ACRU* model enables the reliable prediction of future scenarios. The capacity to simulate different scenarios and anticipate the respective and impending impacts, provides a framework of consolidated information within which it is possible for appropriate planning, decision-making and management to occur, within a given locality.

Noting that the study catchment lies in close proximity to urban and certain former black townships and informal settlements, it is critically important that this area is modelled. This will enable appropriate planning and management strategies for development within the area and prevent development that could otherwise result in environmental degradation and the loss of "quality of life". This is especially so, given the pressures of urbanization and its concomitant development of informal housing settlements. Within this scenario, in the area of study, could result in wide-scale environmental degradation from negative human activities; and hazardous health conditions. One of the means of preventing this is the utilization of the model in this area to plan holistic, environmentally sound human activities, for example, location of housing development, agricultural practices, etc. There are many functions within the *ACRU* model to assist in this manner.

This study aims to contribute to a more informed understanding of the processes and the results of these processes, occurring within the entire catchment, by providing catchment information (including hydrological). This information is also relevant for the effective and holistic planning, development and management that may be accomplished, especially in terms of the impact of dam construction, where "actual" (simulated) figures are required for appropriate strategies to be adopted. With the increased pressure for development and demand for land, it becomes imperative that land be utilized to its optimum. As already attested to, modelling the catchment is useful in terms of its ability in simulating "future scenarios" and testing alternatives. It thereby helps to reduce the possibility of adopting or supporting inappropriate planning, management and development within the catchment and this may include among other issues, policies for safe water and sediment yield. For example, these policies will have to consider among other related questions, the maintenance of minimum flows in order to maintain functioning within ecological systems. This study has modelled and provided values for both streamflow volume and flowrate. Once the classification of the water resources, the resource water quality objectives and the ecological reserve, as required by the National Water Act (1998), have been determined, these requirements will have to be met. The streamflow results of this study, and the further completion of modelling the hydrology of the entire Lower Mgeni will allow one to estimate the streamflow contribution for normal rainfall events. If further supplementation is required, an appropriate dam management and release strategy could assist in meeting these requirements. As discussed in the former chapter the results of this study could also contribute to the sustainable or “safe” sandwinning strategy for the Lower Mgeni. The most recent extraction values as noted by Garland (1998) indicate that current sandwinning exceed the modelled sediment yield by twenty three times the expected yield. This indicates the sediment being mined is pre-Inanda Dam, that is it was *in situ* prior to the construction of the dam, and therefore not sustainable. Therefore the results of this study can serve to inform and direct the development guidelines for sandwinning operations that occur within the lower Mgeni.

5.3 CONCLUDING REMARKS

While the main objective of the study is to model streamflow and sediment yield for the Lower Mgeni catchment; ultimately, the aim should be the effective modelling of streamflow and sediment yield, under different catchment conditions, as it has been applied to the subcatchments of the study area. The development of a model, or the application of an existing model, should be based on the philosophy that the model accounts realistically for the processes involved in streamflow and sediment yield production. The *ACRU* model has been shown to simulate streamflow and sediment yield realistically. The outcomes of this study compare favourably with other studies conducted in hydrology and sediment yield, especially within this geographical area. The results obtained indicate that the simulation is found to be "realistic, accurate and acceptable". It may be assumed therefore that these results can be applied with confidence to enable appropriate planning and management of resources within this catchment. The study conducted reflects on the significant ability of the model to simulate hydrological response and sediment yield in other ungauged catchment areas. This model therefore may be seen as an invaluable tool for accessing relevant information and assessing conditions within any given catchment. The role and application of the *ACRU* model serves as inexpensive and invaluable tool, that will inform and benefit the planning, development and management of resources of a catchment

Finally, it should be stated that the study conducted by the author renders figures of streamflow and sediment yield. The study described in this dissertation is a pilot study of sediment yield modelling in the Lower Mgeni. The outcomes of this study contribute towards the completion of the *ACRU* modelling of the total Mgeni catchment: and expanding and improving on the knowledge of this study area, and the field of study.

REFERENCES

ALLAN, C., 1991: D'MOSS report on the Mgeni River Management Plan. Unpublished draft copy, Physical Environment Services Unit, Durban.

ALLEN, P.M., HOBBS, R. and MAIER, N.D., 1989. Downstream impacts of a dam on a bedrock fluvial system, Brazos River, Central Texas. Bulletin of the Association of Engineering Geologists, 26: 165-189.

