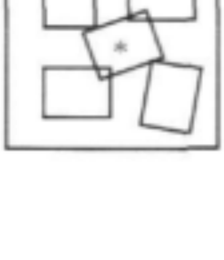
Hydrology and Water Quality of the Mgeni Catchment

Stefan W Kienzle • Simon A Lorentz • Roland E Schulze



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HYDROLOGY AND WATER QUALITY OF THE MGENI CATCHMENT

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EXECUTIVE SUMMARY

The Mgeni Catchment, 4 079 km^2 in area upstream of the Inanda Dam, is the vital water source for both the Greater Durban and Pietermaritzburg Metropolitan areas in KwaZulu-Natal. It supplies water for approximately 45% of the Province's population in a region which produces 20% of South Africa's gross national product. In this area of highly variable rainfall, Umgeni Water manages five dams for water supply. With the population in the Greater Durban and Pietermaritzburg Metropolitan areas projected to expand to between 9 and 12 million by the year 2025, it was recognised over a decade ago that the rapidly accelerating water demand would exceed local raw water resources by the turn of the century. The increased occurrence of return flows, intensified agricultural practices and the presently unco-ordinated growth of large informal settlements which are associated with the population expansion and influxes into the region are expected to lead to severe deterioration of the water quality of streams, rivers and dams. During summer months, frequent convective thunderstorms result in the transport of suspended solids, pathogens and phosphorus from the subcatchments into receiving channels, with the consequence that domestic, agricultural, industrial, ecological and recreational user groups are affected.

In response to these perceived potential water-related problems, the Umgeni modelling group approached the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg in 1988 to undertake a two-phase research programme which would develop a dynamic system model of the Mgeni catchment. Phase 1 of this research programme was completed in 1992. The main objectives of Phase 2 of the research programme, entitled *Development of a Distributed Hydrological Modelling System to Assist with Water Quantity and Quality Management in the Mgeni Catchment, Phase 2* were twofold, viz.:

- the development of a simulation tool, in which the *ACRU* modelling system was to be further developed to incorporate relevant water quality simulation capabilities so as to enable the modelling of selected water quality parameters, viz. sediments, phosphorus and *Escherichia coli* (*E. coli*), which are important to those responsible for planning and management of Mgeni catchment's water resources, and
- setting up of an operating model, in which the extended and verified *ACRU* modelling system was to be applied in simulations of water quantity and water quality in order to implement and evaluate the model for potential catchment scenarios of the future.

In order to meet the above objectives, which require specific and demanding modelling capabilities, the *ACRU* hydrological modelling system was selected. *ACRU* is a physical conceptual model based on a daily timestep and can be applied in a distributed mode. This intensively researched multi-purpose model is centred on daily multi-layer soil water budgeting. It has been structured to be highly sensitive to climate and to land cover and land use changes on soil water and runoff processes.

Streamflow Simulations

The *ACRU* hydrological and water quality modelling system was configured for the Umgeni catchment upstream of Inanda Dam to simulate daily streamflows for 137 subcatchments for the 34-year period from 1 January 1960 to 31 January 1993.

Simulated time series were compared against observed time series and maps and tables were produced to quantify and qualify the following hydrological components, on both a subcatchment and management subcatchment (i.e. Quaternary catchment) basis:

* streamflow production under current conditions,
* streamflow production under pristine conditions,
* the impact of current land use on streamflow production, and
* the impact of possible future land use scenarios on streamflow.

Simulated streamflows were verified against observed runoff data from 6 management catchments. The verifications, an example of which is given in Figure ES1, included time series plots of simulated vs. observed streamflows, a comparison of accumulated totals of streamflows, a comparison of month-by-month simulated and observed flows for median conditions and for conditions in the wettest year in 10 and the driest year in 10. All six verifications gave coefficients of determination above 78%, with four exceeding 84%. In each case simulated streamflow totals were within 6% of observed values with five subcatchments simulating to within 3% of observed flows. Differences of standard deviations were consistently within 15%, with three subcatchments' differences below 4%.

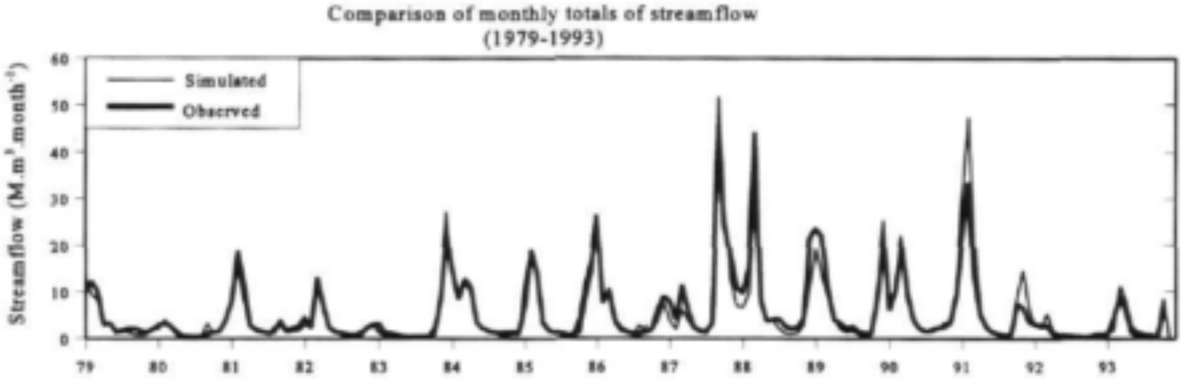
Following the successful verifications of streamflow output from the *ACRU* model, daily streamflow sequences for all 137 subcatchments were produced for the period 1960 to 1993. Mean annual runoff was found to range from 44 to 390 mm in the various subcatchments.

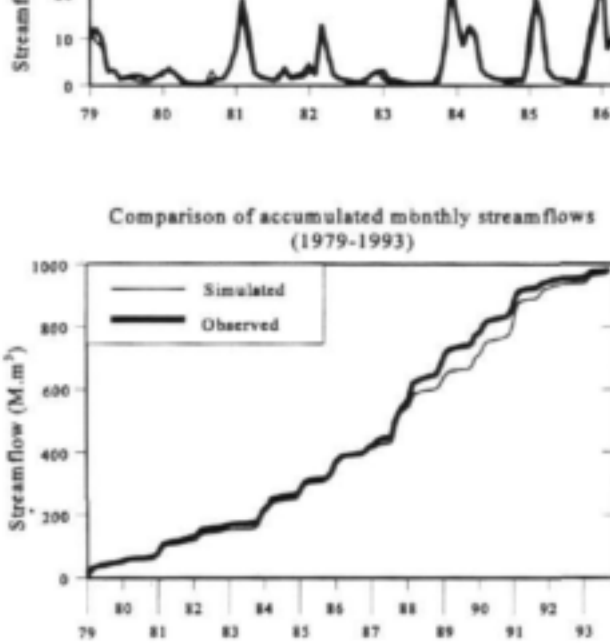
Impacts of present land uses on streamflows were assessed by comparing streamflows produced under "current" and under "pristine" (Acocks' Veld Types) land covers. The hydrological impacts of current land use compared with streamflows under pristine land cover conditions can be significant within individual subcatchments, ranging

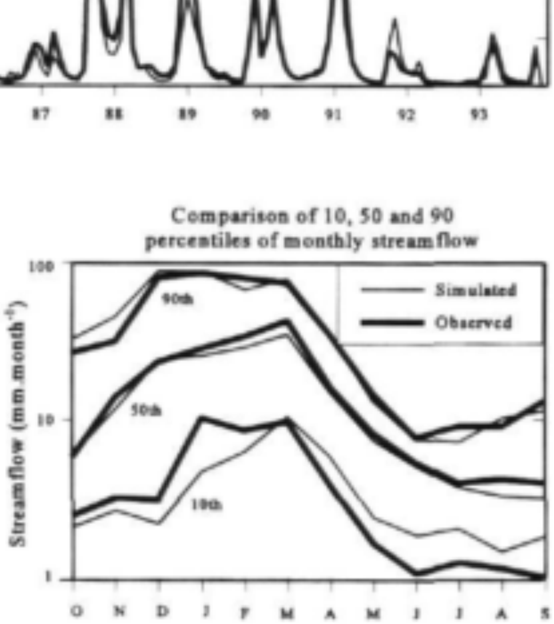
Figure ES1

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Mpendle Management Subcatchment (1979 - 1993)







Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	176	5413
Sum of observed values (mm)	=	618.7	3325.1
Sum of simulated values (mm)	=	3564.1	3471.7
% difference between sums	=	1.5	-4.4
Correlation coefficient, r	=	.939	.823
Slope of regression line	=	.970	.860
Y intercept of regression line	=	.299	.113
Standard deviation of X values (mm)	=	27.8	1.538
Standard deviation of Y values (mm)	=	28.7	1.608
% difference between standard deviations	=	-3.3	-4.5
Coefficient of determination, r^2	=	.883	.677
Coefficient of efficiency	=	.887	.658

Catchment Summary

Catchment area	=	296 km^2
Mean annual precipitation	=	966 mm
Mean annual runoff	=	249 mm
	or	67.5 M.m^3
Runoff coefficient	=	25.8%
Mean annual potential evaporation	=	1596 mm

Land Use (%)

Rural	=	0.3
Forest	=	11.3
Irrigated Agriculture	=	3.3
Dryland Agriculture	=	6.4
Natural Vegetation	=	75.6
Water Bodies	=	3.1

from 100% (i.e. a doubling of) increase in streamflows to a decrease by more than 60%. The highest reductions of streamflows were found in subcatchments which are under intensive agricultural use. In particular, subcatchments with a high proportion of commercial forest and sugarcane plantations exhibit significant reductions in water yield of up to 60%. On the other hand, subcatchments that are either highly urbanised or exhibit a high population density show an increase in water yield as in the Pietermaritzburg area and in the Valley of a Thousand Hills immediately upstream of Inanda dam. This increase in water yield can be attributed to the widespread substitution of pristine vegetal cover with impervious surfaces or highly compacted soil with large proportions of bare ground in many former KwaZulu homeland areas.

In modelling future water yield scenarios, two types of hydrological impact studies were undertaken.

Impact Study I represents the impacts of commercial forest plantations, farm dams and irrigated agricultural streamflows for three management subcatchments. Impact Study II compares the impacts of grassland, eucalypts, sugarcane and maize on five *ACRU* subcatchments ranging in mean annual precipitation from 680-1 200 mm.

While the impacts of unused farm dams *per se* was found not to significantly affect downstream streamflows, the impacts of irrigating crops and pastures was found to be significant on streamflows. The reduction in streamflow varies, depending on the proportion of the catchment under irrigation. Commercial afforestation was found to reduce streamflows significantly, with eucalypts utilising more water than wattle, and wattle more water than pines in their influence on streamflows. In the second Impact Study the highest impacts were found to be in the low rainfall areas of the Umgeni catchments, with impacts decreasing with increasing rainfall. Eucalypts were found to impact streamflows more than sugarcane, which in turn reduced streamflows more than grazing areas and maize.

Water Quality Simulations

Significant water quality impacts in the Umgeni catchment begin with the detachment of soil particles from the parent material. These particles can carry appreciable concentrations of absorbed phosphorus and pathogens, which are indicated by the presence of *E. coli*. It is the phosphorus and pathogens which reach the receiving streams that result in serious water quality problems in rivers and reservoirs in the Umgeni catchment. In order to simulate the transport of non-point source phosphorus and *E. coli*, it is important to first be able to simulate with confidence the likely movement of the soil particles on a catchment scale. The procedure was therefore to simulate the water quality determinands by first generating a spatial distribution of erosion potential and then to simulate subcatchment sediment yield histories and finally to simulate phosphorus and *E. coli* loadings.

A comprehensive digital terrain model dataset related to soil loss related physics was developed. This phase involved the application of the recently developed Revised Universal Soil Loss Equation, RUSLE, at a grid scale of 250 by 250 m. The soil loss potential was determined for each of the 65 256 grid cells making up the area upstream of Inanda Dam. Innovative new procedures were developed to model the rainfall erosivity. This soil loss potential information was used in the *ACRU* sediment yield model to estimate the amounts of stormflow derived at each subcatchment outlet on a daily basis. Hence, those areas which are likely to yield large sediment loads, and potentially carry attached phosphorus and pathogens to the receiving streams, can be identified. The daily sediment yield model could then be used to:

* estimate long-term sediment loads to reservoirs or works,
* determine the effects of extreme sediment yield events on water use criteria, and
* estimate the effects of land use changes on sediment yield within the catchment.

The *ACRU* sediment yield model results were verified in the Mgeni catchment using three separate approaches, viz:

* by comparing with the estimates of sediments trapped in large reservoirs over a period of time,
* by comparing with suspended solids data collected by Umgeni Water on a once-a-week basis, and
* by comparing with suspended solids and discharge data collected by the Department of Agricultural Engineering at the Henley weir at frequent, discharge related intervals during the course of a number of runoff events in 1993 and 1994, using an automatic sediment sampler.

With the confidence gained from the sediment yield verifications using all three approaches, and the ability of the model to reproduce estimated loads of varying magnitude, whether on a long-term basis or for individual events, the *ACRU* model could be used to generate daily, and subsequently long-term average, subcatchment yields from each of the 137 subcatchments. The mean annual simulated sediment yield for the 137 subcatchments ranged from 2 to 629 $t.km^{-2}$. Highest sediment yields were found in the highly eroded Valley of a Thousand Hills as well as in subcatchments in the Edendale area, where large proportions of informal dwellings are located. In analysing findings based on simulated sediment load sequences, it became apparent that single flood events with low recurrence probabilities, such as those experienced during the September 1987 floods, mobilise large amounts of sediments. Hence, for instance, during a single week in September 1987, 18.1% of the total 34-year sediment yield estimate was computed in the Subcatchment 9 of the Midmar Management Subcatchment.

In modelling non-point source phosphorus yield, the phosphorus sources from a number of origins were included in the *ACRU* model, viz:

- fertilizer applications in agriculture,
- livestock depositions,
- depositions from the atmosphere in rainfall (wet deposition) and through adherence to dust particles (dry deposition), as well as from
- human sources through seepage and overflow of pit latrines.

A phosphorus pollution potential map was produced by adding all phosphorus inputs that would be available within the top 10 mm of soil. Values for wet and dry atmospheric deposition, numbers of beef cattle, dairy cows and sheep, amounts and application frequencies of fertilizers for sugarcane, maize and mixed crops as well as inputs from human faeces where inhabitants are without proper sanitation, were summed up to give results in $kg.km^{-2}.a^{-1}$. Values of the 250 by 250 grid cell points for potential loading in the Mgeni catchment varied from less than 250 to more than 4 800 $kg.km^{-2}.a^{-1}$.

Following intensive verification studies of the *ACRU* phosphorus yield model, again using a range of techniques, a map based on subcatchment diffuse source phosphorus yield was produced for the Mgeni catchment. Mean annual phosphorus yield values were simulated to range from 0.5 to 650 $kg.km^{-2}$. The distribution of high and low long-term phosphorus yield values over the Mgeni catchment is quite dissimilar to the distribution of long-term annual sediment yields. Significant non-point source phosphorus loads emanate from the Albert Falls Management Subcatchment, with its many feedlots, whereas the subcatchment has a relatively low sediment yield. It is therefore obvious that the high phosphorus loads are due to the large amounts of source phosphorus in these subcatchments, as is indicated in the phosphorus pollution potential map.

An *E. coli* model for the *ACRU* system was developed, in which account is taken of grazing livestock and humans in areas of inadequate sanitation. Following again an intensive verification study of the *E. coli* model, this pathogen indicator was mapped on a subcatchment basis for 137 subcatchments with *E. coli* concentration ranging from 30 to 18 200 counts.100 $m\ell^{-1}$.

Areas of highest *E. coli* concentrations are associated with informal settlements, in particular along the Msunduzi river in its lower reaches and central parts of the Valley of a Thousand Hills. It is also evident that high *E. coli* concentrations are not always associated with areas of high sediment yield. In Management Subcatchment 10, for example, high average *E. coli* counts are simulated (1 000-10 000 counts.100 $m\ell^{-1}$) even though the average annual sediment yield in this area is relatively low (25-100 $t.km^{-2}$). This is due to the large populations in informal settlements in this area as well as the relatively high stocking rates.

Two future modelling scenarios were evaluated in terms of water quality. In the first scenario an increase in subsistence farming and informal settlements in the Msunduzi catchment, upstream of Pietermaritzburg, indicated sediment yield increases by 17%, phosphorus increases by 76% and *E. coli* concentrations by 40%. Phosphorus yield increases by far the most significant due to its dependence both on the land use changes, that is a population influx as well as agricultural expansion.

In a second impact study on water quality the Table Mountain Management Subcatchment was subjected to a 50% replacement of present savanna and indigenous woodland by, in turn, eucalypt plantations, sugarcane cultivation and intensive smallholder agriculture. Impacts on both sediment yield and phosphorus yield were up to 2 orders of magnitude higher for conversion to smallholdings than for conversion to eucalypts.

Conclusions and Recommendations

General conclusions and recommendations from the hydrology component of this important project include the following:

* A modelling system, with comprehensive datasets for the Mgeni catchment upstream of Inanda Dam, has been established to simulate components of the hydrological cycle.
* Observed and simulated runoff compare very favourably in catchments with significantly different land uses and water yields.
* The system can therefore be used to study the individual components of the hydrological cycle, such as soil moisture content histories, low flow periods, base flows and peak flows.
* The modelling system can furthermore be used to estimate components of the hydrological cycle which determine water quality processes.
* The system is highly suitable for determining the impacts of anticipated land use change scenarios on the aquatic environment.

General conclusions and recommendations that can be made from the achievements in water quality simulations of this study include the following:

* A modelling system, with comprehensive data sets for the Mgeni catchment upstream of Inanda Dam, has been established to simulate non-point source sediment yield, phosphorus loads and *E. coli* concentrations at subcatchment level.
* The system is highly suited to determining the impacts of anticipated land use change scenarios on selected water quality responses.

- A need for adequate water quality monitoring methods to yield reliable estimates of the total loading of sediments and phosphorus has been identified. It is recommended that integrated sampling, or automatic sampling, be instituted in critical catchments.
- A need for experimentation designed to allow for the observation of the transport mechanisms of sediments, phosphorus and *E. coli* within a catchment has also been identified.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Mgeni catchment, 4 387 km^2 in area, is the vital water source for both the Greater Durban and Pietermaritzburg Metropolitan areas in the Province of KwaZulu-Natal (Figure 1*). It supplies water for approximately 45% of the Province's population in a region which produces 20% of South Africa's gross national product. Umgeni Water, the Statutory Water Board responsible for the management and supply of water, has over the past 10 years supplied a mean volume of 204 million m^3 annually to consumers living in and adjacent to the Mgeni catchment area, with the maximum annual supply reaching 270 million m^3 in 1993/1994 (Umgeni Water, 1994). The mean annual volume supplied represents 37% of the long-term annual water yield produced in the catchment area of the Mgeni upstream of, and including Inanda Dam. During the period 1960-1993 the annual precipitation (MAP) for the 4 079 km^2 catchment area upstream of Inanda Dam varied between a low of 578 mm in 1992 and a high of 1 384 mm in 1987, averaging 902 mm per annum for that period. In order to make provision for a secure water supply under these highly variable rainfall conditions, Umgeni Water manages five dams for water supply, with a combined capacity of 745.9 million m^3. These are the Midmar, Albert Falls, Henley, Nagle and Inanda Dams. Their combined volume represents 135% of the mean annual runoff (MAR), under current land use conditions, of the catchment area upstream of Inanda Dam.

Some 1.5 million people live in the area upstream of Inanda Dam, while a further 3 million are supplied by transfers of water captured in the Mgeni catchment to areas downstream of Inanda Dam in the Durban Functional Region. The population in the Greater Durban and Pietermaritzburg Metropolitan areas has been projected to expand to between 9 and 12 million by the year 2025 (Horne Glasson Partners, 1989), with major population concentrations within the former KwaZulu areas in, and adjacent to, the Mgeni catchment. Apart from urban concentrations, areas within the former KwaZulu homelands are amongst the most densely populated areas in the catchment (Figure 2*). It was recognised over a decade ago already that the rapidly accelerating water demand would exceed local raw water resources by the turn of the century (Breen, Akhurst and Walmsley, 1985). Provision is thus currently being made to supplement water resources in the Mgeni system by means of water transfers from adjacent and relatively

* Figure numbers with an asterix are in colour and are found at the end of the document.

undeveloped catchments, such as the Mooi and Mkomazi, which have sources originating in the mountainous region of the southern Drakensberg. The increased occurrence of return flows, intensified agricultural practices and the presently unco-ordinated growth of large informal settlements which are associated with population expansion and influxes into the region are expected to lead to further deterioration of the water quality of streams, rivers and dams. During summer months, frequent convective thunderstorms of high intensity rainfall result in the transport of suspended solids, *E.coli* and phosphorus from the subcatchments into receiving channels, with the consequence that domestic, agricultural, industrial, ecological and recreational user groups are affected. The anticipated decline in water quality will most probably be associated with increased purification costs and health risks in areas where untreated water is widely used for domestic or recreational purposes, as well as in potentially irreversible degradation of the riverine environment.

In response to these perceived potential water related problems, concerned parties met at a workshop entitled *Water Quality Management in the Mgeni Catchment* which was convened by the Natal Town and Regional Planning Commission and the Foundation for Research Development in February 1985 (Breen *et al.*, 1985). Arising from this workshop, the Mgeni Modelling Group was established to work towards answering key questions raised at the workshop, which included:

* development of a dynamic system model of the Mgeni catchment which was to link hydrological responses from rural, urban and industrial areas to make broad predictions of water quality trends,
* compilation of a land use map,
* assessment of the implications of inter-catchment water transfers,
* establishment of the impacts of afforestation on water supply,
* establishment of the relationships between land use and nutrient/pollutant export, and
* evaluation of currently available water quality prediction models with a view to developing improved models.

The Mgeni Modelling Group came to the conclusion that a modelling approach could provide information essential to those responsible for planning the development and management of the Mgeni catchment (Walmsley and Furness, 1987). The Department of Agricultural Engineering (DAE) at the University of Natal in Pietermaritzburg was then requested, through the Mgeni Modelling Group, to undertake a two-phased research programme which would develop the framework of such a model, with funding provided by the Water Research Commission (WRC).

1.2 OBJECTIVES OF RESEARCH

In Phase I of the research programme, entitled *Distributed Hydrological Modelling System for the Mgeni Catchment*, the *ACRU* hydrological modelling system (Schulze, 1989) was set up for the Mgeni, following some substantial model refinement to accommodate the principal hydrological processes associated with large, complex catchments (Tarboton and Schulze, 1992). Furthermore, an extensive data base, required to enable detailed streamflow simulation on a daily time step, was established. Large sections of the data base have since been utilised by other hydrological studies in the Mgeni catchment, such as the *Mgeni River System Analysis Study* (BKS Inc., 1994) and the Department of Water Affairs and Forestry's (DWAF) *Mgeni Catchment Water Quality Management Plan: Hydrology & Hydraulics* (DWAF, UW, BKS and NSI, 1994). The results of Phase I of the research programme are described by Tarboton and Schulze (1992) in the WRC Report No. 234/1/92, which also contains sections on concepts of simulation modelling, a description of the *ACRU* model, verification studies, as well as initial scenario applications.

The main objectives of Phase II of the research programme, entitled *Development of a Distributed Hydrological Modelling System to Assist with Water Quantity and Quality Management in the Mgeni Catchment, Phase II*, were two-fold, viz:

* the **development of a simulation tool**, in which the *ACRU* modelling system was to be further developed to incorporate relevant water quality simulation capabilities so as to enable the modelling of selected water quality parameters, viz. sediments, phosphorus and *E. coli*, which are important to those responsible for planning and management of the Mgeni catchment's water resources, and

* **setting up of an operating model**, in which the extended and verified *ACRU* modelling system was to be applied in simulations of water quantity and water quality in order to implement and evaluate the model for potential catchment scenarios.

Phase II research activities thus focused on improving the hydrological modelling system developed in Phase I, and incorporating selected water quality components and subroutines. Because the major water quality problems occurring in the Mgeni catchment include the eutrophication of reservoirs, with phosphorus being the limiting nutrient, and frequent bacteriological contamination of streams and rivers, the *ACRU* modelling system was enhanced to enable it to simulate the non-point source mobilisation and transport of phosphorus and *E. coli* into receiving water bodies. Besides contributing to deterioration of streamflow and reservoir storage, sediments also constitute the most important transporting medium for phosphate in its insoluble state, and also play a significant role in the movement of *E. coli*. Hence the sources of sediments and their transport into streams were given particular attention in Phase II.

In summary, the foci of Phase II were:

* improvement, extension and verification of daily streamflow simulations of the now 137 (previously 123) subcatchments contributing water to Inanda Dam,
* characterisation of the hydrology and water quality of the 12 so-called Management Subcatchments (based principally on Quaternary Catchments), as they were delineated for the Mgeni Catchment Water Quality Management Plan by DWAF *et al*. (1994),
* the simulation of streamflows assuming pristine catchment conditions, enabling an evaluation of the impacts of current land cover on water yield,
* estimation of impacts of different land uses on water yield,
* simulation of hypothetical future land use scenarios to evaluate their impacts on water yield,
* development and application of digital elevation models (DEMs) to allow for the parameterisation of important hydrological and water quality variables,
* preparation of a set of digital monthly soil erosion potential maps at relatively high spatial resolution (250 by 250 m grid), based on the Revised Universal Soil Loss Equation (RUSLE),
* development, testing and implementing the sediment yield routines and verifying results against available sediment yield and suspended solids data,
* development of a subcatchment sediment yield map,
* modelling and mapping of a non-point source phosphorus,
* development, testing, implementing of subcatchment phosphorus yield routines and verifying results against available phosphorus data,
* preparation of a subcatchment phosphorus yield map,
* production of an *E. coli* source map,
* development, testing and implementing of subcatchment *E. coli* concentration routines and verifying results against available *E. coli* data, and
* preparation of a catchment based *E. coli* concentration map.

1.3 CRITERIA FOR THE SELECTION OF AN APPROPRIATE HYDROLOGICAL MODEL

In order to meet the above objectives, specific and demanding modelling capabilities had to be realised, particularly in terms of modelling concepts and the model's capabilities in representing of the variability of hydrological characteristics and responses in time and space. This section highlights the particular capabilities of the hydrological model chosen for this study.

Hydrological and water quality modelling are traditionally performed using one or more of four different modelling approaches:

* **Stochastic models**. These are so-called "black box" models, in which inputs (e.g. rainfall) are transformed to output (e.g. runoff) with little or no understanding of the processes involved in the transformation. This type of model relies heavily on historical records of both input and output variables being a representative sample over time.

* **Calibration and parameter optimising models**. These are models in which parameters of the model are adjusted to enable the model output to match observations as closely as possible. The major drawbacks of these models are that they are data demanding (for the calibration procedure) and that parameters are identified for a particular catchment, making parameter transfers to ungauged catchments problematic and speculative.

* **Parametric models**. These are so-called "grey box" models, representing a partial understanding of hydrological processes, but in which the system's spatial heterogeneity (e.g. of soils, vegetation, terrain) is not taken account of because inputs (and hence outputs) are spatially averaged (lumped). Consequently, hydrological processes and their variability are integrated such that their parameter expressions are often indices rather than having strictly physically meaningful values.

* **Deterministic, physical conceptually based models.** These belong to the group of "white box" models, in which the behaviour of the hydrological system is described in terms of mathematical relationships which outline the interactions and linkages of the various components of spatially and temporally varying catchment hydrological process.

With the high spatial variability of rainfall, soils, land cover, altitudes, slopes and population distribution within the Mgeni catchment, it is vital to account for the unique hydrological and water quality characteristics of smaller, relatively homogeneous, parts of the subsystem. This can only be achieved by subdividing the Mgeni catchment into a number of subcatchments, thus necessitating a distributed hydrological modelling approach.

In aiming at reliable predictions within the Mgeni system of both present and future hydrological and water quality behaviour in ungauged subcatchments, which may be composed of unique climatic, soil, vegetative, topographical and anthropogenic characteristics, the selection of a "white box" model with the capability of operating in distributed mode was deemed necessary.

Other than the spatial resolution of model inputs, the model's time step plays a major role in representing hydrological processes realistically. In a hydrological system, individual rainfall events, which occur over relatively short time intervals, are the driving forces on which the system's longer term streamflow behaviour is based. A daily time step model, in contrast to one that utilises (say) monthly time steps, is thus capable of responding to the important intra-monthly fluctuations of rainfall. For example, given a monthly total rainfall of say 80 mm, it remains unknown in a monthly model whether the rainfall occurred on a single day, which would probably result in significant runoff generation and potentially in the mobilisation of soil particles, sediments and other pollutants, or whether the rainfall occurred over several days, each with relatively low daily rainfall, which would most likely produce very little runoff and negligible mobilisation of pollutants. To that end, for realistic hydrological and water quality simulations, a model was required with at least a daily time resolution.

The *ACRU* hydrological modelling system contains the modelling capabilities and criteria identified in the requirements outlined above: it is a physical conceptual model, based on a daily time step and can be applied in distributed mode. An additional advantage is that interfaces have been developed to accommodate information from a Geographical Information System (GIS), which plays an integral part in collecting, combining, calculating and overlaying relevant spatial features for a large set of subcatchments.

1.4 A BRIEF INTRODUCTION TO THE *ACRU* MODELLING SYSTEM

The *ACRU* model was developed within the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg. The theoretical background, concepts and capabilities of the *ACRU* model are detailed in a handbook entitled *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Modelling System* by Schulze (1995), while practical considerations are presented in the *ACRU 3.00 User Manual* under editorship of

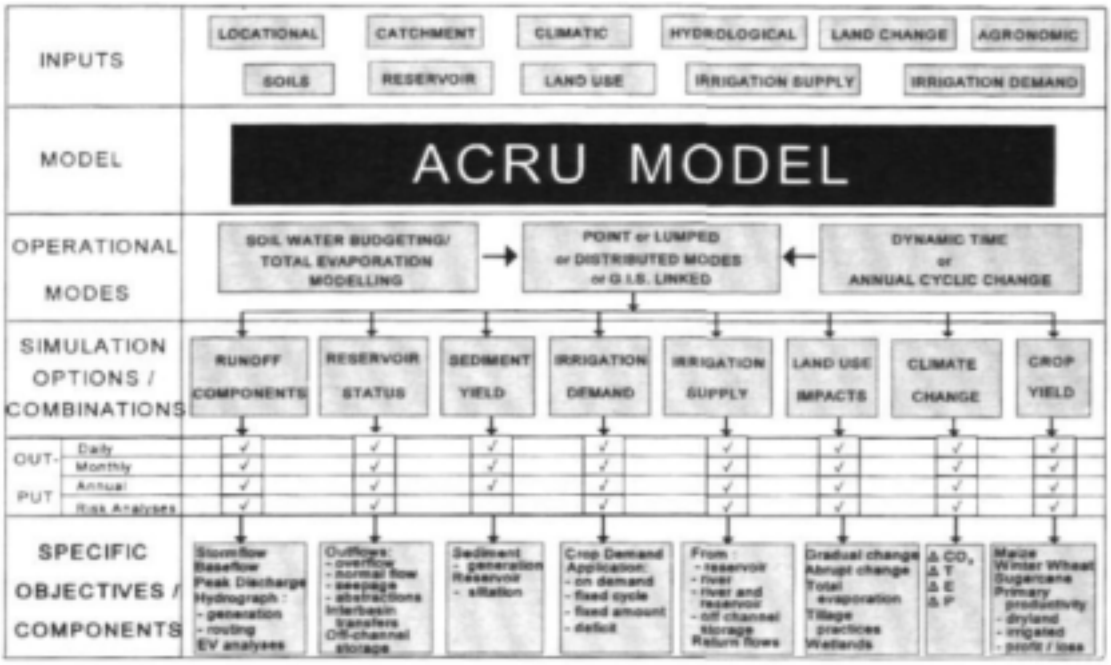


Figure 3 The *ACRU* agrohydrological modelling system: Concepts (Schulze, 1995)

Smithers and Schulze (1995). The model has been verified widely on data from southern Africa, Chile, Germany and the USA (Schulze, 1995). *ACRU* has been used extensively in decision making in southern Africa and internationally in water resources related research and applications in Botswana, Chile, Germany, Lesotho, Namibia, Swaziland and the USA.

The *ACRU* agrohydrological modelling system (Schulze, 1995) has been designed according to the following modelling philosophies (Figures 3 and 4):

* It is a *physical conceptual* model, i.e. it is conceptual in that it conceives of a catchment system in which important hydrological processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly.

* *ACRU* is not a parameter fitting or optimising model and variables (rather than optimised parameters) are, by and large, estimated from physical characteristics of the catchment.

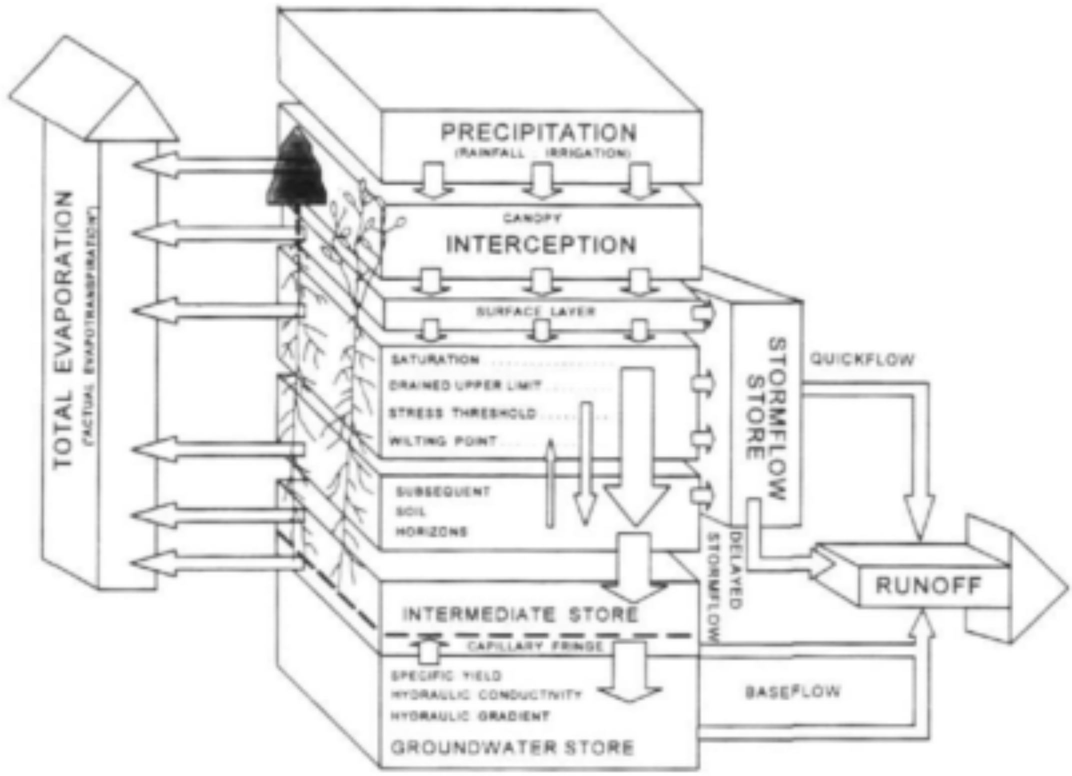


Figure 4 The *ACRU* agrohydrological modelling system: General structure (Schulze, 1995)

* It is a *multi-purpose* model (Figure 3) which integrates the various water budgeting and runoff producing components of the terrestrial hydrological system with risk analysis, and can be applied in design hydrology, crop yield modelling, reservoir yield simulation and irrigation water demand/supply, regional water resources assessment, planning optimum water resource utilisation and resolving conflicting demands on water resources.
* The model operates on *daily time steps* utilising daily rainfall input, thereby making optimal use of available data. Certain more cyclic, conservative and less sensitive variables (e.g. temperature, reference potential evaporation), for which values may have to be input at monthly level (if daily values are not available), are transformed internally in *ACRU* to daily values by Fourier Analysis. In routines in which sensitive intra-daily information (e.g. of rainfall distribution) is required, this is obtained by synthetic disaggregation of daily input within the model.

* The *ACRU* model revolves around daily *multi-layer soil water budgeting*. It has therefore been structured

to be highly sensitive to climate and to land cover/use[1] changes on the soil water and runoff processes. In addition, the water budget is responsive, *inter alia*, to supplementary watering by irrigation, to changes in tillage practices, to changes in vegetation or to the onset and degree of plant stress.

- *ACRU* has been designed as a *multi-level* model, with either multiple options or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of input data available or the detail of output required. Thus, for example, reference potential evaporation, interception losses, values of soil water retention constants, maximum as well as total evaporation, leaf area index, components of the peak discharge estimation, hydrograph routing, reservoir storage : area relationships or the length of phenological periods in crop growth, all may be estimated by various methods according to the level of input data at hand or the relative accuracy of simulation required.

- *ACRU* can operate at a *point* or as a *lumped* catchment model. However, an important option in areas of complex land uses and variability of soils is that *ACRU* can operate as a *distributed* cell-type model. In distributed mode subcatchments are identified, demarcated and flows can take place from "exterior" through "interior" subcatchments according to a predetermined configuration, with each subcatchment able to generate individually requested outputs which may be different to those of other subcatchments, or may operate with different levels of input/information.

- The model includes a *dynamic input option* to facilitate modelling of hydrological responses to climate, land use or management changes in a time series. These changes may be either long-term/gradual changes such as forest growth, urbanisation, expansion of irrigation projects and climate trends, or abrupt changes such as clearfelling, fire impacts, dam construction, irrigation development or introduction of new land management strategies, and changes of an intra-annual nature (e.g. crops with non-annual cycles, such as sugarcane).

- *ACRU* operates in conjunction with the interactive *ACRU Utilities*, which consists of a suite of software tools to aid in the preparation of input information (*ACRU Menubuilder*) and output information (*ACRU Outputbuilder*). The *ACRU Menubuilder* prompts the user with a series of questions, facilitating the parameterisation of a distributed catchment. The *Menubuilder* contains alternative decision paths with preprogrammed *Decision Support Systems*. Furthermore, the *Menubuilder* includes a *help facility*, built-in

1) *Land cover* is distinguished from *land use* in that the term *land use* relates to managed or artificial land surfaces only, i.e. any form of agriculture or settlements, while the term *land cover* associates with any kind of land surface, both managed and pristine, thus including natural landscapes such as savannas, woodlands, veld etc.

default values as well as warning messages which inform the user that unrealistic values have been input.

- *ACRU* combines the monthly soil loss potential, based on the Revised Universal Soil Loss Equation (RUSLE), with daily total runoff volume, daily peak discharge and daily soil water content to calculate daily sediment yield from a subcatchment. Additionally, it can simulate on a daily time step the subcatchment total phosphorus yield and the concentration of *E. coli* bacteria, the indicator organism for pathogens in water.

The *ACRU* model is centred on a daily multi-layer soil water budget (Figure 4), and hence the model simulates the components and processes of the hydrological cycle affecting this soil water budget. These processes include:

- canopy interception of rainfall by vegetation,
- net rainfall reaching the ground surface,
- infiltration of net rainfall into the soil,
- total evaporation (transpiration as well as soil water evaporation) from the various horizons of the soil profile,
- the redistribution of soil water in the soil profile, both saturated and unsaturated, and
- percolation of soil water into the intermediate groundwater zone.

The model can output any of the above components. In its present output routines, provision has been made to output on a daily basis, or as monthly and/or annual totals of the daily values, *inter alia*:

- rainfall,
- effective rainfall,
- reference potential evaporation,
- maximum evaporation from vegetative cover under conditions of freely available soil water,
- total evaporation in the form of transpiration and soil water evaporation, under both wet and dry soil conditions, from top- and subsoil horizons respectively,
- soil water content of top- and subsoil layers and
- drainage into the intermediate zone.

From the soil water budget, the model is capable of outputting simulated elements of streamflow on a daily time step, or as monthly or annual totals of daily values. These include :

- stormflow,
- baseflow,
- accumulated streamflow from all upstream catchments when simulating distributed, multiple subcatchments, and
- peak discharge (including hydrograph routing when simulating distributed multiple subcatchments).

The components of the water budget are integrated with modules embedded within the *ACRU* model to enable output of:

- reservoir yield (overflow, reservoir status, abstractions, transfers),
- sediment yield (daily, monthly, annual; reservoir sedimentation),
- irrigation water demand (for different crops, application efficiencies, modes of scheduling),
- irrigation water supply (from streams, reservoirs and combinations; off-channel reservoir storage),
- wetlands hydrological responses,
- effects of abstractions from the stream (e.g. for domestic purposes) on catchment water yield,
- fluctuations of shallow groundwater under certain conditions,
- hydrological impacts of afforestation,
- effects of other land cover and management (e.g. tillage) changes (gradual or abrupt),
- seasonal crop yields (maize, sugarcane and winter wheat under either dryland or irrigated conditions, as well as for non-crop specific net above-ground primary production),
- the effects of enhanced atmospheric CO_2 levels on transpiration suppression and hence on crop yield and water resources,
- mobilisation and transport of sediments into receiving water bodies,
- export of total phosphorus from non-point sources into receiving water bodies, and/or
- export of *E. coli* from non-point sources into receiving water bodies.

1.5 HOW "GOOD" IS A MODEL? THE WHY AND HOW OF VERIFYING SIMULATED HYDROLOGICAL TIME SERIES

A critical part of the hydrological modelling process is to establish that the streamflow simulated by the model is consistent with that of the physical system it represents. A model can only be applied with confidence once the model output has been tested for accuracy and correctness, i.e. verified, against observed data. The major aims in simulating hydrological responses are to produce simulated values which mimic corresponding observed values as closely as possible on a 1:1 basis, such that for a time series under consideration:

* means of simulated values are conserved when compared with means of observed values; and that
* variances (i.e. deviations about the mean) are also conserved; so that
* simulated and observed values will show a close association (i.e. high correlation coefficient), with
* no systematic under- or over-simulation error, i.e. no bias, between simulated and observed trends, and that
* no significant difference between the sets of values at a given level of probability can be found.

Only once the streamflow has been verified, can one verify any water quality component. One of the major drawbacks in the development of a daily water quality model on meso-scale catchments is the lack of data against which to verify model output. The water quality time series of Umgeni Water available at the time of this study consisted primarily of weekly grab samples for approximately five years. Important behaviour patterns of water quality determinands, such as flow to concentration relationships or loads, cannot be based on weekly grab samples, which may often miss the pollution producing events. In order to initiate a suitable water quality database, the DAE installed two automatic water quality samplers, linked to a data logger, and triggered by variations in flow volume passing the sampling site. This flow integrated sampling was undertaken in close co-operation with Umgeni Water, who also undertook the chemical analyses of samples taken. These samples were analysed for suspended solids and phosphorus.

Verification of the simulation of sediment and phosphorus load and *E. coli* concentration is based on three independent data sources available for parts of the Mgeni catchment, viz:

* sediment yield values as published in the literature,
* flow integrated sampling of individual runoff events, and
* weekly grab samples for approximately five years.

Owing to the strong influence streamflow processes have on water quality, Chapter 2 is devoted entirely to the results of the streamflow simulations. Thereafter Chapter 3 addresses the water quality modelling approaches and results.

CHAPTER 2

STREAMFLOW SIMULATIONS

The *ACRU* hydrological and water quality modelling system was configured for the Mgeni catchment upstream of Inanda Dam to simulate daily streamflows for 137 subcatchments for the 34-year period from 1 January 1960 to 31 December 1993. Simulated time series were compared against observed time series, and maps and tables were produced to quantify and qualify the following hydrological components, on both a subcatchment and Management Subcatchment (Quaternary Catchment) basis:

* streamflow production under current conditions,
* streamflow production under pristine conditions,
* the impact of current land use on streamflow production, and
* the impact of possible future land use scenarios on streamflow.

2.1 MODELLING THE MGENI SYSTEM WITH *ACRU*

2.1.1 Layout of the Mgeni Simulation System

An important task in setting up the *ACRU* model for distributed modelling was the demarcation of the entire study area into subcatchments which, hydrologically, were considered relatively homogeneous. In order to be meaningful for subsequent verification studies and to provide hydrological information required by managers, the division of the Mgeni catchment upstream of Inanda Dam into subcatchments had to comply with the following requirements:

* the subcatchments should ideally not be larger than 50 km^2, except where a high level of homogeneity existed or where the rainfall gauging network was very sparse,
* the subcatchments had to be relatively homogeneous in terms of climate, soils and land cover,
* currently operational gauging weirs with long records, operated by the Department of Water Affairs and Forestry (DWAF), were to be situated at the outlet of a particular subcatchment,
* available water quality sampling stations operated by Umgeni Water (UW) were to be located at the outlet end of a particular subcatchment, and
* individual subcatchments had to be a subset of Quaternary, or so-called Management Subcatchments.

Following these guidelines, the study area was delineated into 137 subcatchments. Figure 5* illustrates the distribution of gauging weirs, water quality sampling stations, useable rainfall stations and the 137 so-called *ACRU* subcatchments. The 12 Management Subcatchments upstream of Inanda Dam and their breakdown into *ACRU* subcatchments are displayed in Figure 6*. When simulating the streamflow generated within a subcatchment, it was important that runoff contributions from any upstream subcatchments would have had to have been determined previously in order to incorporate upstream runoff contributions to a downstream subcatchment. Therefore, the sequence in which subcatchments are analysed was defined *a priori*.

For each of the 137 *ACRU* subcatchments a considerable number of variables and parameters representing the unique hydrological properties of each respective subcatchment had to be collected and integrated into an information input menu. Procedures for this are described in the following section.

2.1.2 Preparation of the Input Menu

Input information and data sets required by the *ACRU* model have already been presented in Figure 3. Owing to the spatial nature of the information collected for the Mgeni catchment, a GIS was developed to facilitate processing and generation of modelling inputs. The sources of key data and their conversion into hydrological variables are described below. For more detail, the reader is referred to Tarboton and Schulze (1992).

2.1.2.1 Subcatchment Information

Subcatchments were delineated on 1:50 000 topographical maps and then digitised and combined with a 250 by 250 m digital elevation model (DEM). Information such as area, geographical location and mean elevation were calculated by the GIS, viz. ARC/INFO 6.1 (ESRI, 1992), exported and written to the *ACRU* data input menu.

2.1.2.2 Climate

Rainfall data constitute the single most important variable in hydrological modelling, and considerable time was spent in obtaining the best possible representation of daily areal rainfall for each subcatchment. The approach followed was the so-called driver station method, whereby one rainfall station was selected to "drive" the hydrological response of a subcatchment. In order to account for the rainfall station's location and elevation relative to the subcatchment it represents, daily precipitation values could be adjusted. The determination of adjustment factors was based on median monthly rainfall values available from Dent, *et al.* (1989) on a one minute by one minute of a degree (1' x 1') latitude/longitude grid, i.e. a grid area of approximately 1.6 by 1.6 km. By infilling any missing daily values using distance weighted values from neighbouring rainfall stations, a complete daily record of 34 years, from 1 January 1960 to 31 December 1993, was generated for all 137 subcatchments. Mean annual precipitation (MAP) values were categorised by subcatchment and are displayed in Figure 7*, which shows areas of relatively high and low MAP. For the 34-year period the MAP for the entire study area was determined to be 902 mm.

Potential evaporation is a more continuous process and is temporally less variable than rainfall; individual daily values thus do not necessarily have to be defined. A 1' x 1' latitude/longitude grid containing mean monthly A-pan equivalent potential evaporation values, developed by Schulze and Maharaj (1994), was superimposed with the subcatchment boundaries, to produce mean monthly A-pan equivalent evaporation values per subcatchment. Monthly values are disaggregated into daily values by Fourier Analysis internally in *ACRU*, taking cognisance of whether or not it rained on a particular day.