ANGUS, G.R., 1987. A distributed version of the ACRU Model. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, Unpublished M.Sc. Eng. Thesis.

BEGG, G.W., 1978. The Estuaries of Natal. Natal Town and Regional Planning Report No. 41, Pietermaritzburg.

BKS INCORPORATED CONSULTING ENGINEERS, 1994. MGENI River System Analysis Study: Executive summary – Hydrology, DWAF PB U000/00/1292, Pretoria.

BLANEY, H.F. and CRIDDLE, W.D., 1950. Determining water requirements in irrigated areas from climatological data. USDA-SCS, Washington D.C., Technical Publications, 96.

BOSWELL, P.S., 1991: Illegal sandwinning along the Mgeni River between Inanda Dam and the Estuary. Unpublished student report, University of Natal, Department of Geographical and Environmental Sciences, Durban.

BROMLEY, K.A., 1989a. Catchment information for the hydrology model for the Mgeni river catchment. Inst. of Natural Resources, University of Natal, Pietermaritzburg, CSIR Report AAL 21.

BROMLEY, K.A., 1989b. Land cover classes in the Mgeni river catchment. Inst. of Natural Resources, University of Natal, Pietermaritzburg, Supplement to CSIR Report AAL 21.

CHIAN, NING, 1985. Changes in river regime after the construction of upstream reservoirs. Earth Surface Processes and Landforms 10, 143-159.

CLEMENCE, B.S.E. & SCHULZE, R.E., 1982. An assessment of temperature-based equations for estimating daily crop water loss to the atmosphere in South Africa. Crop Production, 11, 21-25.

D'MOSS, 1989: Durban Metropolitan Open Space System. Report by the Director Parks, Recreation and Beaches Department, City Engineers, Durban.

DARDIS, G.F., BECKENDAHL, H.R. & STONE, A.W., 1988. Fluvial systems. In MOON, B.P. & DARDIS, G.F., (Eds.): The geomorphology of southern Africa, Chapter 3. Johannesburg, Southern Book.

DENT, M.C. & GEORGE, W.J., 1989. Daily climatic input files. In SCHULZE, R.E., GEORGE, W.J., LYNCH, S.D. & ANGUS, G.R., (Ed.): ACRU - 2: User Manual. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 36: AM4-01 - AM4-8.

DENT, M.C., LYNCH, S.D. and SCHULZE, R.E., 1988. Mapping mean annual and other rainfall statistics over southern Africa. University of Natal, Pietermaritzburg, Department of Agricultural Engineering. ACRU Report, 27 and Water Research Commission, Pretoria, Report, 109/1/89.

DENT, M.C., SCHULZE, R.E. & ANGUS, G.R., 1988. Crop water requirements, deficits and water yield for irrigation planning in southern Africa. University of Natal, Pietermaritzburg, Department of Agricultural Engineering. ACRU Report, 28 and Water Research Commission, Pretoria. Report, 118/1/88, pp 183.

DEPARTMENT OF WATER AFFAIRS, 1986. Management of the Water Resources of the Republic of South Africa. Department of Water Affairs and Forestry, Pretoria.

DEPARTMENT OF WATER AFFAIRS, 1990. Inanda Dam – capacity determination. Directorate Survey Services, Department of Water Affairs and Forestry, Pretoria.

DIAB, R.D. & PRESTON-WHYTE, R.A., 1991. Distribution of rainfall by synoptic type over Natal, South Africa. International Journal of Climatology, 11, 877-888.

GOUDIE, A, 1991 , Editor:.Encyclopaedic dictionary of Physical Geography,. Blackwell Publishers, Oxford.

ERSKINE, D.,1985. Downstream geomorphic impacts of large dams: the care of Glenwaba Dam, New South Wales. Applied Geography 5, 195-210.

GARLAND, G.G., 1998. Estimation of Bedload Sediments of the Mgeni River below Inanda Dam, University of Natal, Department of Geographical and Environmental Sciences., Durban.

GEORGE, W.J., LYNCH, S.D., SCHÄFER, N.W., ANGUS, G.R., WILLS, H.M.M. & SCHULZE, R.E., 1989. Preparation of input menus for use with *ACRU*. In SCHULZE, R.E., GEORGE, W.J., LYNCH, S.D. & ANGUS, G.R., (Ed.): ACRU - 2: User Manual. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 36: AM5-01 - AM5-05.

GOVERNMENT GAZETTE NO. 19182: National Water Act 36 of 1998. Government Printer, Pretoria.