2.1.2.3 Soils

In South Africa major soil associations are mapped by so-called Land Types. Relevant soil information was made available by the former Soil and Irrigation Research Institute (now Institute for Soil, Climate and Water) and the Land Type boundaries were digitised. For each Land Type, hydrological soil parameters, such as thicknesses of top- and subsoil horizons, their soil water contents at saturation, drained upper limit and permanent wilting point as well as saturated soil water redistribution fractions, were determined. The calculations were based on information supplied with the Land Type maps together with an especially developed decision support system. After combining the Land Type map with the subcatchment boundaries, representative subcatchment values for each of the individual hydrological soil parameters were determined by area-weighting.

2.1.2.4 Land Cover

A land cover map (Figure 8*) was produced by the Institute for Natural Resources (Bromley, 1989), based on a SPOT satellite image from 1986, aerial photography, topographical maps and field visits during 1986. The hydrological properties of each of the 21 land cover classes which were identified in the Mgeni catchment, were defined by a number of variables including the crop coefficient, canopy interception value, the fraction of active root system in the topsoil horizon, and a variable which specifies whether or not a catchment is predominantly under forest, in which case enhanced wet canopy evaporation rates are activated. All variables were calculated for each subcatchment by superimposing the land cover with subcatchment maps and area-weighting the relevant values. The land cover map is a raster map with a grid size of 250 by 250 m.

The same hydrological variables, but related to natural vegetation, were determined for assumed "pristine" land cover conditions which, for this study, were represented by Acocks' (1988) Veld Types. Such pristine conditions were deemed to exist before significant anthropogenic land cover changes had occurred in the catchments. Figure 9* shows the distribution of Acocks' vegetation types in the study area.

2.1.2.5 Streamflow Simulation Control Variables

Streamflow information required for each subcatchment consists of a coefficient representing that fraction of total stormflow generated from rainfall on a given day that will exit the subcatchment on the same day as the rainfall event, a variable which regulates the groundwater (baseflow) contributions to total streamflow, the effective depth of soil from which stormflow is generated, the fractions of the catchment that are occupied by impervious areas with or without direct connection to a watercourse, and a coefficient of initial abstraction used to estimate the amount of rainfall abstracted by interception, surface storage and infiltration before stormflow commences.

2.1.2.6 Farm Dams

Information was collected for each of 1138 farm dams located in the study area (Tarboton and Schulze, 1992). The information included location, surface area at full capacity, wall length, axis length, basin slope, dam shape, storage capacity, area/capacity relationship, and drafts. Figure 10* shows the distribution of farm dams.

2.1.2.7 Irrigated Areas

For each irrigated area identified from the land cover map, information was gathered describing the most important parameters of an irrigation project (Tarboton and Schulze, 1992). These parameters included the area irrigated, its soil properties, crop characteristics, mode of irrigation scheduling, irrigation cycle, conveyance losses, farm dam losses and source of irrigation water (either dam or river).

2.1.2.8 Abstractions and Releases from Reservoirs

Values of daily flow releases from the Mgeni and Albert Falls Dams were available from gauging weirs and were obtained from the DWAF. Monthly abstractions and releases from Henley and Nagle Dams were supplied by Umgeni Water. Monthly effluent values and estimates for Darvill Wastewater Works were provided by Umgeni Water. All this information was included in a set of dynamic input files, each enabling the *ACRU* modelling system to access the relevant abstraction and release information, as it changed with time, for the 34-year simulation period.

2.2 VERIFICATION STUDIES

2.2.1 Methodology and Results

The aim of streamflow simulations in the Mgeni catchment was not the perfect matching of daily streamflow with observed runoff records, but rather the generation of streamflow sequences to provide information on the magnitudes of high and low flows with an associated probability of recurrence. In order to ensure that the land cover information used in the study, which is based on a survey undertaken in 1986 (Tarboton and Schulze, 1992), was representative of the actual land cover over a given period, the time period 1979 to 1993 was selected for the verification study. This period represents the year of the land cover survey plus seven years on either end of that year. The distribution of the principal land covers for each subcatchment was assumed to be representative for the period of the verification.

Streamflow values from *ACRU* from six of the twelve Management Subcatchments which are shown in Figure 6*, viz. from the Mpendle, Lions, Karkloof, New Hanover, Nagle and Henley subcatchments, were verified against observed data. Figures 11 to 16 show the summarised results of the verification studies. The following information is displayed for each verification analysis:

- a time series plot of simulated and observed monthly totals of daily streamflows for the verification period,
- a comparison of accumulated monthly totals of daily streamflows for simulated and observed values, and
- a comparison of month-by-month plots of simulated and observed distributions at the 10th, 50th and 90th percentiles of streamflow. These represent the expected non-exceedences of streamflows for any given month, at the median (i.e. expected) streamflow value (50th percentile), and at the highest streamflow expected statistically once in 10 years (90th percentile) as well as the lowest (10th percentile).

Furthermore, the following are shown:

* a plot of distributions of mean monthly precipitation (MMP), mean monthly streamflow (MMR), mean monthly reference potential evaporation (MMPE) and mean monthly total (actual) evaporation (MMTE),
* a pie diagram providing information on the proportional distributions of the major land cover classes,
* a summary of statistics characterising the performance of *ACRU* by comparing simulated and observed monthly totals of daily streamflows, and
* a summary of catchment characteristics, presenting important climatic and hydrological information.

Verification results of monthly totals of daily simulated and observed streamflows show that all simulations of verified Management Subcatchments gave coefficients of determination (i.e. r^2 values) above 78%, with four exceeding 84%. In each case, simulated streamflow totals were within 6% of observed values, with five subcatchments simulating to within 3%. Differences of standard deviations were consistently within 15%, with three Management Subcatchments' differences below 4%. The conservation of the variability of streamflow is particularly important for water resource management and subsequent water quality simulations. Month-by-month comparisons of simulated against observed median as well as highest and lowest streamflows expected once in ten years show a very good correspondence, with highly acceptable representation of their seasonal variations. In addition, the simulated daily flows are also sufficiently correlated with daily flow observations to warrant confidence in using the simulated hydrology in water quality modelling.

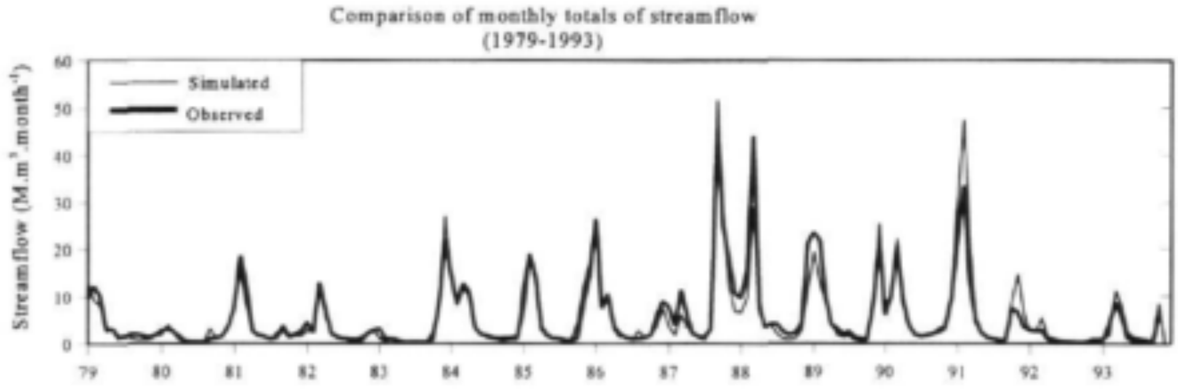
From these highly successful verification studies it may be concluded that the *ACRU* model can be used with confidence to simulate hydrological responses in the Mgeni catchment and that the model can be expected to provide acceptably realistic answers when used to simulate the hydrology of anticipated future land uses.

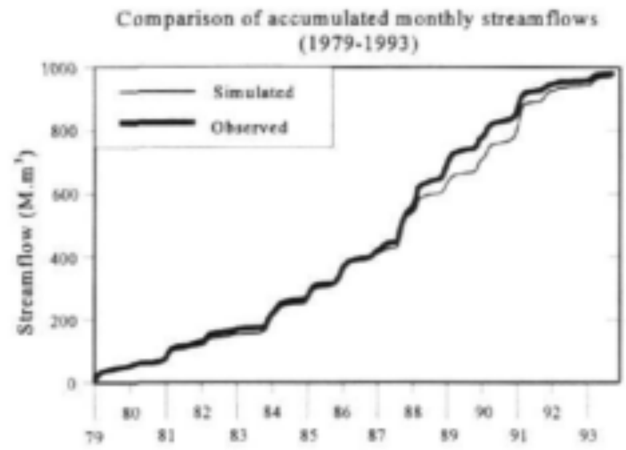
2.2.2 A Note on Data Problems

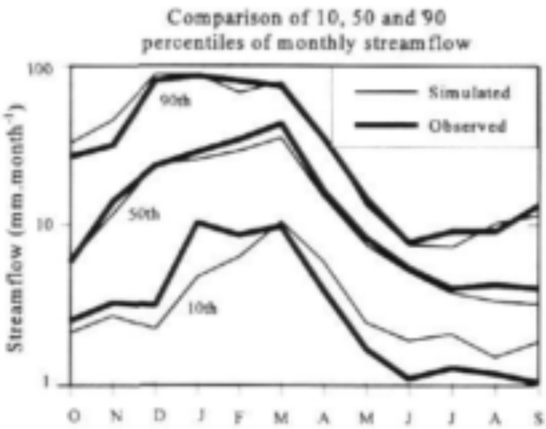
The comparison of a simulated and observed time series of streamflows is associated with problems which can be related to the simulation process, on the one hand, and to the monitoring of rainfall and streamflow on the other. During the data preparation process for streamflow simulation, a number of simplifications were inevitable, such as the representation of each subcatchment's daily rainfall by a single rainfall station, the averaging of divergent soils properties to provide representative values for an entire subcatchment, or the assumption that land cover did not change significantly during the simulation period.

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Mpendle Management Subcatchment (1979 - 1993)







Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	176	5413
Sum of observed values (mm)	=	618.7	3325.1
Sum of simulated values (mm)	=	3564.1	3471.7
% difference between sums	=	1.5	-4.4
Correlation coefficient, r	=	.939	.823
Slope of regression line	=	.970	.860
Y intercept of regression line	=	.299	.113
Standard deviation of X values (mm)	=	27.8	1.538
Standard deviation of Y values (mm)	=	28.7	1.608
% difference between standard deviations	=	-3.3	-4.5
Coefficient of determination, r^2	=	.883	.677
Coefficient of efficiency	=	887	.658

Catchment Summary

Catchment area	=	296 km^2
Mean annual precipitation	=	966 mm
Mean annual runoff	=	249 mm
	or	67.5 M m^3
Runoff coefficient	=	25.8%
Mean annual potential evaporation	=	1596 mm

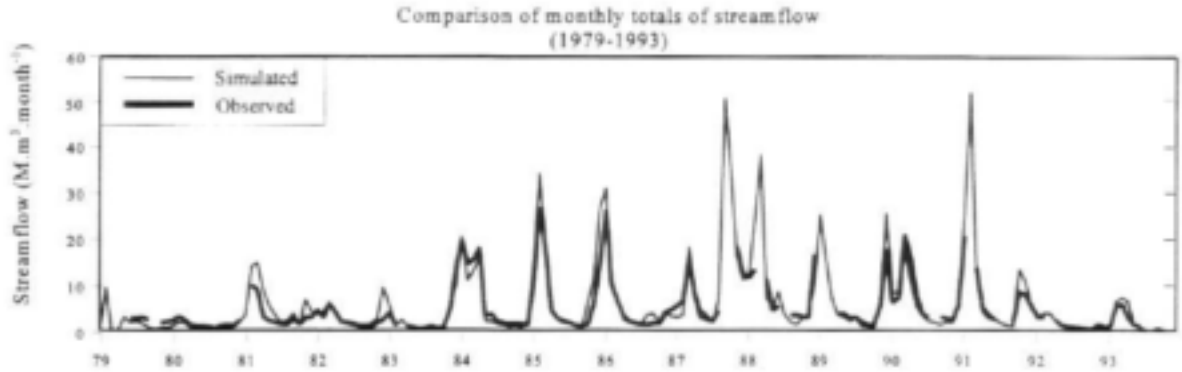
Land Use (%)

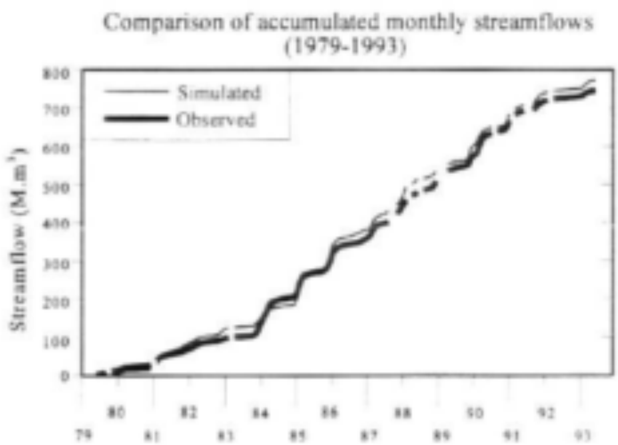
Rural	=	0.3
Forest	=	11.3
Irrigated Agriculture	=	3.3
Dryland Agriculture	=	6.4
Natural Vegetation	=	75.6
Water Bodies	=	3.1

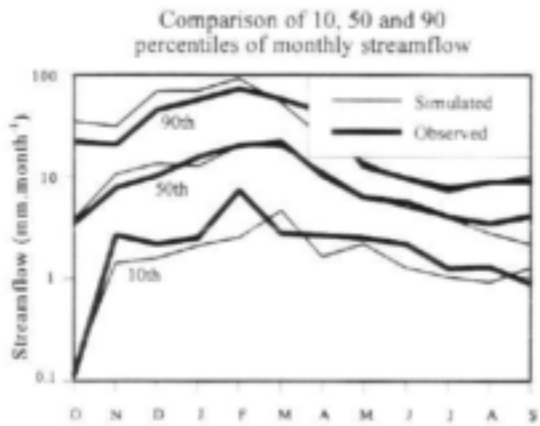
Figure 11 Verification of streamflow for the Mpendle Management Subcatchment

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Lions Management Subcatchment (1979 - 1993)







Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	156	5077
Sum of observed values (mm)	=	2061.1	2439.9
Sum of simulated values (mm)	=	2079.2	2599.9
% difference between sums	=	.9	1.1
Correlation coefficient, r	=	.889	.869
Slope of regression line	=	1.009	1.043
Y intercept of regression line	=	.002	.011
Standard deviation of X values (mm)	=	15.6	.742
Standard deviation of Y values (mm)	=	17.7	.890
% difference between standard deviations	=	-13.5	-20.0
Coefficient of determination, r^2	=	.790	.756
Coefficient of efficiency	=	.749	.753

Catchment Summary

Catchment area	=	362 km^2
Mean annual precipitation	=	947 mm
Mean annual runoff	=	170 mm
	or	61.5 $M.m^3$
Runoff coefficient	=	18.0%
Mean annual potential evaporation	=	1637 mm

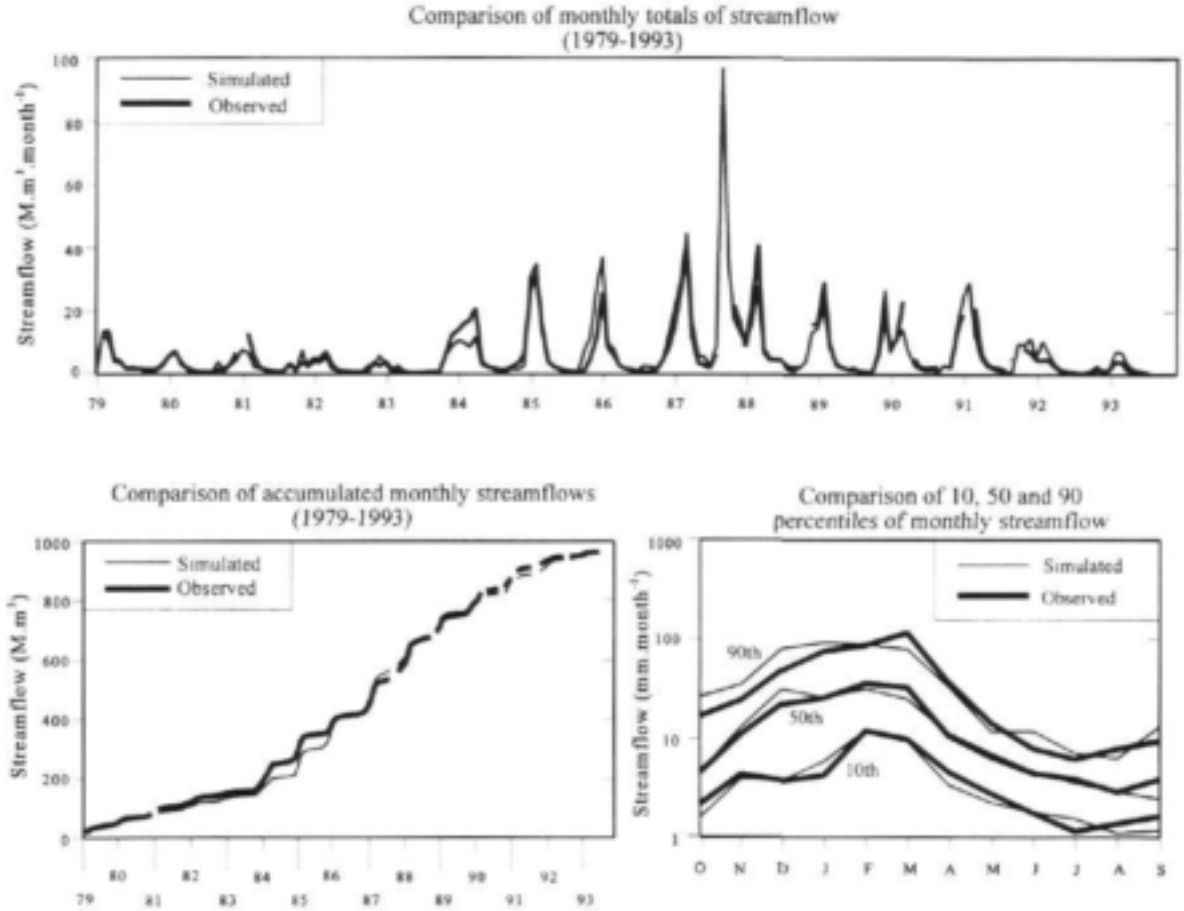
Land Use (%)

Urban	=	0.6
Rural	=	3.4
Forest	=	13.0
Irrigated Agriculture	=	9.0
Dryland Agriculture	=	9.4
Natural Vegetation	=	63.7
Water Bodies	=	0.9

Figure 12 Verification of streamflow for the Lions Management Subcatchment

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Karkloof Management Subcatchment (1979 - 1993)



Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	161	5198
Sum of observed values (mm)	=	2814.9	3068.2
Sum of simulated values (mm)	=	2782.9	3071.7
% difference between sums	=	1.1	-0.1
Correlation coefficient, r	=	.918	.813
Slope of regression line	=	.925	.969
Y intercept of regression line	=	1.11	.019
Standard deviation of X values (mm)	=	23.1	.999
Standard deviation of Y values (mm)	=	23.3	1.190
% difference between standard deviations	=	-0.8	-19.2
Coefficient of determination, r^2	=	.843	.662
Coefficient of efficiency	=	.835	.661

Catchment Summary

Catchment area	=	337 km^2
Mean annual precipitation	=	1032 mm
Mean annual runoff	=	209 mm
	or	70.4 M.m^3
Runoff coefficient	=	20.3%
Mean annual potential evaporation	=	1632 mm

Land Use (%)

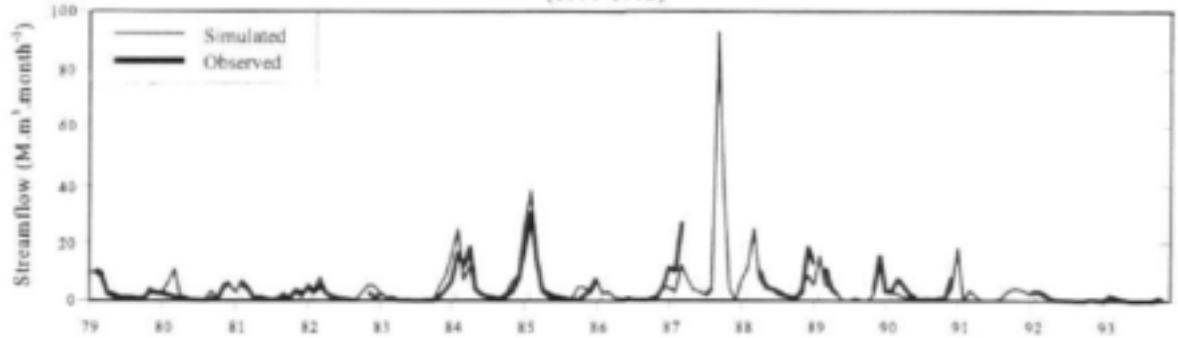
Urban	=	46.6
Rural	=	4.7
Forest	=	32.7
Irrigated Agriculture	=	4.8
Dryland Agriculture	=	11.1
Natural Vegetation	=	0.1

Figure 13 Verification of streamflow for the Karkloof Management Subcatchment

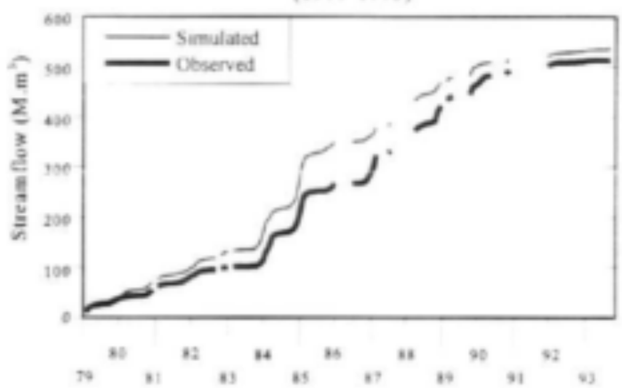
VERIFICATION OF OUTPUT FROM THE ACRU MODEL

New Hanover Management Subcatchment (1979 - 1993)

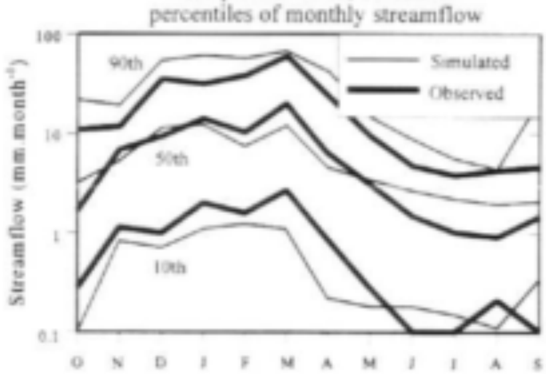
Comparison of monthly totals of streamflow
(1979-1993)



Comparison of accumulated monthly streamflows
(1979-1993)



Comparison of 10, 50 and 90
percentiles of monthly streamflow



Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	132	4947
Sum of observed values (mm)	=	1100.7	1476.0
Sum of simulated values (mm)	=	1109.7	1514.4
% difference between sums	=	.5	-2.6
Correlation coefficient, r	=	.887	.842
Slope of regression line	=	.966	.958
Y intercept of regression line	=	.356	-0.09
Standard deviation of X values (mm)	=	13.0	1.945
Standard deviation of Y values (mm)	=	14.1	1.709
% difference between standard deviations	=	-8.9	13.8
Coefficient of determination, r^2	=	.786	.709
Coefficient of efficiency	=	.745	.708

Catchment Summary

Catchment area	=	430 km²
Mean annual precipitation	=	889 mm
Mean annual runoff	=	115 mm
	or	49.5 M.m³
Runoff coefficient	=	13.0%
Mean annual potential evaporation	=	1690 mm

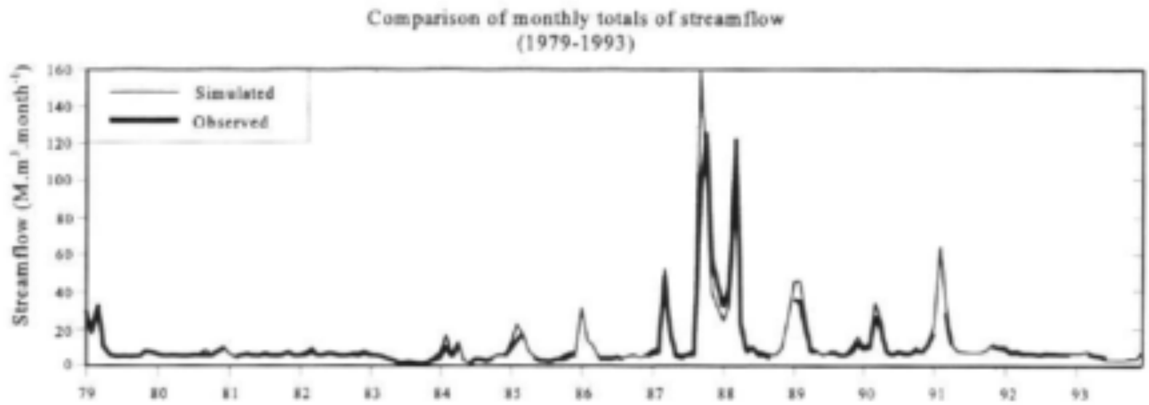
Land Use (%)

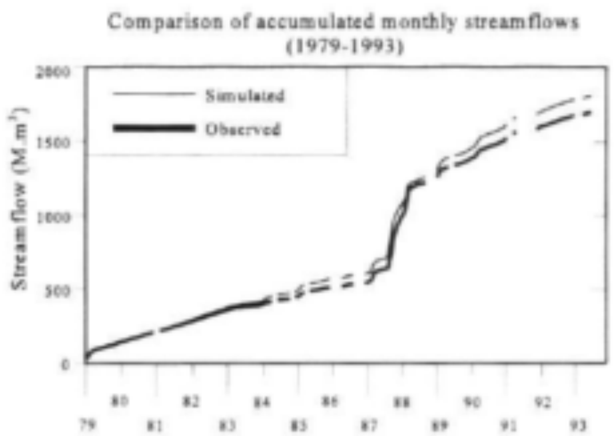
Urban	=	0.9
Rural	=	17.0
Forest	=	40.0
Irrigated Agriculture	=	1.0
Dryland Agriculture	=	30.8
Natural Vegetation	=	10.0
Water Bodies	=	0.3

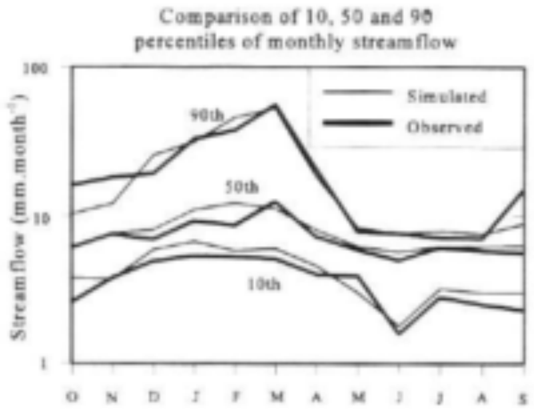
Figure 14 Verification of streamflow for the New Hanover Management Subcatchment

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Nagle Management Subcatchment (1979 - 1993)







Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	152	5008
Sum of observed values (mm)	=	1697.0	1939.7
Sum of simulated values (mm)	=	1802.7	2039.1
% difference between sums	=	6.2	-5.1
Correlation coefficient, r	=	.926	.950
Slope of regression line	=	.953	.724
Y intercept of regression line	=	012	.127
Standard deviation of X values (mm)	=	17.4	1.857
Standard deviation of Y values (mm)	=	17.9	1.415
% difference between standard deviations	=	-2.9	-23.7
Coefficient of determination, r^2	=	.858	.903
Coefficient of efficiency	=	.854	.772

Catchment Summary

Catchment area	=	439 km^2
Mean annual precipitation	=	851 mm
Mean annual runoff	=	140 mm
	or	61.5 M.m^3
Runoff coefficient	=	16.5%
Mean annual potential evaporation	=	1678 mm

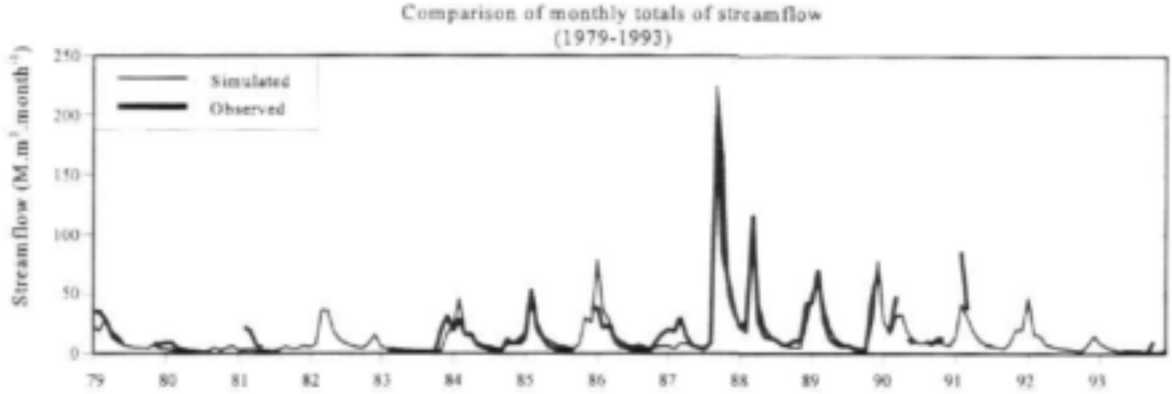
Land Use (%)

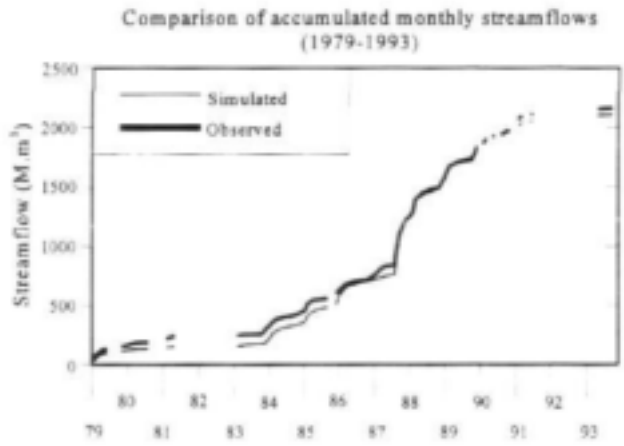
Rural	=	0.3
Forest	=	11.3
Irrigated Agriculture	=	3.3
Dryland Agriculture	=	6.4
Natural Vegetation	=	75.6
Water Bodies	=	3.1

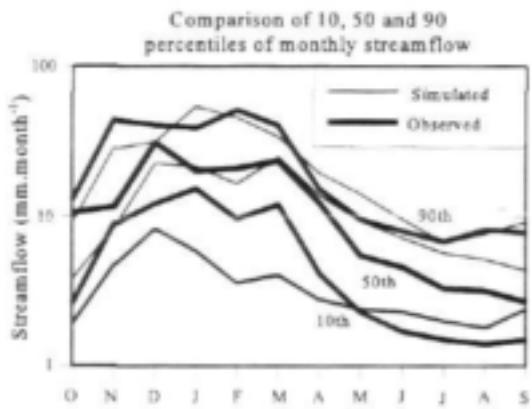
Figure 15 Verification of streamflow for the Nagle Management Subcatchment

VERIFICATION OF OUTPUT FROM THE ACRU MODEL

Henley Management Subcatchment (1979 - 1993)







Statistics of Performance of the *ACRU* Model

Comparison of simulated and observed streamflows		Monthly totals	Daily totals
Number of observations	=	124	4550
Sum of observed values (mm)	=	2166.6	2638.5
Sum of simulated values (mm)	=	2105.1	2839.8
% difference between sums	=	2.8	-7.6
Correlation coefficient, r	=	.918	.864
Slope of regression line	=	1.05	.854
Y intercept of regression line	=	1.364	.129
Standard deviation of X values (mm)	=	25.4	2.027
Standard deviation of Y values (mm)	=	29.0	2.003
% difference between standard deviations	=	-14.3	1.177
Coefficient of determination, r^2	=	.843	.746
Coefficient of efficiency	=	.841	.724

Catchment Summary

Catchment area	=	178 km^2
Mean annual precipitation	=	915 mm
Mean annual runoff	=	196 mm
	or	35 M m^3
Runoff coefficient	=	21.4%
Mean annual potential evaporation	=	1639 mm

Land Use (%)

Peri-urban	=	22.4
Rural	=	2.5
Forest	=	7.3
Dryland agriculture	=	12.5
Natural vegetation	=	53.5
Water Bodies	=	2.1

Figure 16 Verification of streamflow for the Henley Management Subcatchment

On the other hand, streamflow and rainfall data are inevitably not error-free. Operator inefficiency, equipment failure, poor siting of raingauges, changing rating tables or poor calibration of gauging weirs are all problems which are regularly encountered. Figure 17 illustrates some of these problems when matching streamflows and rainfall records. Daily simulated and observed streamflows are compared for gauging station U2H013 for 1991. Simulated streamflow is generated by the rainfall from a driver station considered the most representative for the respective subcatchment. Both types of mismatches, viz. the simulation of streamflow when no streamflow was measured (case B in Figure 17) and the absence or underestimation of simulated streamflow when it was measured (case A in Figure 17), are largely indicative of a sparse or unrepresentative raingauge network in a hilly area with highly variable rainfall. This problem is particularly valid in the months when localised thunderstorms are common. A localised rainfall event with small areal extent and measured by the raingauge will result in the simulation of streamflow, although the subcatchment as a whole may have received relatively little rainfall. Alternatively, a rainfall event followed by the generation of streamflow might occur at some distance from the raingauge, resulting in no simulation of stormflow, while stormflow may have been measured at a gauging weir. While these data shortcomings in the simulation process tend to be self-cancelling in statistics of total monthly flow accumulations, these imperfections may be the cause of poor matching of simulated and observed streamflows at a daily level. The only solution to this problem is to establish a denser raingauge network, with particular emphasis being focused on the installation of additional raingauges in the higher lying areas.

Since the aim of these simulations was the generation of sequences of daily streamflows with associated risk analysis to provide information on the recurrence of high and low flows, these data problems do not, in the final analyses of a 34 year simulation period, present the problem that they would for simulations of a short duration.

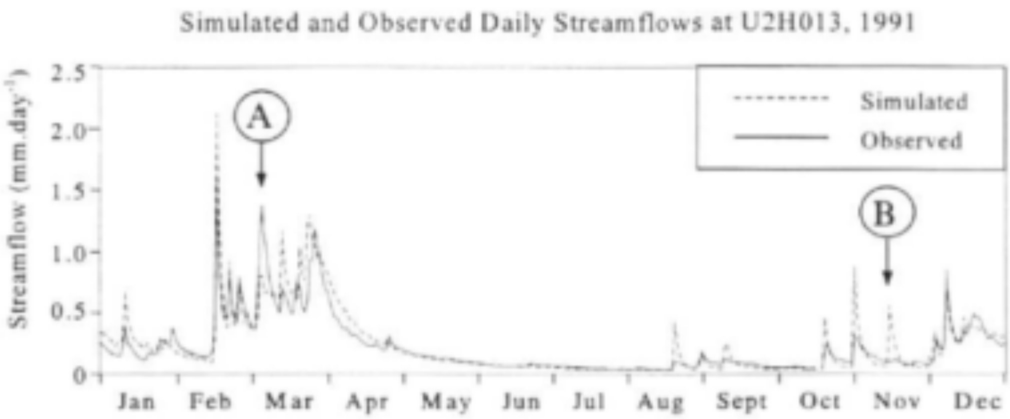


Figure 17 Evidence of data problems when simulating daily streamflows at gauging station U2H013 in 1991: A = underestimation of streamflow; B = overestimation of streamflow

2.3 WHERE IN THE MGENI CATCHMENT IS STREAMFLOW GENERATED?

Following the successful verifications of streamflow output from the *ACRU* model, daily streamflow sequences for all 137 subcatchments were produced for the period 1960 to 1993. Based on this simulation, mean annual runoff (MAR) values were calculated for all 137 subcatchments and a suite of maps was produced to indicate the distribution of streamflow generation in the study area. In addition, in combination with MAP values, long-term runoff coefficients were determined (i.e. percentage of MAP that runs off as streamflow).

The MAR for the study area is 162 mm (i.e. 162 x 10^3 $m^3.km^{-2}$), with a range of 44 to 390 mm between wet and dry years. Figure 18* illustrates the subcatchment distribution of MAR under current land use. Subcatchments with low values receive either a relatively low rainfall (cf. Figure 7*), as is the case for subcatchments in the area between the Nagle Dam and Inanda Dam, or are under intensive agricultural uses with high water demands. Land uses associated with high water demands include commercial plantations of eucalypts, pines and wattle as well as areas under sugarcane (cf. Figure 8*), as in the Karkloof and New Hanover Management Subcatchments. Those subcatchments with a high MAR receive either a high rainfall (e.g. upper parts of Lions and Karkloof Management Subcatchments), or have large proportions of impervious areas, such as urban areas or areas with a high population density (cf. Figures 1* and 2*).

Considering the entire study area, it appears that generally the MAP of a subcatchment has a dominating influence on the subcatchment's streamflow generation when compared with the influence of land use. This is demonstrated by the relatively high annual water yield of 300 mm in the upper Karkloof subcatchments, which are intensively afforested but receive the highest annual rainfall in the study area (1 100 to 1 250 mm). Conversely, subcatchments in the Valley of a Thousand Hills have a high population density and low proportions of vegetal cover, indicative of a high runoff potential; and yet these subcatchments, which receive an annual rainfall below 800 mm, produce a disproportionately low water yield of less than 150 mm.

With given climatic conditions within a subcatchment, the impact of land cover on its water yield can nevertheless be highly significant, as will be shown in the following sections.

2.4 MODELLING HISTORICAL SCENARIOS: GENERATION OF STREAMFLOWS UNDER PRISTINE CATCHMENT CONDITIONS

The *ACRU* hydrological modelling system, being physical conceptual in structure and in particular being able to account the most important hydrological characteristics of various land covers and land uses, can be applied to scenarios that simulate catchment conditions other than those occurring under present climate and land cover.

Pristine streamflow is defined here as the streamflow that would occur under climatic conditions similar to those at present, but with the catchment assumed to be covered entirely by natural vegetation under pristine conditions and in equilibrium with climatic conditions. Pristine streamflow is used in water resources analysis to evaluate subsequent anthropogenic impacts and to obtain a streamflow record that may serve as an objective base against which to compare catchment scenarios, such as the evaluation of the impact of current land cover conditions on pristine streamflow and water quality.

The simulation of hydrological responses from a catchment in pristine conditions was achieved with the *ACRU* modelling system by:

* assuming all farm dams and reservoirs not to have existed,
* disregarding all water abstractions and transfers, and
* replacing current land use, i.e. in urban and rural areas, both irrigated and dryland agriculture as well as exotic forest plantations, with the naturally occurring vegetation, as represented by the vegetation described in Acocks' (1988) Veld Types (Figure 9*).

Since the pristine vegetation has different hydrological response characteristics to those of the current land uses, the following *ACRU* variables were adjusted to represent these natural vegetation types:

* crop coefficients (month-by-month),
* canopy interception values in mm per rainday (month-by-month),
* fraction of active root system in the topsoil horizon (month-by-month),
* the variable which specifies whether the catchment is predominantly under forest, in which case enhanced wet canopy evaporation rates are activated,
* the effective depth of the soil considered to be contributing to stormflow generation,
* porosity values of the topsoil horizon (increased due to tillage of agricultural land, which changes the topsoil's bulk density and hence soil water content held at porosity),

* coefficients of initial abstractions (month-by-month), which are used to estimate the rainfall abstracted by surface depression storage and infiltration before runoff commences, and
* the fraction of impervious area.

All variables which represent spatially distributed features, such as crop coefficients, interception values, root fractions or porosity values, were calculated by area-weighting the relevant values for each subcatchment. All other variables remained the same, and the *ACRU* modelling system was rerun to simulate streamflow sequences for the study area under pristine conditions, against which impacts of current land use could then be assessed.

2.5 MODELLING CURRENT SCENARIOS : EVALUATING IMPACTS OF PRESENT LAND USES ON PRISTINE STREAMFLOWS

Impacts of present land use on streamflows are assessed by comparing streamflows produced under "current" land covers (from 1986 satellite imagery) and under "pristine" land covers (Acocks' Veld Types). Results are summarised in Figure 19*, which displays the simulated change in streamflows for the 137 individual subcatchments of the study area, and in Figure 20, which shows a statistic of the overall change in streamflows. For the 12 Management Subcatchments Table 1 presents mean annual runoff and runoff coefficients for both present land use and pristine land cover scenarios, together with streamflow changes, selected catchment information and climatic variables.

The hydrological impact of current land use (1986 satellite imagery), compared with streamflows under pristine land cover conditions, can be significant within individual subcatchments, ranging from a 100% increase (i.e. doubling of) in streamflows to a decrease by more than 60% (Figure 19*). The highest reductions of streamflow are found in those subcatchments which are under intensive agricultural use. In particular, subcatchments with a high proportion of commercial forest or sugarcane plantations exhibit high reductions in water yield of up to 60%. On the other hand, subcatchments that are either highly urbanised or exhibit a high population density, show an increase in water yield, as in the Pietermaritzburg area and in the Valley of a Thousand Hills immediately upstream of Inanda Dam. This is due to the widespread substitution of pristine vegetal cover with impervious surfaces or highly compacted soil with large proportions of bare ground in many former KwaZulu homeland areas. A number of other subcatchments situated in the upper reaches of the study area also show a higher water yield under current conditions, although they are neither urbanised nor highly populated. This can be explained by the different hydrological properties associated with the respective land covers. For example, three subcatchments in the NW corner of the study area, all part of the upper reaches of the Karkloof Management Subcatchment, are currently

Table 1 Selected hydrological characteristics of the 12 Management Subcatchments

Management Subcatchment	1 Mpendle	2 Lions	3 Midmar	4 Karkloof	5 Albert Falls	6 New Hanover	7 Nagle	8 Henley	9 Pietermaritzburg	10 Table Mountain	11 Mqeku	12 Inanda
ACRU Subcatchments	1-7	10-15	8-9, 16-17, 27-34	18-25	26, 35-45	49-60	47-48, 61-72	76-84	85-105	106-116	118-125	73-75, 117, 126-137
Area (km^2)	295.7	362.0	269.2	334.3	392.0	429.5	452.1	220.0	318.6	342.8	243.9	418.8
Cumulative Area[1] (km^2)	295.7	362.0	926.9	334.3	1653.2	429.5	2534.8	220.0	538.6	881.4	243.9	4078.9
Mean Altitude (m)	1555	1390	1195	1336	948	899	744	1268	841	658	788	421
Altitude Range (m)	1080-2013	1058-1947	1028-1719	1068-1725	644-1428	633-1492	394-1097	928-1582	605-1437	356-974	245-1054	104-968
MAP (mm)	969	979	874	1081	951	926	849	927	874	744	952	790
Cumulative MAP[1] (mm)	969	979	945	1081	974	926	944	927	896	837	952	905
MAPE[2] (mm)	1596	1637	1668	1314	1695	1690	1678	1642	1688	1682	1646	1679
MATE[3] (mm)	597	604	589	617	602	617	593	618	554	496	644	545
Virgin[4] MAR (mm)	241.2	233.2	219.4	345.6	240.1	218.5	223.8	204.2	193.2	164.3	234.9	201.6
Present[6] MAR[5] (mm)	236.9	204.5	207.5	277.3	177.0	130.1	143.0	193.1	170.7	145.1	186.9	84.3
Virgin[4] MAR (Mm^3)[7]	71.3	84.4	203.4	115.5	396.9	93.8	567.3	44.9	104.1	144.8	57.3	822.3
Present[6] MAR[5] (Mm^3)[7]	70.1	74.0	192.3	92.7	292.6	55.9	362.5	42.5	91.9	127.9	45.6	343.9
Virgin[4] R_c[8]	24.9	23.8	23.2	32.0	24.7	23.6	23.7	22.0	21.6	19.6	24.7	22.3
Present[6] R_c[8]	24.4	20.9	22.0	25.7	18.2	14.0	15.1	20.8	19.1	17.3	19.6	9.3
Streamflow Change[9] (%)	-1.7	-12.3	-5.4	-19.8	-26.3	-40.5	-36.1	-5.4	-11.6	-11.7	-20.4	-58.2

1 Includes all upstream catchments
2 Mean annual potential evaporation
3 Mean annual total (actual) evaporation
4 Assuming Acocks' (1988) Veld Types
5 Includes contributions and abstractions from upstream subcatchments
6 For period 1960 - 1993
7 Million m^3
8 Runoff coefficient (MAR/MAP)
9 Comparison of present (1960 -1993) with virgin streamflows

predominantly under grazing in fair condition (Figure 8*). The original land cover was Highland & Döhne Sourveld (Figure 9*), which is considered to have higher canopy interception values and a higher evaporative demand than that under grazed veld, thus resulting in a lower streamflow production.

Simulations in all 12 Management Subcatchments revealed an overall reduction in streamflow. In the so-called "internal" Management Subcatchments, upstream contributions and abstractions of streamflow from neighbouring subcatchments are considered, thus altering the results exhibited in Figure 19* somewhat. The highest reduction in streamflow was simulated in the New Hanover (40.5%) and Nagle (36.1%) subcatchments, both of which are highly afforested or under intensive sugarcane cultivation. The lowest reductions in streamflows were found in the Mpendle, Midmar and Henley subcatchments, which are largely under grassveld. The relatively large reduction of streamflow in the Lions subcatchment can be attributed to its relatively large proportion of irrigated agriculture with its associated water losses due to increased evaporation during and after irrigation applications, as well as to conveyance losses. The highly significant overall decrease of 58% in streamflow in the Inanda subcatchment can be explained by significant water abstractions from Nagle Dam to supply areas below Inanda Dam.

In Figure 20, exceedence curves of present and pristine MARs are compared, using streamflow simulations from the 137 *ACRU* subcatchments. The two curves are relatively parallel, with the curve representing pristine streamflows being, on average, 40 mm (i.e. 40 000 $m^3.km^{-2}.a^{-1}$) above the present streamflow line. This represents an overall decrease in streamflow under present land use conditions of 19%, when compared to streamflow under pristine land cover conditions.