GUSTARD, A., 1992. Analysis of river regimes. In CALOW, P. & PETTS, G.E., (Eds.): The Rivers Handbook: Hydrological and ecological principles, Vol. 1, Chapter 1. Oxford, Blackwell Scientific.

GUY, P.R., 1980/81. Riverbank erosion of the mid-Zambezi Valley, downstream of Lake Kariba, Biological Conservation 19, 199-212.

HORNE GLASSON PARTNERS, 1989. Water Plan 2025. Umgeni Water Board, Pietermaritzburg.

KENNEDY, B.A., 1994. Requiem for a Dead Concept. Annals of the Association of American Geographers, 84(4), 702-705.

KIENZLE, S.W., LORENTZ, S.A. and SCHULZE, R.E., 1997. Hydrology and Water Quality of the Mgeni Catchment. Water Research Commission Report TT87/97, Pretoria.

KRUMBEIN, F.A. and GRAYBILL, W.C., 1968: An Introduction to Statistical Models in Geology. McGraw-Hill, New York.

LE ROUX, J.S., 1990. Spatial variation in the rate of fluvial erosion. Water SA, 16, 185-194.

LINACRE, E.T. (1984). Unpublished manuscript. School of Earth Sciences, Macquarie University, Sidney, Australia.

LINACRE, E.T., 1977. A simple formula for estimating evaporation rates in various climates using temperature data alone. Agricultural Meteorology, 18, 409-424.

LORENTZ, S.A. & SCHULZE, R.E., 1995: Sediment yield. In: Hydrology and Agrohydrology: A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research

Commission, Pretoria, Report TT69/95. pp AT16-1 to AT16-32.

LYNCH, S.D. 1993. Guide to using the ACRU utilities. Unpublished memo. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

MACVICAR, C.N., LOXTON, R.F., LAMBRECHTS, J.N.N, LE ROUX, J, DE VILLIERS, J.M., VERSTER, E., MERRYWEATHER, VAN ROOYEN, T.H. & VON.M. HARMSE, H.J., 1977: Soil Classification: A Binomial System for South Afrca. The Soil and Research Institute, Department of Agricultural Technical Services, Pretoria.

MARTIN, A.K., 1987. Comparison of sediment rates in Natal Valley, south-west Indian Ocean, with modern sediment yields in east coast rivers of southern Africa. South African Journal of Science, 83, 716-724.

M^{c}CORMICK, S., COOPER, J.A.G. & MASON, T.R., 1992. Fluvial sediment yield to the Natal coast: A review. South African Journal of Aquatic Sciences, 18 (1/2), 74-88.

MIDGELY, D.C., PITMAN, W.V., MIDDLETON, B.J. 1994a. Surface Water Resources of South Africa 1990. User's Manual. WRC 298/1/94.

MIDGELY, D.C., PITMAN, W.V., MIDDLETON, B.J., 1994b. Surface Water Resources of South Africa 1990. Volume VI Drainage Regions U, V, W, X – Eastern Escarpment. Appendices. WRC 298/6.1/94.

MIDGELY, D.C., PITMAN, W.V., MIDDLETON, B.J., 1994c. Surface Water Resources of South Africa 1990. Volume VI Drainage Regions U, V, W, X – Eastern Escarpment. Book of Maps. WRC 298/6.2/94.

ONSTAD, C.A., 1984. Sediment yield modelling. In HADLEY, E.F. & WALLING, D.E., (Ed.): Erosion and sediment yield: Some methods of measurement and modelling: p74. Cambridge, Geo Books.

PENMAN, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society,.London, A193, 120-146.

PHILIPS, J.D., GOMEZ, B., 1994. In Defense of Logical Sloth. Annals of the Association of American Geographers, 84(4), 697-701.

PITMAN, W.V., MIDDLETON, B.J. and MIDGLEY, D.C., 1981. Surface water resources of South Africa, Hydrological Research Unit Report No. 9/81, University of Witwatersrand, Johannesburg.

PRESTON-WHYTE, R.A.,1991: Impacts of Inanda Dam. University of Natal, Department of Geographical and Environmental Science, Durban.

RENARD, K.G., FOSTER, G.R., WEESIES, G.A. AND McCOOL, D.K., 1991. Predicting soil erosion by water. A guide to conservation planning with the The Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Research Service, Tuscon, Arizona, USA.

ROOSEBOOM, A., 1975. Sedimentproduksiekaart vir Suid Afrika. Department of Water Affairs, Pretoria, Technical Report No. 61.

ROOSEBOOM, A., 1978. Sedimentavoer vir Suider-Afrikaanse Riviere.Departement Siviele Ingenieurwese, Universiteit van Pretoria, Pretoria.

ROOSEBOOM, A., VERSTER, E., ZIETSMAN, H.L. & LOTRIET, H.H., 1992. The development of the new sediment yield map of southern Africa. Water Research Commission, Pretoria. Report, 297/2/92.

SCHMIDT, E.J. & SCHULZE, R.E., 1984. Improved estimations of peak flow rates using modified SCS lag equations. Univ. of Natal, Pietermaritzburg, Department of Agricultural Engineering. ACRU Report 17.

SCHMIDT, E.J. & SCHULZE, R.E., 1989. Simulation of peak discharge. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT10-01 - AT10-08.

SCHMIDT, E.J., & SCHULZE, R.E., 1987a. User Manual for SCS-based design runoff estimation in Southern Africa. Water Research Commission, Pretoria, Technology Transfer Report,33/87.

SCHMIDT, E.J., & SCHULZE, R.E., 1987b. Flood volume and peak discharge from small catchments in southern Africa based on the SCS technique. Water Research Commission, Pretoria, Technology Transfer Report,31/87.pp164

SCHMIDT, E.J., 1989. Simulation of sediment yield. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT11-01 - AT11-09.

SCHULZE, R.E. & GEORGE, W.J., 1989. User guidelines for setting up formation. In SCHULZE, R.E., GEORGE, W.J., LYNCH, S.D. & ANGUS, G.R., (Ed.): ACRU - 2: User Manual. Univ. of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 36: AM7-01 - AM7-122.

SCHULZE, R.E. & MAHARAJ, M., 1989. Regional lapse rates in southern Africa for monthly means of daily maximum and minimum temperatures. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, Unpublished tables and maps.

SCHULZE, R.E. & MAHARAJ, M., 1991. Mapping A-pan equivalent potential evaporation over southern Africa. Proc. 5th S. Afr. Nat. Hydrol. Symp., Stellenbosch, 4B-4-1 to 4B-4-8.

SCHULZE, R.E., 1975. Catchment evapotranspiration in the Natal Drakensberg. University of Natal, Pietermaritzburg, Department of Geography, Unpublished Ph.D. Thesis.

SCHULZE, R.E., 1987. Hydrological science and hydrological practice: Reflections as we approach the 1990's. Proc. Hydrol. Sci. Symp., Dept. of Geog., Rhodes Univ., Grahamstown, 1-19.

SCHULZE, R.E., 1989a. Hydrological modelling and ACRU: Aims and philosophy. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT1-01 - AT1-03.

SCHULZE, R.E., 1989b. (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35.

SCHULZE, R.E., 1989c. Simulation of streamflow. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT8-01 - AT8-04.

SCHULZE, R.E., 1989d. Potential evaporation. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT4-01 - AT4-18.

SCHULZE, R.E., 1989e. Soils. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT5-01 - AT5-19.

SCHULZE, R.E., 1995: Hydrology and Agrohydrology: A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria, Report TT69/95.

SCHULZE, R.E., ANGUS, G.R. & GEORGE, W.J., 1989. ACRU concepts and structure. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT2-01 - AT2-13.

SCHULZE, R.E., DENT, M.C. & SCHAFER, N.W., 1989. Rainfall. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT3-01 - AT3-17.

SCHULZE, R.E., GEORGE, W.J. & ANGUS, G.R., 1989. Vegetation and land use. In Schulze, R.E., (Ed.): ACRU: Background, concepts and theory. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 35: AT6-1 - AT6-16.

SCHULZE, R.E., GEORGE, W.J., LYNCH, S.D. & ANGUS, G.R., 1989b. ACRU - 2: User Manual. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 36.

SCHULZE, R.E., MAHARAJ, M. & LYNCH, S.D., 1989. Monthly means of daily maximum and minimum temperatures for southern Africa. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, Unpublished documents and maps.

SIRI, (1987). Land type series. Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, Pretoria. Memoirs on the agricultural natural resources of South Africa.

SMITHERS, J.C. & SCHULZE, R.E., 1995: *ACRU* Agrohydrological Modelling System : User Manual : Version 3.00. Water Research Commission, Pretoria, Report TT70/95.