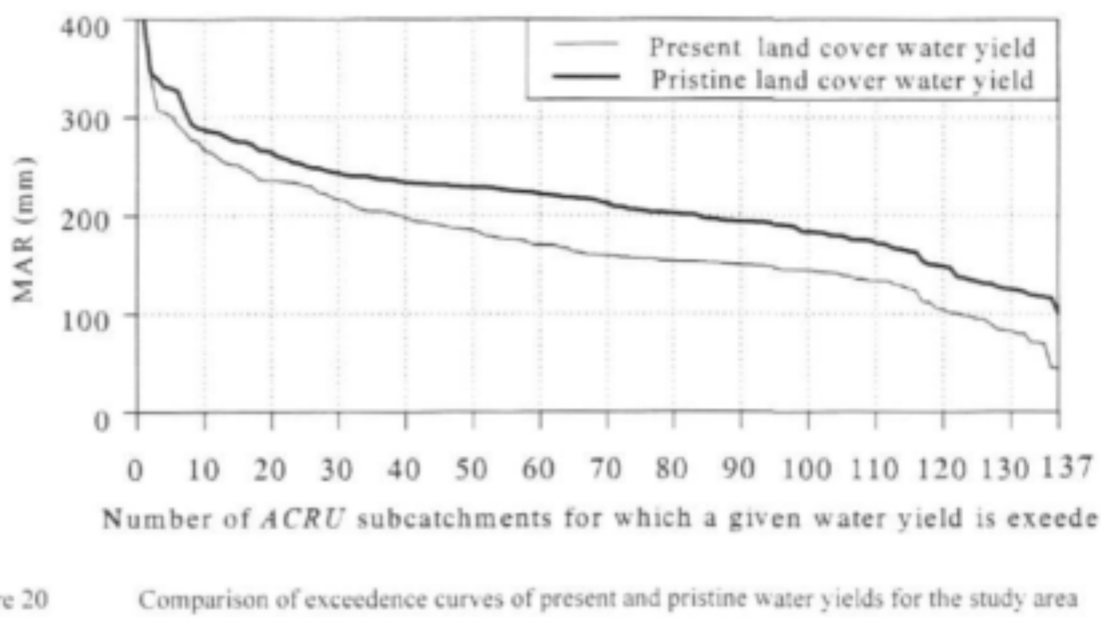


Figure 20 Comparison of exceedence curves of present and pristine water yields for the study area

2.6 MODELLING FUTURE SCENARIOS : EVALUATING IMPACTS OF LAND USES ON STREAMFLOWS

Two types of hydrological impact studies were undertaken. Impact Study I represents the impacts of commercial forest plantations, farm dams and irrigated agriculture on streamflows for three Management Subcatchments. Impact Study II compares the impacts of grassland, eucalypts, sugarcane and maize on five *ACRU* subcatchments ranging in MAP from 683 to 1 186 mm.

2.6.1 Study I : Impacts of Afforestation, Farm Dams and Irrigation

Impact Study I had the objective of evaluating the impacts of commercial forest plantations, farm dams and irrigated agriculture on three Management Subcatchments, viz. the Lions, Karkloof and New Hanover subcatchments (cf. Figure 6*). Streamflow responses were investigated for nine catchment scenarios:

* Scenario A: present land cover (cf. Figure 8*).
* Scenario B: pristine conditions (assuming vegetation according to Acocks' Veld Types, cf. Figure 9*),
* Scenario C: impact of farm dams (i.e. pristine conditions plus present farm dams),
* Scenario D: impact of irrigated agriculture (i.e. pristine conditions plus present irrigation),
* Scenario E: impact of forest plantations, assuming present species composition (i.e. pristine conditions plus present plantations),
* Scenario F: impact of forest plantations, assumed to be entirely under pines, i.e. *Pinus patula* (i.e. pristine conditions plus total present forest = pines),
* Scenario G: impact of forest plantations, assumed to be entirely under eucalypts, i.e. *Eucalyptus grandis* (i.e. pristine conditions plus total present forest = eucalypts),
* Scenario H: impact of forest plantations, assumed to be entirely under wattle, i.e. *Acacia mearnsii* (i.e. pristine conditions plus total present forest = wattle),
* Scenario I: impact of a doubling of the area under forest plantations, assuming present species composition.

During the configuration of the *ACRU* modelling system for the individual simulations, a number of input variables had to be modified, each representing one of the various hydrological attributes of the different land uses, or else characterising farm dams or irrigation projects. These variables included those described in the section on modelling pristine streamflows as well as the following:

* storage capacities of farm dams,
* surface areas of farm dams,
* normal flows (which represent legal daily releases from the reservoir, in order to maintain a minimum flow to downstream and riparian owners),
* seepage from dams,
* irrigated areas (month-by-month),
* irrigation scheduling methods (month-by-month),
* amounts of net water application per irrigation (month-by-month),
* irrigation cycle length,
* irrigation field efficiencies,
* conveyance losses,
* crop coefficients of irrigated crops (month-by-month),
* coefficients of initial abstractions for irrigated areas (month-by-month),
* soil characteristics of irrigated areas,
* the variable specifying the fraction of the plant available water of a soil horizon at which total (actual) evaporation is assumed to reduce to below maximum (potential) rates during drying of the soil, and
* specific hydrological parameters representing each forest genus (Schulze, 1995, Chapter 20).

The results of the scenario simulations are summarised in Table 2 and are interpreted below.

2.6.1.1 Scenario A

Mean annual streamflow is a reflection of both the climatic regime and present land use superimposed on catchment soil and physiographic characteristics. The Lions subcatchment has an MAP of 979 mm and is mainly under grassland, resulting in an annual streamflow typical of that of the Natal Midlands at around 200 mm. The higher streamflow of over 270 mm per annum produced in the Karkloof subcatchment results from the higher catchment precipitation, which at an average of 1 081 mm is the highest in the Mgeni system. The New Hanover subcatchment displays the lowest MAP of the three selected subcatchments and has only 10% under grassland, with the remaining 90% of the catchment area used for agricultural purposes. These characteristics combined result in relatively low streamflow values of 130 mm per annum in the New Hanover subcatchment and a corresponding low runoff coefficient.

Table 2 Impacts of land use on mean annual streamflow for various catchment scenarios

Scenario	**Mean Annual Streamflow (mm)**[1]					
	Lions Subcatchment (MAP = 979 mm)		**Karkloof Subcatchment (MAP = 1081 mm)**		**New Hanover Subcatchment (MAP = 926 mm)**	
A: Present Land Cover	204.5[1]	(-12.3%)[2]	277.3	(-19.8%)	130.1	(-40.5%)
B: Pristine Conditions = Acocks' Veld Types	233.2		345.6		218.5	
C: Pristine Conditions + Farm Dams	233.9	(+ 0.3%)	345.3	(- 0.1%)	218.4	(- 0.1%)
D: Pristine Conditions + Farm Dams + Irrigation	180.2	(-22.7%)	319.7	(- 7.5%)	208.9	(- 4.4%)
E: Pristine Conditions + Present Forest Plantations	192.9	(-17.3%)	272.0	(-21.3%)	156.7	(-28.3%)
F: Pristine Conditions + Present Forest = Eucalypt	189.4	(-18.8%)	261.6	(-24.3%)	148.4	(-32.1%)
G: Pristine Conditions + Present Forest = Pine	195.9	(-16.0%)	277.9	(-19.6%)	165.0	(-24.5%)
H: Pristine Conditions + Present Forest = Wattle	195.4	(-16.2%)	279.2	(-19.2%)	163.2	(-25.3%)
I: Pristine Conditions + 2x Present Forest Plantation	178.4	(-23.5%)	241.6	(-30.1%)	134.4	(-38.5%)

1 The streamflow is expressed in mm to render inter-catchments results comparable. One mm of streamflow is the equivalent volume of the entire catchment area being one mm under water. One mm is the equivalent to 1000 $M.km^{-2}$.

2 The bracketed percentages in each case are in comparison with Scenario B

2.6.1.2 Scenario B

The replacement of present land use with pristine vegetation results in increases in simulated streamflows. Comparing Scenario A with Scenario B, there is a decrease in streamflow (percentages given under scenario A in brackets). Simulated decreases in streamflow are similar for the Lions and Karkloof subcatchments. In the New Hanover subcatchment, however, the decrease in simulated MAR is about 40%, which is attributed to the high intensity to which this catchment is already utilised agriculturally at present. Under pristine conditions, runoff coefficients (R_c) shown in Table 1 are larger than those under present land uses. These R_c values also increase with catchment MAP from 23.6% in the New Hanover to 23.8% in the Lions to 32.0% in the Karkloof subcatchment.

2.6.1.3 Scenario C

Overall, the effect of farm dams *per se* (i.e. without abstractions from them) on streamflow is negligible. The reason for this is that an unused farm dam is filled typically within the first year of construction and then spills over for most of the rainy season, thus not significantly affecting streamflow. In the Lions subcatchment, the effect of farm dams is even a slightly positive one in terms of streamflow production. There are two reasons for this behaviour.

First, the combined surface area of the dams is relatively large, viz. 1.1% of total catchment area, and any rain falling onto that surface would be converted directly to runoff. Secondly, a water surface does not "abstract" rainfall by interception and infiltration into the soil, nor does it evaporate water at the same rates that exposed wet soil surfaces or vegetation with high crop coefficients do.

2.6.1.4 Scenario D

The effects on streamflows of irrigating crops and pastures can be significant. The reduction in streamflows varies, depending on the proportion of a catchment under irrigation. In this case study it is highest in the Lions subcatchment, which has 9.4% of its area under irrigation. Although the proportion of irrigated areas in the Karkloof subcatchment is exactly half of that of the Lions subcatchment, streamflow reduction is only a third of that in the Lions. This is mainly as a result of the higher catchment MAP and subsequent higher runoff coefficient in the Karkloof subcatchment. For the same reasons, but with opposite effects, the impact of irrigating crops is relatively high in the New Hanover subcatchment with its lower MAP, considering that only 1% of the catchment area is irrigated.

2.6.1.5 Scenario E

The same principles as outlined in Scenario D apply to this scenario, where not irrigated agriculture, but commercial afforestation (assuming present species composition) is considered. The higher the proportion of commercial afforestation in a catchment, the higher the streamflow reduction; and the higher the MAP, the lower the relative impact. Considering that the afforested area in the Lions subcatchment is 9.0%, a streamflow reduction of 17.3% appears to be surprisingly high. In order to explain this, one has to consider the location of the plantations within the catchment. In the Lions subcatchment, the majority of the commercial plantations are in the lower catchment areas which receive only 920 mm of MAP. It is in these areas that the streamflow reductions thus become relatively more marked.

2.6.1.6 Scenario F

Of the three commercial forest species considered, eucalypts display the highest consumptive water use and continue to transpire fully even when the soil is already relatively dry (Schulze, 1995). Their potential for maximum evaporation is thus very high, still drying out the soil at maximum rates at times when other species have already started to reduce their water consumption. Simulations of streamflows from eucalypt plantations thus resulted in consistently lower streamflows when compared to those with forests under present species composition.

2.6.1.7 Scenario G

While pines have a high interception capacity (because of high surface tension associated with their needled leaves), they are known to utilise soil water conservatively, reducing their maximum evaporation rates at an early stage in the soil drying process, when the soils are still relatively wet (Schulze, 1995). The result is a streamflow reduction that is consistently smaller than that under mixed species conditions.

2.6.1.8 Scenario H

Wattles are assumed to have a higher consumptive water use than pines, a lower interception capacity and a physiological response to the reduction of soil water content which lies between that of pines and eucalypts. This results in a streamflow reduction that is slightly higher than that under pine plantations in the Lions and New Hanover subcatchments, but moderately lower in the Karkloof catchment. This indicates that, under specific catchment conditions, certain hydrological processes dominate over others.

2.6.1.9 Scenario I

The doubling of afforestation areas does not result in a doubling of streamflow reduction. When one compares results from Scenario I with those from Scenario E, the further reduction of MAR due to doubling the afforested area is thus not 100%, but only between 45 and 57% more.

2.6.2 Study II : Impacts of Different Dryland Agricultural Systems

In this impact study, comparative simulations of water use by pristine vegetation (represented by Acocks' Veld Types), presently occurring natural grassveld (assumed to be in fair hydrological condition, as found in most parts of the Mgeni catchment), maize (planted on 1 November, with a 140-day growing season), sugarcane (assuming whole farm operations) and eucalypt plantations (age 5 years, with pitting as the typical site preparation technique) and their impacts on long-term catchment streamflows were performed. In order to assess the principal impacts of these land cover scenarios for a range of climatic conditions present in the Mgeni catchment, five *ACRU* subcatchments were selected, representing catchments with respective MAPs approximating 700, 800, 900, 1 050 and 1 200 mm. Apart from MAP, each subcatchment retained its unique characteristics regarding potential evaporation and soils. Streamflows from these catchments were simulated for a range of land use scenarios, substituting in turn a natural grassveld cover reduced by 25, 50, 75 and 100% with a corresponding increase in maize, sugarcane and eucalypt land uses. In total, 70 simulations were performed, and from each simulation output the mean, median, 10th and 90th percentiles of streamflow were extracted for each month. As an example, seasonal patterns for a year of median streamflow yield and 100% land cover under the respective land uses for five rainfall regimes are presented in Figure 21.

Results of the simulations displayed in Figure 21 indicate the following:

- Eucalypt plantations have the highest water demand of the land uses assessed, reducing catchment water yields considerably more than other land uses do. Indeed, streamflows from catchments entirely under eucalypt plantations would become extremely low in climatic regions which would be considered marginal to forest production, these being areas with an MAP of 800 mm or less.

- Sugarcane simulations reveal a reduction in the water yield which is less than eucalypt plantations but more than veld or pristine (virgin) catchment conditions.

- Relative and absolute reductions in water yield increase with decreasing MAP.

- In these simulations catchments fully under maize are simulated to produce the highest streamflows. This is hypothesised to be due to the relatively sparse canopy cover and associated low interception in the period before planting in November; also to the increased soil porosity of the plough horizon. Both these factors result in a relatively high groundwater recharge potential early in the rainy season, which in turn produces a strong baseflow. These impacts decrease with increasing MAP.

Table 3 summarises the annual streamflows produced by five catchments receiving varying rainfall under five land uses, for a year with median rainfall and a year with the lowest rainfall expected once in ten years. To render results comparable, runoff coefficients were calculated and are given in percentages. The simulated results indicate the following:

- The hydrological system does not respond linearly and, for a given land use, an increase in MAP does not necessarily result in an increase in streamflow. This is explained by the different catchments selected for this study, each having a unique combination of physiographic characteristics, particularly regarding soils, physiographic and climatic conditions

- Catchments under grassveld in fair conditions tend to produce higher streamflows when compared to pristine catchments, except when the MAP is very high. This is due to the natural vegetation's generally higher biomass, which is associated with higher consumptive water use and rainfall interception. This effect is no longer evident in regions which receive very high rainfalls where the natural vegetation of short sourveld grasses has replaced denser grassveld and bushveld (cf. Figure 9*).

* In a year with median streamflows, a catchment under maize produces about the same annual streamflow as a catchment completely under grassveld, when the MAP is 900 mm or higher; where the MAP is lower than 900 mm, catchments entirely under maize produce higher streamflows than catchments under grassveld. During the 225 days a year when maize is not actively growing, relatively high groundwater recharge can occur, resulting in the production of relatively strong baseflows.

* In a year with median rainfall, catchments completely under dryland sugarcane plantations are simulated to produce approximately twice as much annual streamflow as catchments entirely covered by eucalypt plantations. Catchments entirely under eucalypts would produce no or very little groundwater recharge, because of the trees' high interception capacity, their high consumptive use of soil water and deep rooting systems. These are the major reasons for the significant impact of eucalypts on streamflows. Plantations, however, do not cover entire

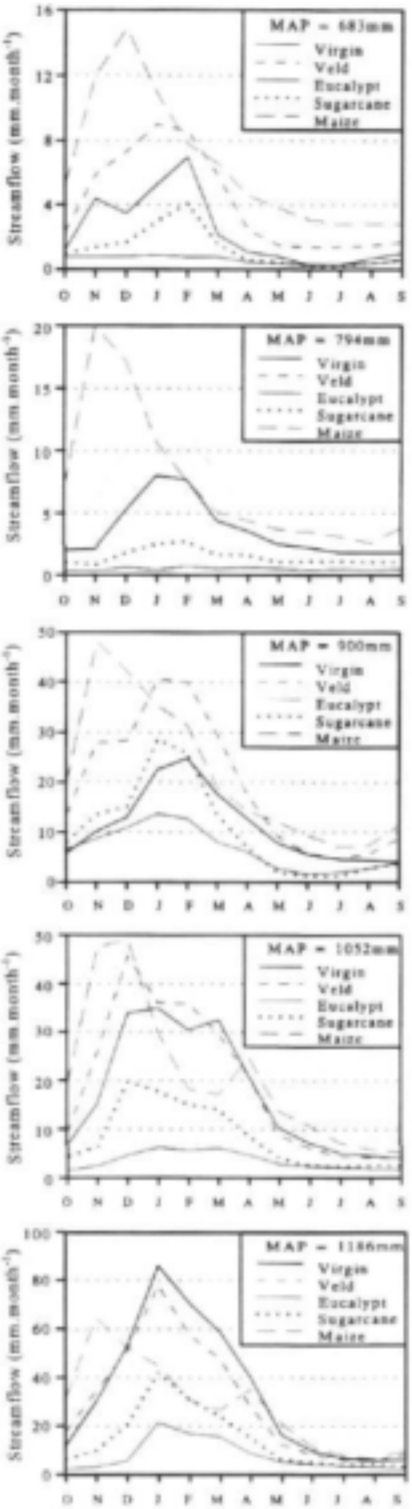


Figure 21 Impacts of various land uses on median monthly streamflows for five rainfall regions in the Mgeni catchment

Table 3 Annual streamflows (in mm) and runoff coefficients (bold: in %) produced by five catchments receiving varying rainfall under five land uses

Land Use	**Year with median streamflow**					**Year with lowest rainfall expected once in 10 years**				
	MAP (mm)					**MAP (mm)**				
	683	**793**	**900**	**1 052**	**1 186**	**683**	**793**	**900**	**1 052**	**1 186**
Grassveld (in fair condition)	68.9 **10.1**	71.2 **9.0**	291.9 **32.4**	343.7 **32.7**	460.1 **38.8**	32.2 **4.7**	26.3 **3.3**	143.0 **7.9**	120.8 **11.5**	227.0 **19.1**
Pristine (Acocks' Veld Types)	55.4 **8.1**	56.6 **7.1**	176.9 **19.7**	308.5 **29.3**	516.4 **43.5**	23.0 **3.4**	23.2 **2.9**	65.8 **8.3**	88.8 **8.4**	259.9 **21.9**
Maize	98.7 **14.5**	116.2 **14.7**	292.4 **32.5**	308.6 **29.3**	462.8 **39.0**	48.5 **7.1**	49.5 **6.2**	177.4 **22.4**	153.6 **14.6**	200.6 **16.9**
Sugarcane	35.7 **5.2**	25.2 **3.2**	158.5 **17.6**	150.1 **14.3**	237.0 **20.0**	12.4 **1.8**	7.3 **0.9**	88.5 **11.2**	53.2 **5.1**	82.5 **7.0**
Eucalypt	10.4 **1.5**	7.9 **1.0**	89.1 **9.9**	67.2 **6.4**	139.1 **11.7**	4.5 **0.7**	0.3 **0.04**	55.2 **7.0**	15.4 **1.5**	22.4 **1.9**

catchments under operational conditions. During a year with median rainfall, if the catchments were only 75% covered by eucalypts, and the remainder covered by grassveld, simulated streamflows would be about two thirds of those from catchments completely under dryland sugarcane. For the driest year in ten these conditions would produce approximately half of a dryland sugarcane catchment's streamflow.

- Under conditions of complete cover with one land use and in the driest rainfall year in ten, a catchment under dryland sugarcane would produce approximately two to four times more streamflow than a catchment entirely under eucalypt plantations.

Results reported in this study are based on simulations and certain inherent simplifications of the complex hydrological system. Both impact studies indicate that the effects of different land uses on streamflows are very complex and cannot be reported within a single graph or table. The governing physiographical and climatical characteristics of a specific catchment as well as the occurrence of drier and wetter periods have to be taken into account. The regulating factors which have an impact on streamflow production are rainfall and evaporation as well as soils and land cover. All available relevant variables were accounted for. In the case of trees, results correspond with catchment experiment results obtained in Mpumalanga (Van Lill *et al.*, 1980) and within the Mgeni catchment (Moerdyk and Schulze, 1991). While these results are considered to be realistic in their relative magnitudes, one has to bear in mind that models do not represent natural systems perfectly. Hence, the above results obtained should be used as an index of impacts rather than as absolute values.

Hydrological impacts of various land uses will have an impact on the water quality of the respective streams. One important impact on water quality is the reduction in streamflow, which corresponds with a reduction of the dilution potential of a stream or river. An effluent with a given load of pollutants will thus have a stronger negative effect on a stream's water quality under low flow conditions than under higher flowing conditions. This is valid for both point and non-point source pollution.

ACRU's simulation capabilities for three important water quality variables, viz. sediments, phosphorus and *E. coli*, as well as results from these simulations are presented in the following chapter.

CHAPTER 3

WATER QUALITY SIMULATIONS

Significant water quality impacts in the Mgeni catchment begin with the detachment of soil particles from the parent material. These particles can carry appreciable concentrations of absorbed phosphorus and pathogens, which are indicated by the presence of *E. coli*. The phosphorus and pathogens which reach the receiving streams can result in serious water quality problems in rivers and reservoirs in the Mgeni catchment. Apart from being the main transporting agent for water quality constituents of concern, sediments themselves are a potential hazard to water resources management. Sediments become trapped in reservoirs, decreasing their storage capacities and the elevated concentration of suspended solids in flowing water reduces the environmental quality of the rivers.

In order to simulate the transport of non-point source phosphorus and *E. coli*, it is important to first be able to simulate, with confidence, the likely movement of the soil particles on a catchment scale. In order to do this, it is thus expedient to initially identify areas prone to soil loss. Therefore the procedure in simulating the water quality determinands is to first generate a spatial distribution of erosion potential, then to simulate subcatchment sediment yield histories and finally to simulate phosphorus and *E. coli* loadings. The loading histories are reported on a daily basis for each subcatchment in the Mgeni system to allow for immediate identification of unacceptably high sources of sediment, phosphorus or electrical conductivity. In this study no stream routing of the sediments from the outlet of one subcatchment to another was performed. Hence it is only non-point source water quality determinands that have been included in the simulations.

3.1 WHERE IN THE MGENI CATCHMENT IS THE SOIL PRONE TO EROSION?

Soil particles are detached by rainfall impact and are entrained and scoured by overland flow. The potential of these particles reaching and impacting a receiving stream is dependent on the amount of soil detached and the carrying capacity, or energy, of the overland flow. These processes are modelled in two separate phases, using comprehensive data sets associated with soil loss related physics. In the first phase source erosion is estimated while in the second phase the amount of sediment delivered to the catchment outlet is estimated. The first phase involves the application of the recently developed Revised Universal Soil Loss Equation, RUSLE (Renard *et al.*, 1991). Because RUSLE is a field scale rather than a catchment scale model, the study area was subdivided into small grid cells, each 250 by 250 m. The soil loss potential was determined for each of the 65 256 individual grid cells making up the area upstream of Inanda Dam. The concept of soil loss estimation is based on combining the main components of the soil loss process into a single equation. The main components and a brief outline of their preparation are described in the following section. Because soil loss is a very dynamic process, is driven by rainfall and regulated by soil cover and soil moisture, the average soil loss potential was estimated for each month of the year and then summed, rather than deriving a mean annual value using averaged annual inputs.

3.1.1 The Revised Universal Soil Loss Equation, RUSLE

The Universal Soil Loss Equation, USLE, was developed empirically from a large data base and the component factors of the equation, while being physical determinands of soil loss, represent multiplicative statistical, and not strictly physical, interrelationships. The method is also used to indicate sources of potential erosion problems which would develop over a period of years. The USLE's erosion potential mapping is therefore reported on an average annual basis in order to identify areas of low and high erosion potential. The USLE and the RUSLE equation is given as

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

where:

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

3.1.2 Data and Information Requirements for Monthly Soil Loss Potential Maps

The preparation of each of the RUSLE factors is based on sets of data and information. Data and information gathered and represented for each grid cell include:

- rainfall erosivity factor (month-by-month)
  - mean monthly rainfall (month-by-month)
  - elevation

* soil erodibility factor
  - per cent silt plus very fine sand
  - per cent sand
  - per cent clay
  - soil permeability
  - per cent organic matter
  - soil structure
  - slope
  - surface curvature
  - flow accumulation in the catchment
* slope length and gradient factor
  - slope (per cent and degree)
  - land cover class
  - flow accumulation in the catchment
* cover and management factor
  - per cent covered by canopy cover (month-by-month)
  - per cent covered by ground cover (month-by-month)
  - mass of buried residue and roots (month-by-month)
* support practice factor
  - land cover class
  - slope
  - management practice.

3.1.3 Fundamental Principles in Determination of RUSLE Factors

The fundamental principles in the determination of the five main RUSLE factors are described briefly below.

3.1.3.1 Rainfall Erosivity, R

In order to represent the rainfall erosivity factor, expressed in so-called EI_{30} units in which E is rainfall energy and I_{30} is the highest intensity for a 30-minute period of rainfall in an event, an approach initially developed by Smithen and Schulze (1982), using data from autographic rainfall records, was used as a first step. This approach recognises that the estimated average annual erosion potential is significantly different when using average annual rainfall erosivity applied to average annual crop cover factors versus using average monthly rainfall erosivity applied to average monthly crop cover factors and then summing the average monthly erosion potentials to derive an estimate of the average annual erosion potential. Using average monthly analysis is deemed to generate more accurate erosion potential estimates since high summer rainfall erosivity associated with convective rainfall can then be applied to appropriate crop cover factors representing denser rainy season vegetation with greater ground protection against soil losses. Low winter rainfall erosivity values can similarly be applied to poorer dry season cover protection indicators. The average monthly EI_{30} erosivity values were determined by correlating average monthly EI_{30} to average monthly rainfall at recording rainfall stations at various altitude from the coast to the highest recording station in the catchment. From the correlation of monthly EI_{30} and monthly rainfall at each station, typical relationships were derived associating EI_{30} to the elevation and MAP, this being considered a novel approach. The relationships were used with the 250 x 250 m elevation grid and the median monthly rainfall coverage to produce a coverage of median monthly EI_{30} values.

3.1.3.2 Soil Erodibility, K

Soils information is reported by the erstwhile Soil and Irrigation Research Institute (SIRI) as percentages of areas covered by a certain soil type on a specific terrain unit within the soil associations termed Land Types. In order to translate Land Type information into the soil properties required to calculate the RUSLE soil erodibility factor, the terrain units of the study area were first delineated spatially by combining slope, surface curvature and flow accumulation information according to the SIRI definition of terrain units (SIRI, 1987). Detailed spatial distribution of soil physical and hydraulic properties could then be estimated by overlaying the terrain unit coverage with the Land Type coverage and associated database which reflects the distribution of soil types. The soil erodibility factor was then calculated for each grid using the data and algorithms.

3.1.3.3 Topography (Slope Length and Gradients), LS

The slope gradient was initially calculated for each grid cell from the 250 x 250 m DEM. The slope length, which is related to slope gradient, terrain and land cover, was calculated by a set of RUSLE equations (Renard *et al*., 1991), using advanced techniques that combined slopes, flow accumulation and algorithms developed on the GIS.

3.1.3.4 Land Cover (Cover and Management), C

For each month and each of the 21 land cover classes delineated for the Mgeni catchment (Figure 8*), information on canopy cover, mulch cover, litter mass, root mass of the top 100 mm of soil was used to develop the RUSLE cover factor for the cover class. The cover factors were then incorporated into a GIS coverage resulting in a set of monthly C factors, for each individual grid cell, representing the land cover influence on soil loss.

3.1.3.5 Conservation (Support) Practices, P

Factors representing the reduction of soil loss due to conservation practices were estimated by combining land cover and slope information and assigning a set of rules for farming practices across the range of agricultural land uses in the Mgeni catchment.

3.1.4 Preparation of Final Soil Loss Potential Maps

Each of the maps of R, K, LS, C and P was produced in ARC/INFO's GRID environment as a grid map, with the catchment area upstream of Inanda Dam being subdivided into 65 256 square grid cells, each with an associated area of 0.0625 km^2 (i.e. 250 m x 250 m). A digital elevation model of the study area was an important data base from which further information could be derived. The preparation of monthly soil loss potential maps was based on the combination of 27 maps, each representing an individual factor of the RUSLE, with the rainfall erosivity and land cover factors being represented on a month-by-month basis. Thirteen soil loss potential maps were prepared, one for each month and one for the mean annual soil loss potential. The map displaying the mean annual soil loss potential is presented in Figure 22*. The detailed information displayed in this map was not used directly in the sediment yield modelling described below. However, the factors used in deriving the map were transferred, where relevant, to the sediment yield study. The soil loss potential map in Figure 22* gives an overview of the distribution of sediment source areas in the study area. The main sediment source areas include the Valley of a Thousand Hills, areas with informal settlements (cf. Figure 8*) and those areas that are steep, have erodible soils and poor management practices. Areas under grassveld, forest plantations, well managed agricultural practises and urban areas were estimated to have a low soil loss potential.

While the general trends displayed in the set of soil loss potential maps are realistic, the underlying assumptions and generalisations made in the preparation of input data dictate that the maps be viewed as an initial result. Thus, while the values displayed are in the correct order of magnitude (Kelbe and Snyman, 1993), values displayed should be assumed to give a relative indication (low vs. medium vs. high) rather than an absolute measure of the true soil loss potential in the different areas.

3.2 MODELLING SEDIMENT YIELD WITH *ACRU*

3.2.1 From Soil Loss to Sediment Yield

Not all of the soil particles detached from the parent material in a catchment are transported to the stream network. Progressive deposition and re-entrainment of the sediments occur within a catchment. Hence, while Figure 22* shows the areas within the Mgeni catchment upstream of Inanda Dam which are prone to erosion, these are not necessarily the areas which yield the highest sediment loads into receiving streams. Indeed, the sediment delivery process may significantly reduce the amount of source erosion reaching the subcatchment outlet. The *ACRU* sediment yield model therefore estimates the amount of stormflow derived sediment reaching the outlet of each subcatchment on a daily basis. Hence, those areas which are likely to yield large sediment loads, and potentially carry attached phosphorus and pathogens to the receiving streams, can be identified. The results of the simulations presented here will aid in defining catchment management practices aimed at maintaining acceptable sediment, phosphorus and pathogen loads to receiving waters.

3.2.2 Requirements of a Sediment Yield Model for the Mgeni Catchment

The processes of sediment detachment, overland transport and in-stream deposition and entrainment comprise a complex combination of physical and hydraulic mechanisms. These are traditionally described with varying degrees of simplification in order to model sediment yield at the scale of a catchment of (say) 50 km^2. The theoretical considerations and data requirements vary widely for the different approaches. In order to develop an appropriate sediment yield modelling system for the Mgeni catchment, a state-of-the-art review of methods of sediment yield modelling, ranging from the use of empirical algorithms to models invoking detailed physical process modelling, was undertaken. Special attention was paid to the three-way compromise between the advantages of model simplicity, the complex spatial variability of catchment hydrological response and the economic limitations of field parameter measurement. This review is available on request from the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg.

It was established that the approach offered by the Modified Universal Soil Loss Equation (MUSLE) would be well suited for application in the Mgeni catchment. The method simulates the entrainment and transporting energy of the runoff using the total stormflow and the peak discharge which are derived in the *ACRU* hydrological model on an event by event (daily) basis. The source of sediment which is available for transport is defined using the soil, slope, cover and practice parameters derived from the RUSLE and used in the development of the soil loss potential map (Figure 22*). The sediment yield for individual events is modelled and is output on a daily basis. The daily sediment yield model can thus be used to:

* estimate long-term sediment loads to reservoirs or works,
* determine the effects of extreme sediment yield events on water use criteria, and to
* estimate the effects of land use changes on sediment yield within the catchment.

3.2.3 Preparation of Information for the Sediment Yield Model

The RUSLE parameters for the soil erodibility, slope length/steepness, vegetation cover and management practices were averaged for each of the 137 *ACRU* subcatchments using the 250 m x 250 m GIS database in Section 3.1 by overlaying the respective maps with the *ACRU* subcatchment boundaries. The input information to the sediment yield model comprises parameters affecting the soil loss potential and the subsequent transfer of sediments to the basin outlet.

3.2.3.1 Soil Loss Potential

A single slope steepness factor and the management factor were derived by averaging these parameters over the *ACRU* subcatchments. Monthly cover factors for each subcatchment were derived as an area-weighted average of monthly cover factors of the different land uses making up the subcatchment. A unique approach was adopted with respect to the soil erodibility factors in that they were designed in the model to be dependent on the prevailing soil moisture status. This phenomenon has been described by Renard *et al.* (1991) and current experimentation is being conducted by the Department of Agricultural Engineering at the University of Natal to verify the effects of soil moisture status on soil erodibility in the Mgeni catchment. In the *ACRU* sediment yield model, therefore, the soil erodibility potential is greater in dry soil moisture conditions, resulting in significantly enhanced yield from a catchment when a storm event occurs subsequent to a prolonged dry period. This phenomenon, the so-called *first flush effect*, has been identified as occurring in the Mgeni catchment from a study of the sediment yield data.

3.2.3.2 Sediment Transfer

The dual processes of source erosion by rainfall impact and runoff energy (erosion) and of sediment entrainment and transport (delivery) are modelled in *ACRU* using principles of the Modified Universal Soil Loss Equation (Lorentz and Schulze, 1995). The storm discharge and the peak flow rate of each runoff event are simulated in the *ACRU* hydrology modelling system and are used to simulate the energy of soil erosion and sediment delivery in the *ACRU* sediment yield model.

3.3 VERIFICATION STUDIES OF SEDIMENT YIELD

3.3.1 Approaches to Verifying Sediment Loads

Three separate approaches to verifying the prediction of sediment loads in the subcatchments were adopted.

* The first approach involved comparing the estimates of sediments trapped in large reservoirs over a period of time, with the estimate of the total sediment load reaching the reservoir, derived by summing the daily sediment yields simulated by the *ACRU* model over the same period.
* The second approach made use of the suspended solids data collected by Umgeni Water on a once a week basis over the period 1989 to 1994 at five selected sites. On the sampling day, a single (grab) sample was taken manually from the stream at a variable time during the day. Estimates of daily sediment loads were made using these data for the days on which the grab samples were taken, together with measured flow data for the same day. These loads were then compared with those predicted on the same day using the *ACRU* model.
* The third method made use of suspended solids and discharge data collected by the Department of Agricultural Engineering of the University of Natal at the Henley weir at frequent, selected intervals during the course of a number of runoff events in 1994, using an automatic ISCO sediment sampler. The sediment loads resulting from these events were estimated by integrating the sediment fluxes derived from the concentration of suspended solids samples and the associated streamflow. The load estimates were then compared with the predicted total loads for each of the different events.

An example of each verification approach is presented in the sections which follow.

3.3.2 Verification Using Reservoir Survey Studies and Estimates

Estimates of the total loads of sediments trapped in selected reservoirs in the Mgeni catchment have been made by Rooseboom *et al.* (1992) for a period when consecutive surveys of the reservoir basin have been made. The additional amount of sediment passing through the reservoir was also estimated by considering reservoir trap efficiencies. In addition to reporting the sediment yield results for individual reservoirs in the Mgeni catchment, Rooseboom *et al.* (1992) present a method, based on statistical analyses of sediment yield data, for estimating sediment yields at sites where no measurements are available. This method has been used in a study reported by BKS (1994) to estimate the sediment yield for catchments forming part of *ACRU* sediment yield simulations over the identical period, where rainfall records permitted. The results of these three estimates of sediment yield are presented in Table 4 for the subcatchments contributing to the Midmar, Albert Falls and Henley Dams.

Table 4 Comparison of simulated sediment yield ($t.km^{-2}.a^{-1}$) with estimates derived from reservoir surveys (Rooseboom *et al.*, 1992; BKS, 1994)

Catchment	**Rooseboom *et al.* (1992)**	**BKS (1994)**	***ACRU***
Midmar Dam catchment	10 (1965-1983)	9.67 (1965-1983)	19.8 (1965-1983)
Albert Falls Dam catchment	31 (1974-1983)	30.08 (1974-1983)	37.2 (1974-1983)
Henley Dam catchment	46* (1942-1987) * after correction for catchment area	58.92 (1942-1987)	69.5 (1960-1987)

Simulated results of the long-term sediment yield loadings at these three locations compare favourably with those estimated from reservoir survey techniques. However, the sediment yields simulated by the *ACRU* model exceed those of the other two estimates in all three cases. This is hypothesised to be due to the use of relatively recent (1986) land use information for the entire period of simulation. Since the sediment yield parameters used in the simulation are based on higher percentages of agriculture and informal settlements than were prevalent in these areas during the period between surveys, the resulting simulated loads can be expected to be higher than those based on reservoir survey techniques. Nonetheless, the model successfully predicts low average annual sediment yields where these have been observed (Midmar) and high loads in catchments where these are observed (Henley).

3.3.3 Verification Using Weekly Grab Samples

Suspended solids data collected over the five-year period 1989-1993 from five of the subcatchments in the upper Mgeni catchment were used to verify the sediment yield predictions made using the *ACRU* model. The subcatchments used are listed in Table 5. Estimates of measured sediment load for the day on which the measurement was taken were derived by multiplying the measured suspended solids concentration with the total discharge in the river at the sample point for the day on which the sample was taken.

Table 5 Comparison of simulated and estimated daily sediment loads at five sites in the upper Mgeni catchment

Umgeni Water Sampling Station	**1**	**2.1**	**5.1**	**11.1**	**57**
***ACRU* Subcatchment Numbers**	**10-15**	**1-7**	**18-25**	**49-60**	**76-80**
Location Description	**Lions River**	**Mpendle**	**Karkloof**	**New Hanover**	**Msunduzi at Henley weir**
Estimated Average Daily Loads (t) Derived from Suspended Solids Measurements, 1989-1993	20.6	5.0	6.0	6.8	16.1
Simulated Average Daily Loads (t) on Days of Sampling, 1989-1993	20.2	24.3	21.1	7.9	24.1
Simulated Average Daily Loads (t) over Five-Year Period, 1989-1993	13.0	38.0	24.8	12.5	23.5

These samples were not always collected at the same time of day. During significant runoff events, the data collected may not represent the average sediment discharge conditions for the day. Nonetheless, in this verification study, the suspended solids concentration of this single grab sample is assumed to represent the flow-weighted concentration for the day. These load estimates were then compared with those simulated by the *ACRU* model. A typical comparisón is shown in Figure 23 for the Umgeni Water Station 57 (U2H011), on the Msunduzi river. The parameters used in the *ACRU* sediment yield model to estimate the long-term loadings described in the previous verification study were identical to those used in this verification study.

The loads estimated from the measured suspended solids concentrations rarely fall on days on which the sediment load was predicted by the *ACRU* model to be at a maximum. Two exceptions were observed for two separate events occurring in early February and late June of 1989 at the Henley weir, as shown in Figure 23. In addition, the loads estimated from measured data do coincide with the magnitude of the simulated loads on the day concerned. A comparison of all the simulated and measured loads for the 5-year period is made in Table 5. These compare favourably for Umgeni Water's Sampling Stations 1, 11.1 and 57. However, the average simulated sediment yield at Stations 2.1 and 5.1 exceed those estimated from the sample data.

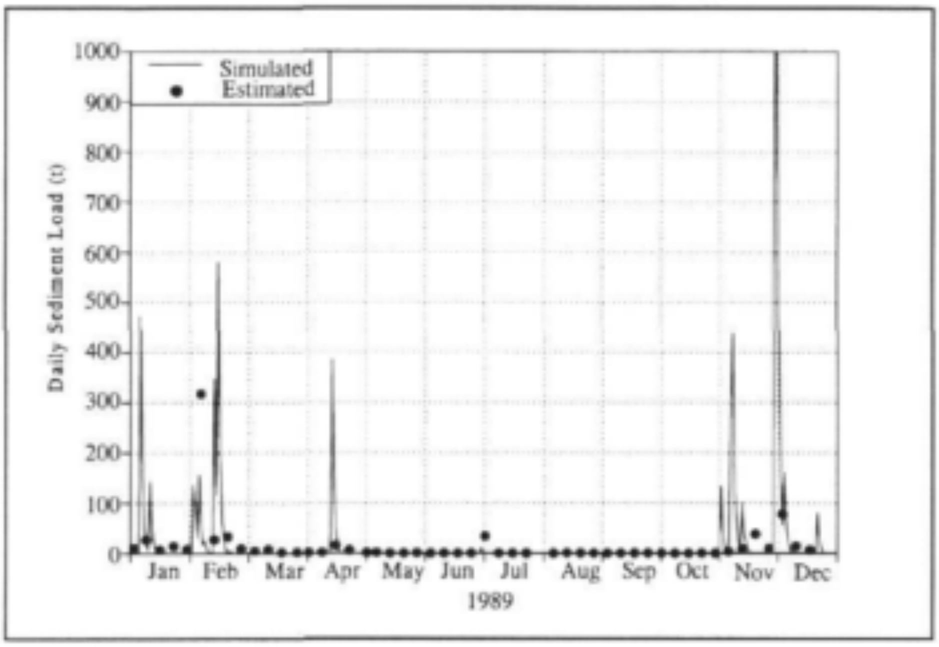


Figure 23 Comparison of simulated and estimated (from suspended solids) sediment loads for 1989 at Station 57, Msunduzi River

This could well be due to inaccuracies in the loads derived from measured data. The results shown in the comparison serve to highlight the need for reliable methods of measuring the total sediment load, whether on a daily basis or on the basis of variable time intervals, as in the verification study discussed below.

3.3.4 Verification Using Flow Integrated Sediment Sampling Techniques

A number of separate runoff events were monitored at the Henley weir during 1993, 1994 and 1995 by taking samples automatically during the event. An ISCO automatic water sampler was programmed to pump a water sample from the river at an interval related directly to incremental volumes of river discharge. This resulted in samples being taken more frequently at high flow rates than during lower flows, allowing for adequate definition of the rapidly changing concentrations during the peak flows of the event. Incremental sediment fluxes could then be summed for the duration of the event to yield the total sediment yield. The data collected during a typical event is presented in Figure 24. A comparison of the sediment loads measured during the events and those simulated by extending the *ACRU* simulation period into 1995 is given in Table 6. Two additional autographic rainfall measuring stations were set up in the catchment to provide more accurate rainfall data for modelling the events which were monitored.

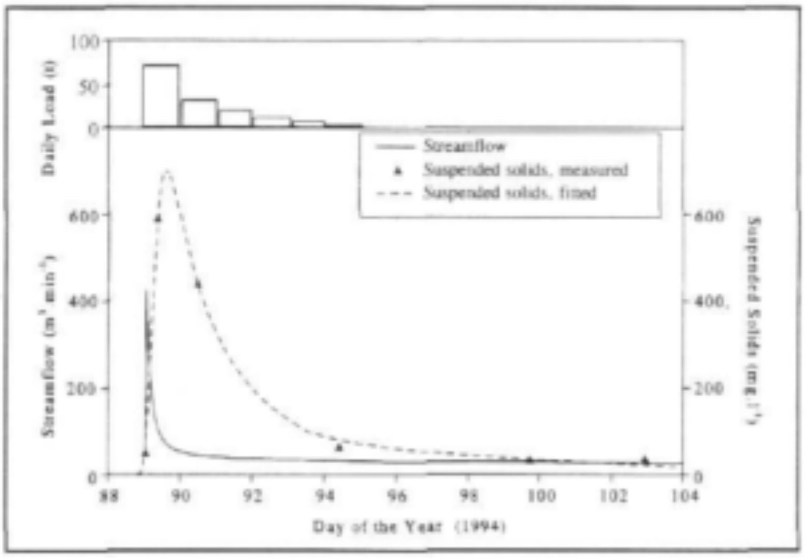


Figure 24 Hydrograph and associated suspended solid concentrations for a runoff event in the Msunduzi River at gauging station U2H011, 1994

Table 6 Comparison of estimated and simulated sediment loads from automatic monitoring at Henley Weir for seven events

Event No.	Date of Event (Day, month, year)	Estimated Sediment Load (t) for the Event	Simulated Sediment Load (t) for the Same Duration
1	08.10.93	60	140
2	08.01.94	581	1 278
3	01.02.94	1 246	1 586
4	29.03.94	140	2
5	25.07.94	90	105
6	15.11.94	13	0
7	27.12.94	550	313

Despite two anomalies the sediment loads generally compare favourably with those estimated for the measured events. This is significant since the estimated event loadings vary from 13 tons to 1 246 tons and the sediment yield model has therefore been tested over a wide range of event loadings. The two anomalies occur in Events 2 and 4. In Event 2 on 08.01.94 the simulated load is more than twice than that estimated from measurements and does not follow the order of magnitude agreement that is evident in the other events. This anomaly can be explained by examining the observed event runoff volume and peak flow and comparing these with the simulated volume and peak flow. The simulated values are greater than those observed, indicating that the poor sediment yield simulation results from poor hydrological simulations. Similarly, in Event 4, the simulated sediment yield is lower by an order of magnitude than that estimated from measurements. Again, this is related to the hydrological simulation of the runoff volume and peak flow, which, in turn, is dependent on the rainfall input. The rainfall which was recorded and used in the simulation was clearly less than that which actually occurred in the catchment during that event. Using the measured runoff volume and peak flow recorded at the Henley weir in the simulation of sediment yield results in a load of 196 tons for Event 4, which is of the correct order of magnitude to that estimated from suspended solids measurements, viz. 140 tons. It is evident, therefore, that accurate sediment yield simulations are dependent on accurate hydrological simulations, which in turn are linked to representative rainfall measurements for the subcatchments. It is encouraging, however, that simulated sediment yield loads compare well with those estimated from measurements in those cases where the hydrology is simulated adequately.

3.3.5 Conclusions on Sediment Verification Studies

Results of the verification studies are encouraging, with the simulated results comparing favourably with those estimated from the reservoir surveys and from river sample data. The ability of the model to reproduce the magnitude of the estimated loads appears to be sound for loads of varying magnitude, whether on a long-term basis or for individual events. This is acceptable, given the wide range of yields predicted by Rooseboom *et al.* (1992) for the region in which the Mgeni catchment falls.

The verification studies of sediment yield have, however, exposed the limited use of weekly grab samples, both for estimating long-term average sediment loads and for estimating the magnitude of daily loads. The need for adequate methods of continuous or integrated sampling which can be used to estimate daily, and consequently long- term, sediment loads is glaringly apparent. Such monitoring strategies would facilitate an invaluable data base with which to test and refine the predictions of sediment yield using the *ACRU*, or any other, model. Such testing and refinement would enhance the ability of the *ACRU* sediment yield model to provide even more accurate estimates both of the distribution of sediment yields and of the effects of land use changes, as well as improving estimates of phosphorus yield and *E. coli* counts.

These sediment yield verifications indicate that a robust simulation model of sediment yield has been developed and can be applied to estimate the distribution of sediment yield in the subcatchments of the Mgeni basin.

3.4 WHERE IN THE MGENI CATCHMENT ARE SEDIMENTS PRODUCED ?

The average annual subcatchment sediment yields were derived by first simulating daily sediment loads for each subcatchment for the period 1960-1993 and then computing annual averages. Figure 25* displays the average annual sediment yield for the 137 *ACRU* subcatchments of the Mgeni catchment upstream of Inanda Dam. The mean annual simulated sediment yield for the 137 *ACRU* subcatchments ranged from 2 to 629 $t.km^{-2}$. This range compares well with that reported by Rooseboom *et al.* (1992) of 20 to 723 $t.km^{-2}.a^{-1}$ for the same region. Within the study area the Valley of a Thousand Hills delivers the highest sediment yields. Another area of high simulated sediment yield is a subcatchment in the Edendale area, where large proportions of informal dwellings are located. When comparing Figures 22* and 25* it appears, on first inspection, that the sediment yield map displays similar spatial distributions to that of the soil loss potential map. This is not so everywhere, however. For example, an *ACRU* subcatchment in the upper region of the Mqeku Management Subcatchment has a medium soil loss potential, comprising the full range of very low to very high soil loss potentials, resulting in a mean annual soil loss potential of 2 030 $t.km^{-2}$. The mean annual sediment yield was simulated to be 195 $t.km^{-2}$, which is in the medium to low range compared with the rest of the Mgeni catchment, indicating a low sediment delivery ratio of 9.6%. In contrast, the subcatchment comprising Inanda Dam was estimated to have a low mean annual soil loss potential of 641 $t.km^{-2}$, but shows a mean annual sediment yield of 287 $t.km^{-2}$. This indicates a sediment delivery ratio of 44.8%.