STOCKING, M, 1984. Rates of erosion and sediment yield in the African environment. International Association of Hydrological Sciences, 144, 285-293.

TARBOTON, K.C. and SCHULZE, R.E., 1992. Distributed hydrological modelling system for the Mgeni catchment. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report 39.

THORN, C.E., WELFORD, M.R., 1994. The Equilibrium Concept in Geomorphology. Annals of the Association of American Geographers, 84(4), 666-696.

THORNTHWAITE,C.W., 1948. An approach towards a rational classification of climate. Geographical Review, 38, 55-94.

UNITED STATES DEPARTMENT OF AGRICULTURE, SOIL CONSERVATION SERVICE, 1972. National Engineering Handbook, Section 4, Hydrology. USDA-SCS, Washington D.C., USA.

WARD, D.W., 1984. The sediment yields of African rivers. International Association of Hydrological Sciences, 144, 265-283.

WARD, R.C., 1990. Principles of Hydrology. Published London; New York: McGraw-Hill, 286-287.

WALLING, D.W., 1984. The sediment yields of African rivers. International Association of Hydrological Sciences, 144, 265-283.

WEDDEPOHL, J.P., 1988. Design rainfall distributions for southern Africa. Unpublished M.Sc. thesis. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, pp162.

WHITMORE, J.S., 1971. South Africa's water budget. South African Journal of Science, 67, 166-176.

WILLIAMS, J.R., & BERNDT, H.D., 1977. Sediment yield based on watershed hydrology. Transactions ASAE, 20, 1100 - 1104.

WILLIAMS, J.R., 1975. Sediment yield prediction with universal equation using runoff energy factor. Proceedings of Sediment Yield Workshop. USDA, Sedimentation Laboratory, Oxford, Mississippi, USA, 244 - 252.

WISCHMEIER, J.R. & SMITH, D.D., 1978. Predicting rainfall erosion losses - a guide to conservation planning. USDA, Washington DC, Agricultural Handbook, 537.

WISCHMEIER, J.R., JOHNSON, C.B. and CROSS, B.V. (1971). A soil erodibility nomograph for farmland construction sites. Journal of Soil and Water Conservation, 28, 189-193.

PERSONAL COMMMUNICATIONS

COOPER, J.A.G., 1993. Department of Geology, University of Natal, Durban.

De VOS, R., 1994. Computing Centre for Water Research, University of Natal, Pietermaritzburg.

FITTON, J., 1994. Umgeni Water, Pietermaritzburg.

HORN, M., 1993. Computing Centre for Water Research, University of Natal, Pietermaritzburg.

JEWITT, G.P., 1994. Department of Agricultural Engineering, University of Natal Pietermarizburg.

KIENZLE, S.W., 1994. Department of Agricultural Engineering, University of Natal Pietermarizburg.

LORENTZ, S.A., 1994. Department of Agricultural Engineering, University of Natal Pietermarizburg.

LUMSDEN, T., 2000. Department of Agricultural Engineering, University of Natal Pietermarizburg.

MAHARAJ, M., 1994. Department of Agricultural Engineering, University of Natal Pietermarizburg.

NUNDLALL, R., 1994. Computing Centre for Water Research, University of Natal, Pietermaritburg.

ROBERTS D., 1991. Department of Geographical and Environmental Sciences, University of Natal, Durban.

APPENDIX 1

Subcatchment Land Type Distribution and K-Factors

CATCHMENT 1

LANDTYPE	K-FACTOR	% CATCH	WEIGH.K-FACT
C486	0.3399	1.26	0.0043
C905	0.3399	10.97	0.0373
C911	0.3785	24.98	0.0945
C912	0.4051	42.46	0.1720
C945	0.3497	7.27	0.0254
C946	0.3538	6.70	0.0237
D50	0.4355	6.36	0.0277
TOTAL		100.00	**0.3850**

CATCHMENT 2

LANDTYPE	K-FACTOR	% CATCH.	WEIGH.K-FACT
C486	0.3399	23.51	0.0799
C893	0.7500	11.95	0.0896
C910	0.4355	0.61	0.0027
C911	0.3785	23.45	0.0888
C945	0.3497	29.23	0.1022
D50	0.4355	11.26	0.0490
TOTAL		100.01	**0.4122**