3.5 FINDINGS BASED ON SIMULATED SEDIMENT LOAD SEQUENCES

With the confidence from three independent verification approaches that the dominant dynamics of sediment yield are being simulated realistically in the *ACRU* model, simulation runs can be used to gain insight into long-term response patterns of sediment yield. Figure 26 shows monthly sediment yields for the 34-year simulation period for three *ACRU* subcatchments with low, medium and high sediment yields, respectively. What is apparent is that single flood events with low recurrence probabilities, such as those experienced during the September 1987 floods, mobilise very large amounts of sediments. Simulations in *ACRU* Subcatchment 9 in the Midmar Management Subcatchment resulted in a total sediment load of 11 927 t for the simulation period. During the single week in September 1987, when a flood with a recurrence interval of approximately 50 years resulted in substantial sediment movement, a simulated load of 1 867 t was transported. This represents 18.1% of the total 34-year sediment yield estimate. In subcatchments with an already high sediment load, extreme events such as the September flood of 1987 play a relatively lesser role, because the background sediment load is higher. For *ACRU* Subcatchment 132, in the Inanda Management Subcatchment for example, it was simulated that 10.8% of the total 34-year sediment load was transported during the September 1987 floods, a considerably lower amount than in the case of Subcatchment 9.

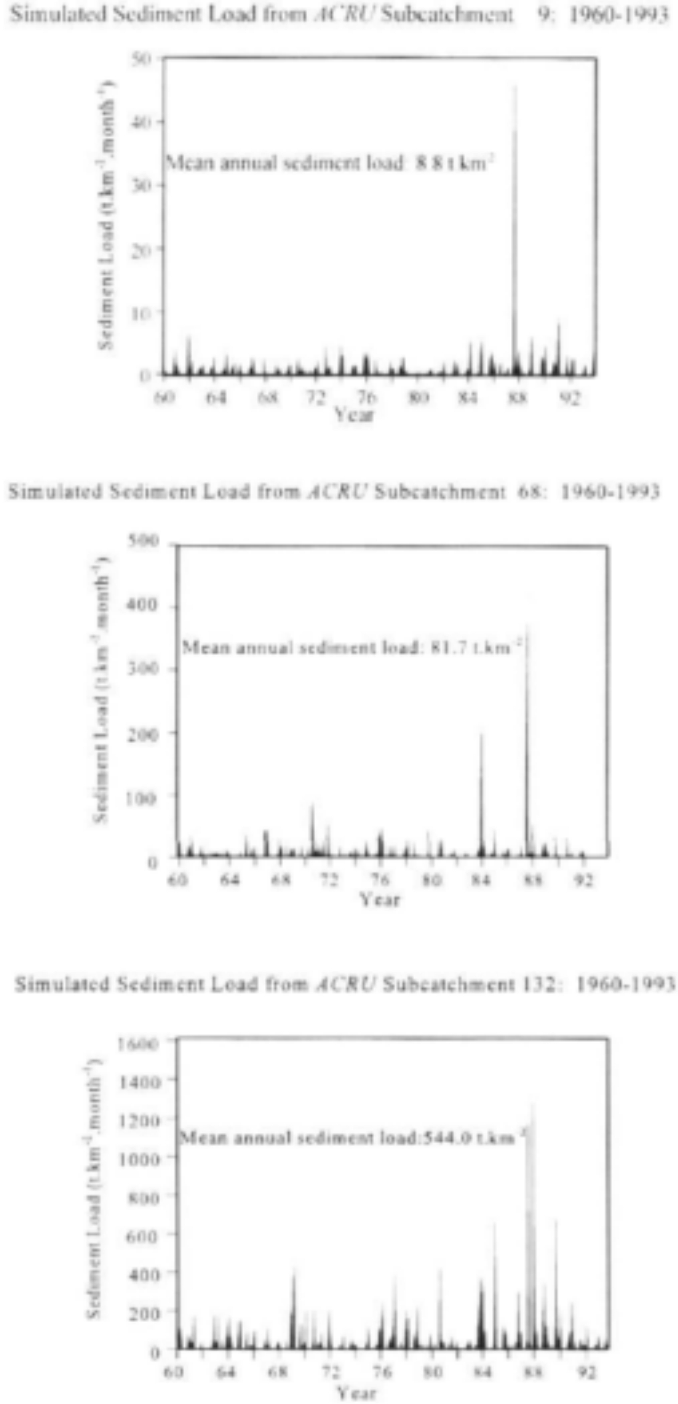


Figure 26 Time series of simulated sediment loads for three *ACRU* subcatchments

3.6 MODELLING NON-POINT SOURCE PHOSPHORUS YIELD WITH *ACRU*

3.6.1 Sources of Phosphorus

Phosphorus from non-point sources enters the aquatic environment from a number of origins including:

* fertilizer applications in agriculture,
* livestock deposition,
* depositions from the atmosphere in rainfall (wet deposition) and through adherence to dust particles (dry deposition), as well as from
* human sources through the use of detergents in open waterways and the seepage and overflow of pit latrines.

The rate at which, and the mechanisms through which, phosphorus enters the hydrological cycle varies with the type of source. Consequently, these rates and mechanisms need to be considered separately for each source type.

3.6.2 Requirements of a Phosphorus Yield Model for Application in the Mgeni Catchment

A phosphorus yield model for application in the Mgeni catchment will be required for:

* the estimation of the long-term loadings of phosphorus to reservoirs and waterways in order to simulate the deterioration of water quality through eutrophication,
* the determination of the effects of land use changes in Umgeni Water's Management Subcatchments on the phosphorus yield and for
* catchment managers to anticipate the duration and frequency of elevated levels of phosphorus concentrations in waterways.

As with sediment yield modelling techniques, the methods of describing the fate of phosphorus in the hydrological cycle vary in complexity and data requirements. Therefore, a state-of-the-art literature review of phosphorus modelling techniques (available from the Department) was performed with a view to designing a modelling methodology suited to the Mgeni catchment and which could be used with readily available data. It was also evident that the dominant processes of phosphorus source production and transport should be included in the model so that the observed variation in phosphorus loading could be simulated successfully. Consequently, phosphorus is modelled in two separate, but interacting, states - these being the adsorbed and dissolved states.

The different sources of phosphorus and the mechanisms of phosphorus transport in a catchment are represented schematically in Figure 27. In the *ACRU* phosphorus model, total available phosphorus is added to the top 10 mm of soil (the so-called mixing zone) in maize, sugarcane and mixed crop land uses via fertilizer during the appropriate period of application. Phosphorus is also added to the agricultural land uses as well as to the rest of the catchment via atmospheric deposition. The phosphorus added to the soil from these sources is distributed between the adsorbed state and the dissolved state according to an adsorption process which is dependent on:

- per cent clay in the soil,
- per cent soil organic matter,
- soil pH and
- prevailing soil moisture status.

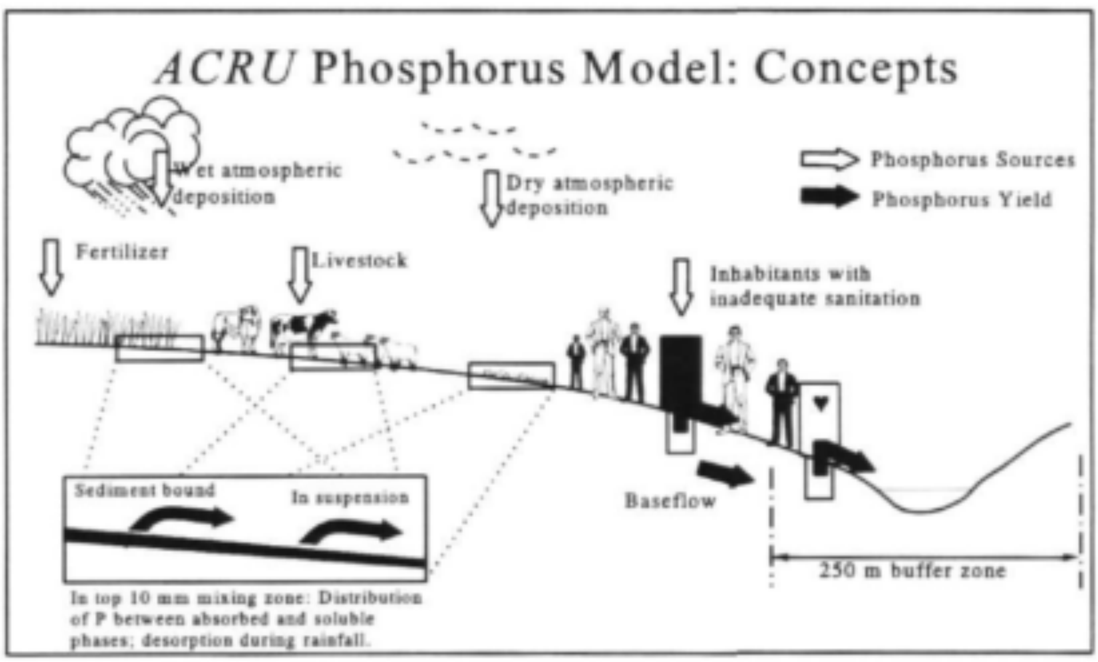


Figure 27 Concepts of the *ACRU* phosphorus model

During a rainfall event, a proportion of the phosphorus is desorbed from the sediments into the dissolved state. This proportion depends on the soil parameters listed above, as well as on the water/soil mixing ratio determined from the depth of rainfall and the prevailing soil moisture status. After the desorption process, the final concentrations in the adsorbed and dissolved states are applied to the quantity of sediment and stormflow respectively, to yield the total phosphorus from these sources. The phosphorus from human sources is added to the dissolved state in the event of rainfall and runoff of sufficient magnitude causing a septic tank to discharge into the catchment.

Detailed discussion of the processes modelled, the algorithms used and the inherent assumptions made can be obtained from the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg.

3.6.3 Preparation of Information

3.6.3.1 Agricultural and Distributed Sources of Phosphorus

The application of phosphorus in fertilizers varies from location to location and from year to year. Typically, however, commercial farmers will aim at applying sufficient phosphorus to the soil so that an adequate quantity is available to the crop. The amount available to the crop depends on the adsorption characteristics of the soil. Therefore, in the *ACRU* phosphorus model, the application rates of fertilizer based phosphorus at any location are determined by the relevant soil adsorption characteristics as well as the type of crop grown at that location. These soil characteristics and associated application rates were determined in consultation with soil scientists at the University of Natal, Cedara Agricultural Research Institute and the Institute of Commercial Forestry Research. In addition, a GIS was used with an expert system algorithm to estimate the soil per cent organic matter and the likely soil pH. This information; together with the clay content of the soil, are used in a further GIS algorithm to determine the distribution of soil adsorption and desorption parameters.

Wet and dry deposition rates were estimated from sampled data of bulk atmospheric deposition near Midmar Dam. From data supplied, the dry phosphorus deposition was estimated to be 0.66 $g.ha^{-1}.day^{-1}$, while the wet phosphorus deposition was 0.145 $g.ha^{-1}.mm^{-1}$ of rainfall, which equals 0.0145 $\mu g.\ell^{-1}$. Dry deposition rates for urban areas were doubled. Dry deposition rates were assumed to be constant throughout the year.

3.6.3.2 Livestock Sources of Phosphorus

Information on livestock densities of beef cattle, dairy cows and sheep was based on a survey undertaken by the Department of Agriculture and Fisheries (1981). Commercial livestock numbers are assumed not to have varied much during the past 15 years. The distribution of dairy cows, beef cattle and sheep for the 137 *ACRU* subcatchments were derived from livestock density maps. The following assumptions were made for the spatial distribution of livestock:

* commercial livestock is associated with either pasture or grassland,
* cows graze predominantly on planted pasture, at a maximum stocking rate of 300 animal units per km^2,
* and the remaining livestock would be distributed over grassland.

The daily output of phosphorus used in *ACRU* was 43 g per dairy cow, 11 g per beef cattle and 2.5 g per sheep.

3.6.3.3 Human Sources of Phosphorus

The *ACRU* phosphorus model includes the impact of pit latrines in rural and informal urban settlements. Areas with this form of sanitation, which is liable to effluent to the natural water regime, are divided between those within a buffer zone adjacent to a stream (i.e. within 250 m) and those which are more remote from the stream network. The impact of those areas within the buffer zone is elevated in the model compared to the impact of more remote sites, but the impacts of both are dependent on extreme events of rainfall. It is in the modelling of the effects of inadequate sanitation that observed phosphorus load data have been used to guide the setting of the magnitude of these impacts. Adequate monitoring of the impacts of rural sanitation to receiving streams at a catchment scale is therefore recommended.

3.6.4 Production of a Phosphorus Pollution Potential Map

A phosphorus pollution potential map was produced by adding all phosphorus inputs that would be available within the top 10 mm of soil. Values for wet and dry atmospheric deposition, numbers of beef cattle, dairy cows and sheep, amounts and application frequencies of fertilizers for sugarcane, maize and mixed crops as well as inputs from human faeces where inhabitants are without proper sanitation, where summed up to give results in $kg.km^{-2}.a^{-1}$.

Analysis was based on a 250 by 250 m grid cell for the Mgeni catchment upstream of Inanda Dam (Figure 28*). Highest input values are in areas where irrigated pastures are assumed to be stocked with dairy cows, or where livestock is kept on grassland with high stocking rates. Values range from < 250 to more than 4800 $kg.km^{-2}.a^{-1}$, with Figure 28* highlighting distinctly those areas of high stocking rates as well as with informal settlements.

3.7 VERIFICATION STUDY OF PHOSPHORUS YIELD

3.7.1 Verification Using Long-Term Weekly Grab Sample Record

Umgeni Water weekly sampling data were used in a similar manner to that described in the sediment yield verification study. A typical sequence showing phosphorus loads derived from the grab samples and those simulated by the *ACRU* phosphorus model is shown for Station 57 for 1989 in Figure 29. The simulated average phosphorus loads and those estimated from measurements for the five-year verification period are summarised in Table 7. It is clear that for all stations, except for Station 11.1, the simulated results exceed the measured values. This is hypothesised to be due to an inherent oversimulation of the sediment yield as reported in Table 5. Moreover, similar inadequacies in the use of grab sample data to estimate daily phosphorus loads as those described in the sediment yield verification study are also thought to be responsible for the differences. However, the overall agreement between these initial simulated results and the few measured data is nevertheless encouraging and further indicates the potential of the model and the value of appropriate monitoring strategies.

A further comparison between simulated and measured results is shown in Figure 30*. This indicates the relationship between phosphorus loads and sediment loads for estimated and simulated results. The relationship shown is typical of those of the five catchments used in the verification study. The data indicate that the relationship between the sediment and the phosphorus loads are similar for the measured and simulated data. The extension of the simulated loads beyond those measured is an indication that either the measured data do not include extreme events or that the model is oversimulating the phosphorus and sediment yield loads. The results of comprehensive monitoring experiments, such as the one initiated at the gauging station U2H011 in the Msunduzi river by the Department of Agricultural Engineering of the University of Natal, will prove invaluable in verifying further the phosphorus model output and indicating the mechanisms that may be causing the discrepancies between observations and simulated results.

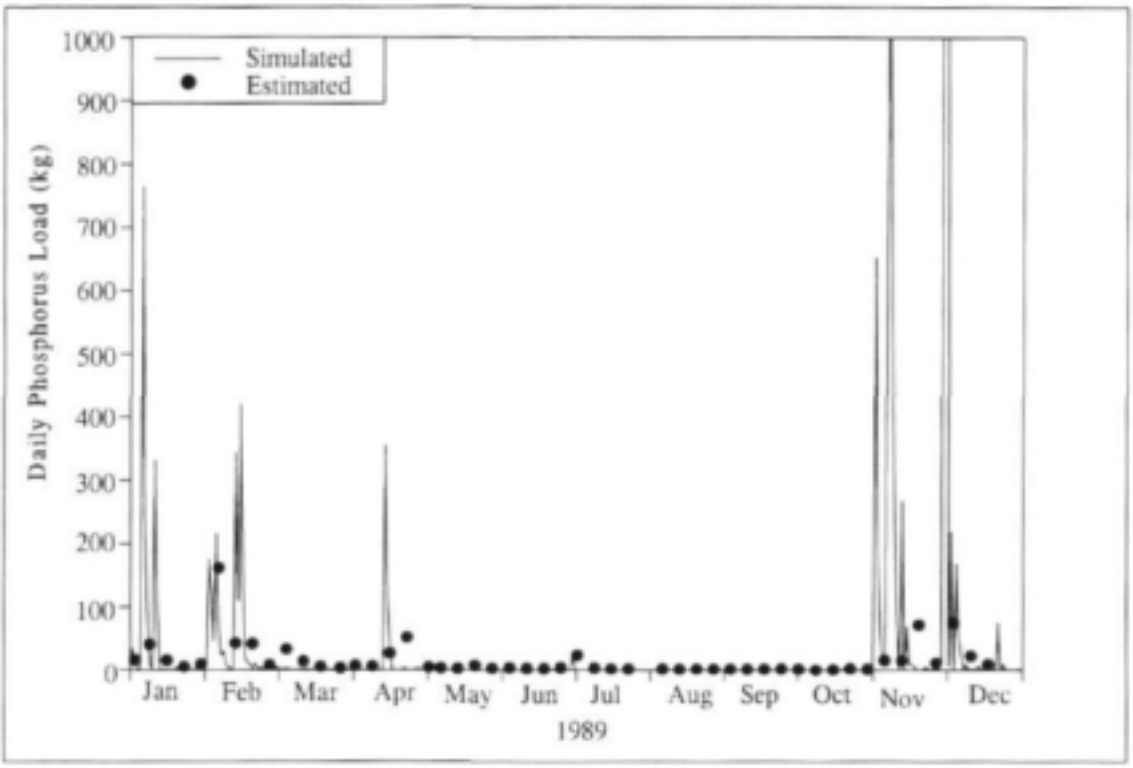


Figure 29 Comparison of simulated and estimated phosphorus loads for 1989 at Station 57, Msunduzi River

Table 7 Comparison of estimated and simulated daily phosphorus loads for 1989 to 1993

Station	**Estimated Average Daily Loads 1989-1993 (kg)**	**Simulated Average Daily Loads on Days of Sampling, 1989-1993 (kg)**	**Simulated Average Daily Loads over Five-Year Period, 1989-1993 (kg)**
1	17.3	27.9	29.0
2.1	11.2	30.1	19.3
5.1	12.1	33.6	53.0
11.1	7.1	4.2	7.7
57	11.4	37.2	35.1

3.7.2 Verification Using Flow Integrated Sampling of Phosphorus

The samples taken of runoff events at the Henley weir, reported in Section 3.3.4 "*Verification Using Flow Integrated Sediment Sampling Techniques*", were also analysed for total phosphorus and loads were estimated by integration of flow and concentration hydrographs. A typical event is shown in Figure 32 and a summary of the events monitored successfully in 1994 is presented in Table 8.

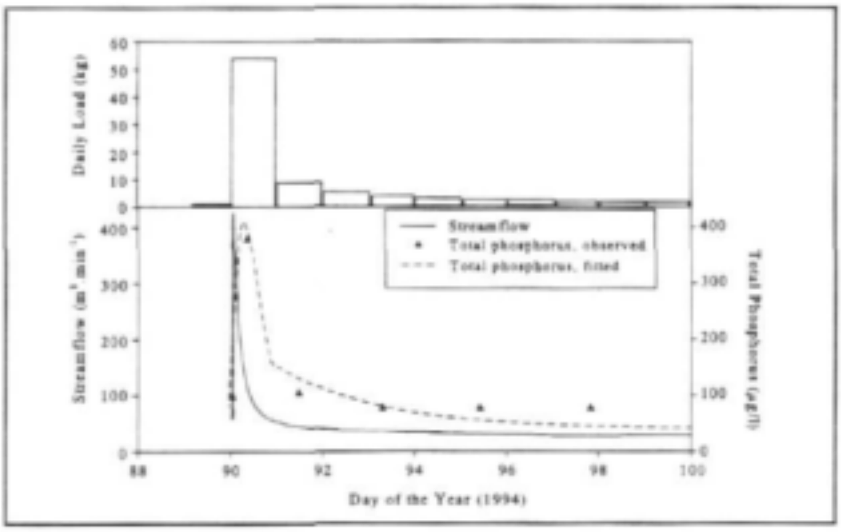


Figure 32 Hydrograph and associated phosphorus concentrations for a runoff event in the Msunduzi River at gauging station U2H011, 1994

Table 8 Comparison of estimated and simulated phosphorus loads from automatic monitoring at Henley Weir for four events

Event No.	Date of Event (Day, month, year)	Estimated Phosphorus Load (kg) for the Event	Simulated Phosphorus Load (kg) for the Same Duration
4	29.03.94	96	11
5	25.07.94	62	231
6	15.11.94	16	3
7	27.12.94	134	606

The first three events reflect the same differences as indicated in the sediment yield estimates presented in Table 6. The differences between simulated and estimated total phosphorus for these events is similar to the differences between simulated and estimated sediment yields for the same events. The simulated total phosphorus load is greater than that estimated for the last event sampled, whereas the simulated sediment yield is less than that estimated for the same event. This is due to the large rainfall depth associated with the event and thus a large contribution of total phosphorus simulated from pit latrine sources. This aspect of the total phosphorus model therefore requires some refining.

3.8 WHERE IN THE MGENI CATCHMENT IS NON-POINT SOURCE PHOSPHORUS PRODUCED ?

Figure 33* displays the phosphorus yield as it was simulated for the 137 *ACRU* subcatchments. Mean annual phosphorus yield values ranged from 0.5 to 850 kg.km^{-2}. The distribution of high and low annual phosphorus yield values over the Mgeni catchment is quite dissimilar to the distribution of long-term annual sediment yields. Significant non-point source phosphorus loads emanate from the Albert Falls Management Catchment, with its many feedlots, whereas this subcatchment has a relatively low sediment yield. It is therefore obvious that the high phosphorus loads are due to the large amounts of source phosphorus in these subcatchments, as is indicated in the phosphorus pollution potential map.

Additional monitoring by means of continuous, or integrated, sampling would prove invaluable in further verification of the subcatchment loadings shown in Figure 33*.

3.9 MODELLING *E. coli* WITH *ACRU*

Modelling *E. coli* in the Mgeni catchment was undertaken from a series of suppositions of dominant processes. *E. coli* modelling is in a development phase and is presented here to indicate the state of development and verification. In modelling the fate of *E. coli* in a catchment, two sources have been considered. These are from grazing livestock and from humans in areas of inadequate sanitation (Figure 34). The livestock considered are those distributed in the grassland and pasture land use areas and not those in intensive feedlots which is considered a point source, which is not as yet considered in the model. The source of *E. coli* from the livestock is distributed between that existing in the sediment bound state and that in suspension in the soil water or runoff water. The transport of the *E. coli* from this source is modelled in the same manner as the distributed source phosphorus. The *E. coli* emanating from areas of inadequate sanitation is modelled in the same manner as the phosphorus from this source, and is dependent predominantly on population density and extreme rainfall events. The parameters which define the loading of the *E. coli* from both these sources are poorly documented in the literature. Use was therefore made of the measured *E. coli* data in estimating the relative impacts of these sources.