CATCHMENT 3

LANDTYPE	K-FACTOR	% CATCH.	WEIGH.K-FACT
C388	0.3790	0.52	0.0020
C486	0.3399	0.53	0.0018
C849	0.4584	23.51	0.1078
C888	0.4584	0.83	0.0038
C890	0.4025	18.55	0.0747
C891	0.4584	0.75	0.0034
C893	0.7500	0.07	0.0005
C900	0.4422	14.23	0.0629
C902	0.3399	41.01	0.1394
TOTAL		100.00	**0.3963**

CATCHMENT 4

LANDTYPE	K-FACTOR	% CATCH.	WEIGH.K-FACT
C486	0.3399	21.67	0.0737
C839	0.3612	0.18	0.0007
C890	0.4025	0.00	0.0000
C891	0.4584	10.64	0.0488
C893	0.7500	20.18	0.1514
C900	0.4422	20.15	0.0891
C902	0.3399	14.28	0.0485
C910	0.4355	6.54	0.0285
C911	0.3785	3.32	0.0126
C945	0.3497	1.56	0.0055
INANDA	MISSING	1.49	0.0000
TOTAL		100.01	**0.4586**

APPENDIX 2

Sample of spreadsheet used to determine K-factor values for Land Type c911

LANDTYPE	SERIES 1	U-DEPTH	L-DEPTH	TERRAIN	PERCENT	TERRAIN	PERCENT	TERRAIN	PERCENT	TEXTURE	HORIZON	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	ORGANIC	STRUCTURE	PERM	K-FACT	WEIGHT K	WEIGHT K	WEIGHT K
				UNIT 1	AREA 1	UNIT 2	AREA 2	UNIT 3	AREA 3	CLASS		Cl	Si	Sa Tot	Si+VFSa	Sa Coarse	MATTER	CODE	CODE		T UNIT 1	T UNIT 2	T UNIT 3
C911	R	0	0	1	0	3	0	5	0			0	0	0	0	0	0	0	0	0	0.000	0	0
C911	Ms10	100	350	1	4	3	4	5	0	SaLm-SaClLm	A	20	10	70	52	28	2	3	4	0.45	0.018	0.016	0.000
C911	Gs17Gs18	200	450	1	58	3	46	5	0	SaLm-SaClLm	A	20	10	70	52	28	1.5	3	3	0.43	0.250	0.198	0.000
C911	Cf21Cf22	350	600	1	0	3	4	5	0	SaLm-SaClLm	A	20	10	70	52	28	0.5	3	4	0.50	0.000	0.020	0.000
C911	Hu27	600	1000	1	38	3	32	5	0	SaCl-Cl	A	35	13	52	44	20.8	0.75	2	2	0.24	0.091	0.077	0.000
C911	Hu37	600	1000	1	0	3	3	5	0	SaCl-Cl	A	35	13	52	44	20.8	0.75	2	3	0.27	0.000	0.008	0.000
C911	Oa16Oa17	600	1000	1	0	3	3	5	0	SaCl-Cl	A	30	8	62	45	24.8	0.5	3	3	0.35	0.000	0.011	0.000
C911	Oa36	600	1000	1	0	3	8	5	10	SaClLm-SaCl	A	28	8	64	46	25.6	2	3	3	0.33	0.000	0.026	0.033
C911	Du10	800	1200	1	0	3	0	5	20	SaLm-SaCl	A	25	10	65	49	26	2	3	3	0.36	0.000	0.000	0.073
C911	S	0	0	1	0	3	0	5	70					100	60	40	0	3	1	0.65	0.000	0.000	0.455
					100		100		100			23.6666667	9.111111	60.5	93.27778								
																			AVERAGE K VALUE		0.359	0.358	0.561
																			UNIT 1		0.359	15	0.05385
																			UNIT 2		0.358	75	0.2685
																			UNIT 3		0.561	10	0.0561
																							0.37845

APPENDIX 3

List of Land Use and C-factors

LANDUSES OF STUDY CATCHMENTS	C-FACTOR
Wetland	0.0000
Mixture undifferentiated forest	0.0010
Indigenous forest	0.0010
CBD & Industrial	0.0300
High density residential	0.0670
Medium density residential - few trees	0.0735
Woodland	0.0757
Medium density residential - trees	0.0805
Tree bush savannah	0.0928
Parks, sportsfields, etc	0.0955
Undifferentiated open space	0.0985
Grassland	0.0985
Valley of 1000 hills	0.1406
Low density smallholdings	0.1500
Sugar cane	0.1500
Undifferentitated cropping	0.1700
Low density residential - gardens	0.2565
Rural urban transition	0.2700