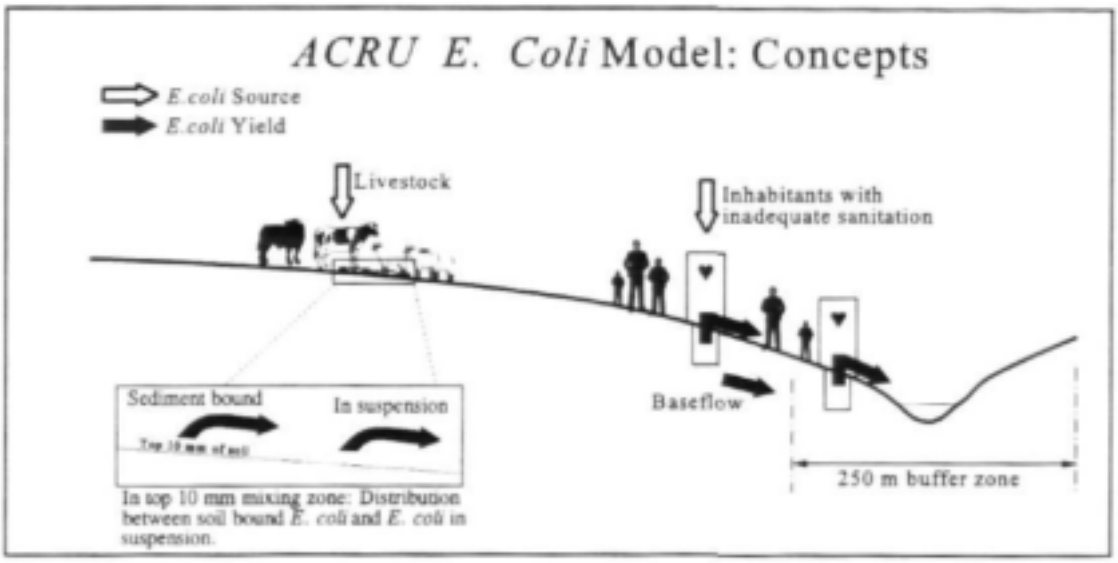


Figure 34 Concepts of the *ACRU E. coli* model

3.10 VERIFICATION STUDY OF *E. coli* CONCENTRATION

3.10.1 Umgeni Water Weekly Sampling

Results of the comparison between measured and simulated *E. coli* concentrations are shown in Figure 35 for the Station 57 for 1989. The comparison is the poorest of the three water quality determinands studied. The simulated average *E. coli* concentrations at Station 57 for the period 1989 to 1993 is lower than for the measured data during the same period. The reverse is true for all of the other four catchments used in the verification study as indicated in Table 9. The relationship between *E. coli* and sediment load presented in Figure 31* for Station 5.1 shows that simulated *E. coli* loads are predominantly higher than the loads estimated from the grab samples, indicating that the model is oversimulating the loads. This is hypothesised to be caused by the impact of the livestock numbers having been set too high and the impact of human sources set too low in the initial compilation of the *ACRU E. coli* model. Since the setting of these parameters is based on the observed data, these adjustments can easily be made in the model. However, monitoring experiments of the fate of *E. coli* in the surface and subsurface environment are highly recommended.

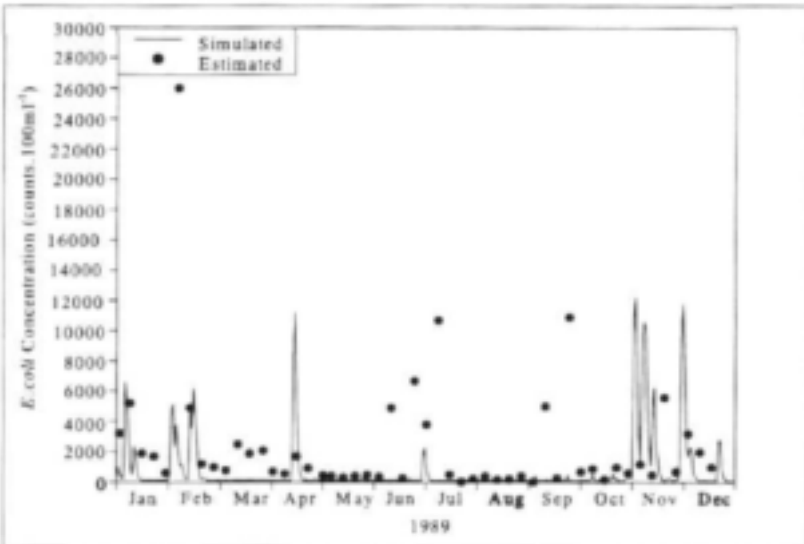


Figure 35 Comparison of simulated and observed *E. coli* concentrations for 1989 at Station 57, Msunduzi River

Table 9 Comparison of measured and simulated *E. coli* concentrations for 1989 to 1993

Station	**Measured Concentrations 1989-1993 (counts.100mℓ⁻¹)**					**Simulated Concentrations over Five-Year Period 1989-1993 (counts.100mℓ⁻¹)**					**Selected Average Measured Concentrations Reported by BKS (1994) (counts.100mℓ⁻¹)**				
	10 %	50 %	90%	Ave	Max	10 %	50%	90%	Ave	Max	10 %	50 %	90%	Ave	Max
1	88	360	1400	915	30000	125	126	4795	1924	60470	110	395	2200	241	30000
2.1	52	200	640	310	2500	99	100	2037	667	14359	80	240	770	360	2600
5.1	80	310	1310	677	18100	99	100	4175	1189	17781	100	340	1200	637	6000
11.1	60	230	1100	501	7400	98	100	2991	1110	54666	46	220	1100	566	9200
57	220	730	8600	288	32000	99	100	2240	1153	58170	220	930	8600	3533	83000

3.11 WHERE IN THE MGENI CATCHMENT IS NON-POINT SOURCE *E. coli* PRODUCED ?

While the distribution of average *E. coli* counts shown in Figure 36* allows for convenient identification of potentially high yield areas, it does not necessarily map expected concentrations accurately. Mean annual simulated *E.coli* concentrations in the 137 *ACRU* subcatchments range from 30 to 18 200 counts.100mℓ$^{-1}$. Areas of highest

E. coli concentrations are associated with informal settlements, in particular along the Msunduzi river in its lower reaches and central parts the Valley of a Thousand Hills. It is also evident that high *E. coli* concentrations are not always associated with areas of high sediment yield. In Management Subcatchment 10, viz. Table Mountain (cf. Figure 6*), high *E. coli* counts are simulated (1 000-1 0 000 counts.100 $m\ell^{-1}$) even though the sediment yield in this area is relatively low (25-100 $t.km^{-2}$). This is due to the large populations in informal settlements in this area as well as the relatively high stocking rates.

3.12 MODELLING FUTURE SCENARIOS : EVALUATING IMPACTS OF LAND USES ON WATER QUALITY

In order to demonstrate the versatility and value of *ACRU* model in the Mgeni Catchment, two scenarios of realistic future land use change are examined in regard to their impacts on hydrology and water quality. These are:

- Scenario A : An increase in subsistence farming and informal settlements in the Msunduzi catchment, upstream of Pietermaritzburg.
- Scenario B : Change of land use in the Table Mountain Management Subcatchment from savanna and woodland to each of eucalyptus plantations, sugarcane fields or intensive cropping.

3.12.1 Study I: Impacts of Increases in Subsistence Farming and Informal Settlements Upstream of Pietermaritzburg

This scenario was modelled by altering the parameters for a catchment comprising *ACRU* Subcatchments 76 to 91 (Henley and upper Pietermaritzburg Management Subcatchments) to reflect a twofold increase in the area of subsistence agricultural smallholdings and a doubling of the informal settlement population. The hydrology and water quality were then simulated in the catchment with the revised land uses and compared to the simulations under present conditions. This comparison is summarised in Figure 37.

Water quality deterioration is immediately apparent due to the informal settlements and subsistence agriculture. The relative increase in the different water quality determinands is significant. While simulated sediment yield increases by 17%, the phosphorus yield increases by 76% and the *E. coli* concentrations by 40%. Phosphorus yield increase is by far the most significant due to its dependence on both the land use changes, i.e. a population influx

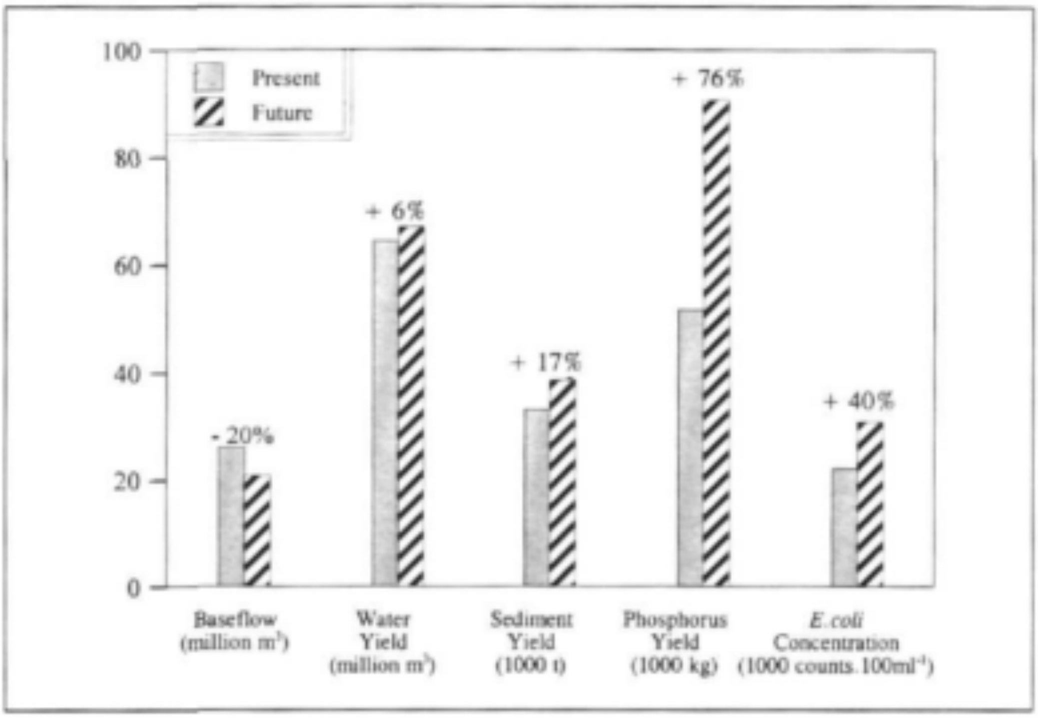


Figure 37 Comparison of the hydrology and water quality upstream of Pietermaritzburg between present and a future land use scenario comprising a doubling of areas under subsistence agriculture and informal settlements

as well as agricultural expansion. The *E .coli* is affected by the population increase, together with the livestock increase associated with informal settlement units. The sediment yield is predominantly affected by the increase in tillage and, to a lesser extent, the increase in runoff caused by the expansion of impervious and compacted areas associated with settlements. The hydrology is not as severely affected as the water quality. Baseflow decreases by some 20%, but the total streamflow increases by 6%. These changes are associated primarily with the increases in impervious and compacted areas.

3.12.2 Study II: Impacts of Increases in Eucalypt Plantations, Sugarcane Cultivation or Intensive Smallholder Agriculture in the Table Mountain Management Subcatchment

This scenario was compiled using three different simulations. In the first simulation, 50% of the present savanna and indigenous woodland in a typical Table Mountain Management Subcatchment (*ACRU* Subcatchment 113) was replaced by eucalypt plantations. In the second simulation, 50% of the present savanna and woodland was replaced with sugarcane plantations and in the third by intensively cropped agriculture. The comparison of these three simulations with the simulation of present conditions is summarised in Figure 38.

As already illustrated in Chapter 2, it is clear that the streamflow is influenced most by the eucalypt plantation, showing a marked decrease. However, the eucalypt plantations also result in the highest improvements in water quality, significantly reducing sediment and phosphorus loads. The other two land use changes result in an increase in sediment and phosphorus loadings as a result of tillage practices and fertilizer applications.

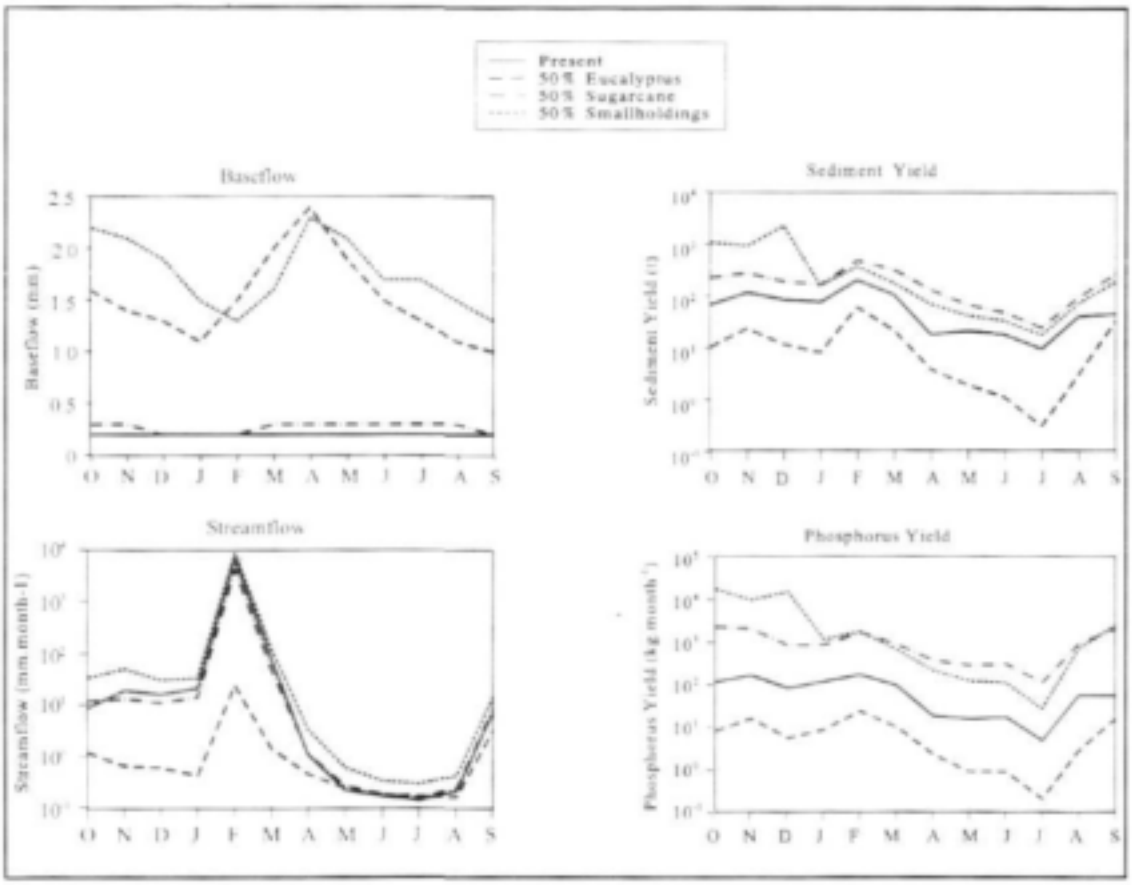


Figure 38 Comparison of hydrological and water quality responses in the Table Mountain area between present and a future scenario in which present land cover is replaced by 50% other land uses

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

General conclusions and recommendations that can be made from the hydrological simulations with the *ACRU* model in this study include the following:

- The *ACRU* modelling system, with comprehensive data sets for the Mgeni catchment upstream of Inanda Dam, was configured to simulate components of the hydrological cycle.
- Simulated and observed streamflows compare very favourably in catchments with significantly different land uses and water yields.
- The modelling system can therefore be used to assess magnitudes and time sequences of individual components of the hydrological cycle, such as soil moisture content, low flows and peak flows, as well as generating hydrological processes which determine water quality.
- The system is uniquely adapted to determining the impacts of anticipated land use change scenarios on the aquatic environment.

Further conclusions and recommendations that can be made from the water quality simulations with the *ACRU* model in this study include the following:

- A modelling system, with comprehensive data sets for the Mgeni catchment upstream of Inanda Dam, was established to simulate sediment yield, phosphorus loads and *E. coli* concentrations at subcatchment level.
- The modelling system is uniquely adapted to determining the impacts of anticipated land use change scenarios on selected water quality responses.
- A need for adequate water quality monitoring methods to yield reliable estimates of the total loading of sediments and phosphorus has been identified. It is recommended that integrated sampling, or automatic sampling, be instituted in critical catchments.
- A need for experimentation designed to allow for the observation of the transport mechanisms of sediments, phosphorus and *E. coli* within a catchment has also been identified.

REFERENCES

ACOCKS, J.P.H. (1988). Veld types of South Africa. Botanical Research Institute, Pretoria. *Botanical Survey of South Africa, Memoirs* **57**. 146 pp.

BREEN, C.M., AKHURST, E.G.J. and WALMSLEY, R.D. (1985). Water Quality Management in the Umgeni Catchment. Natal Town and Regional Planning Commission, Pietermaritzburg. Supplementary Report **12**.

BKS Inc. (1994). Mgeni River System Analysis Study. BKS Incorporated, Pretoria. Report 9557/05.

BROMLEY, K.A. (1989). Land Cover Classes in the Mgeni River Catchment. Institute of Natural Resources, University of Natal, Pietermaritzburg. Supplement to CSIR Report AAL 21.

DENT, M.C., LYNCH, S.D. and SCHULZE, R.E. (1989). Mapping Mean Annual and Other Rainfall Statistics over Southern Africa. Water Research Commission, Pretoria. Report 109/1/89. 198 pp plus Appendices.

DEPARTMENT OF AGRICULTURE and FISHERIES (1981). *Agriquest* 1980. Cedara Agricultural Research Institute, Cedara.

DWAF, UW, BKS and NSI (1994). Mgeni River System Analysis Study - Phase I, Water Quality Statement, Vol 1-4. DWAF PB U 000/00/0892. Department of Water Affairs and Forestry, Pretoria.

ESRI (1992). Environmental Systems Research Institute Inc. 380 New York Street, Redlands, CA, USA.

HORNE GLASSON PARTNERS (1989). Water Plan 2025. Umgeni Water, Pietermaritzburg.

KELBE, B. and SNYMAN, N.M. (1993). Water quality response to land use for short duration, high intensity storms. *Proceedings, 6th South African National Hydrology Symposium*, University of Natal, Pietermaritzburg, Department of Agricultural Engineering. Vol II, 507-514.

LORENTZ, S.A. and SCHULZE, R.E. (1995). Sediment Yield. *In*: Schulze, R.E. 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 AT16-34.

MOERDYK, M. and SCHULZE, R.E. (1991). Impacts of forestry site preparation on surface runoff and soil loss. *Agricultural Engineering in South Africa* **23** 319-325.

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 Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Research Service, Tucson, AZ, USA, Report.

ROOSEBOOM A., VERSTER, E., ZIETSMAN, H.L. and LOTRIET, H.H. (1992). The Development of the New Sediment Yield Map of Southern Africa. Water Research Commission, Pretoria, Report 297/2/92.

SCHULZE, R.E. (1989). *ACRU*: Background, Concepts and Theory. Water Research Commission, Pretoria, *Report* 154/1/89. 235 pp.

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. 552 pp.

SCHULZE, R.E. and MAHARAJ, M. (1994). 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, Pretoria, Soil and Irrigation Research Institute. *Memoirs on the Agricultural Natural Resources of South Africa*.

SMITHEN, A.A. and SCHULZE, R.E. (1982). The spatial distribution in southern Africa of rainfall erosivity for use in the Universal Soil Loss Equation. Water SA **8** 74-78.

SMITHERS, J.C. and SCHULZE, R.E. (1995). *ACRU* Agrohydrological Modelling System: User Manual Version 3.00. Water Research Commission, Pretoria, Report TT70/95. 368 pp.

TARBOTON, K.C. and SCHULZE, R.E. (1992). Distributed hydrological modelling system for the Mgeni catchment. Water Research Commission, Pretoria, Report 234/1/92. 98 pp.

UMGENI WATER. (1994). Water supply statistics. Personal communication.

VAN LILL, W.S., KRUGER, F.J. and VAN WYK, D.B. (1980). The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et Cham. on streamflow from experimental catchments at Mokubulaan, Transvaal. Journal of Hydrology, **48** 107-118.

WALMSLEY, R.D. and FURNESS, H.D. (1987). A programme description for water resource research in the Mgeni catchment. Natal Town and Regional Planning Commission, Pietermaritzburg, Supplementary Report 21.

Mgeni Catchment Overview

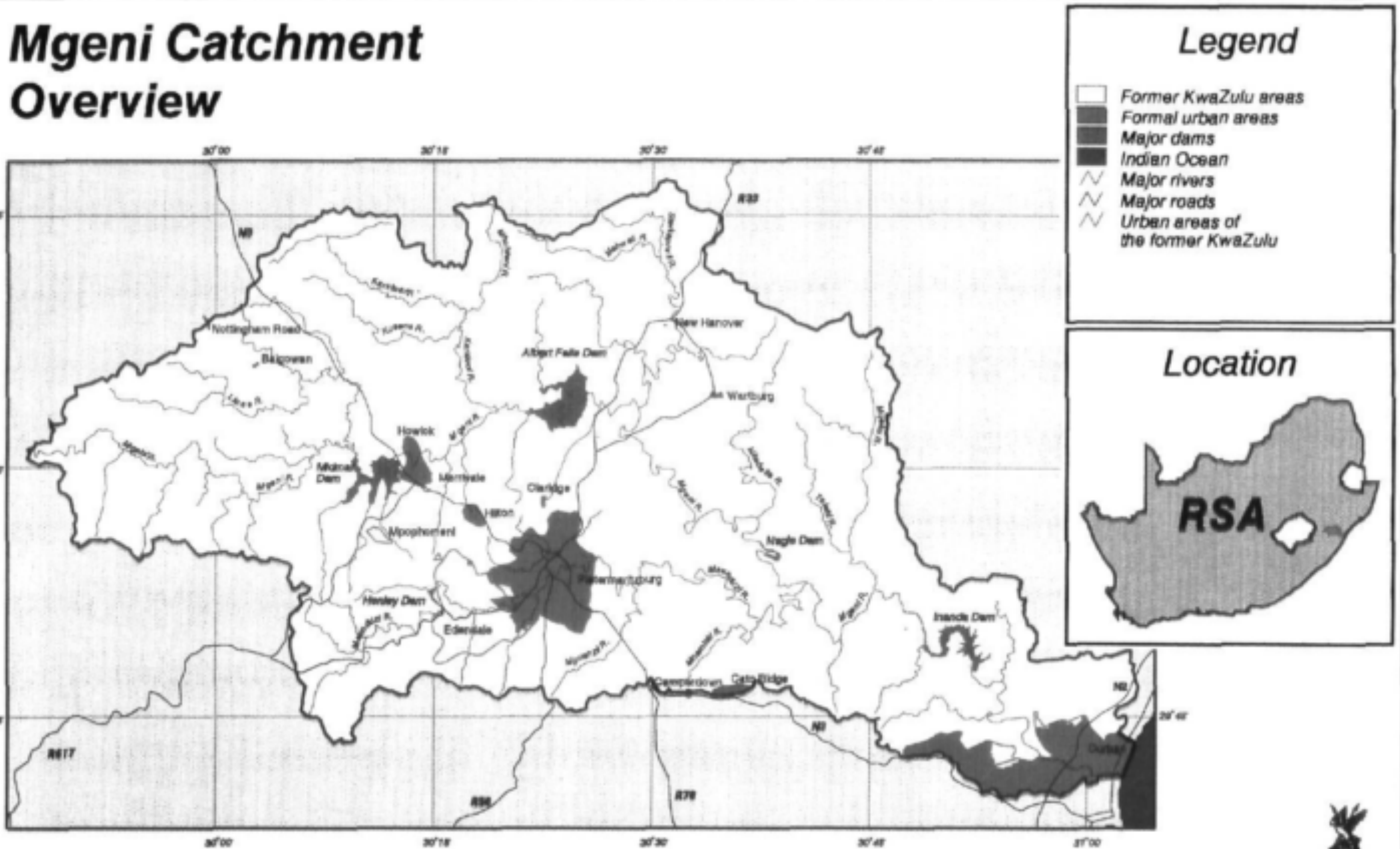


Figure 1

Kilometre
0 5 10 15 20 25

Gauss Conformal Projection (31°)
May, 1996

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Mgeni Catchment

Population Density (1991)

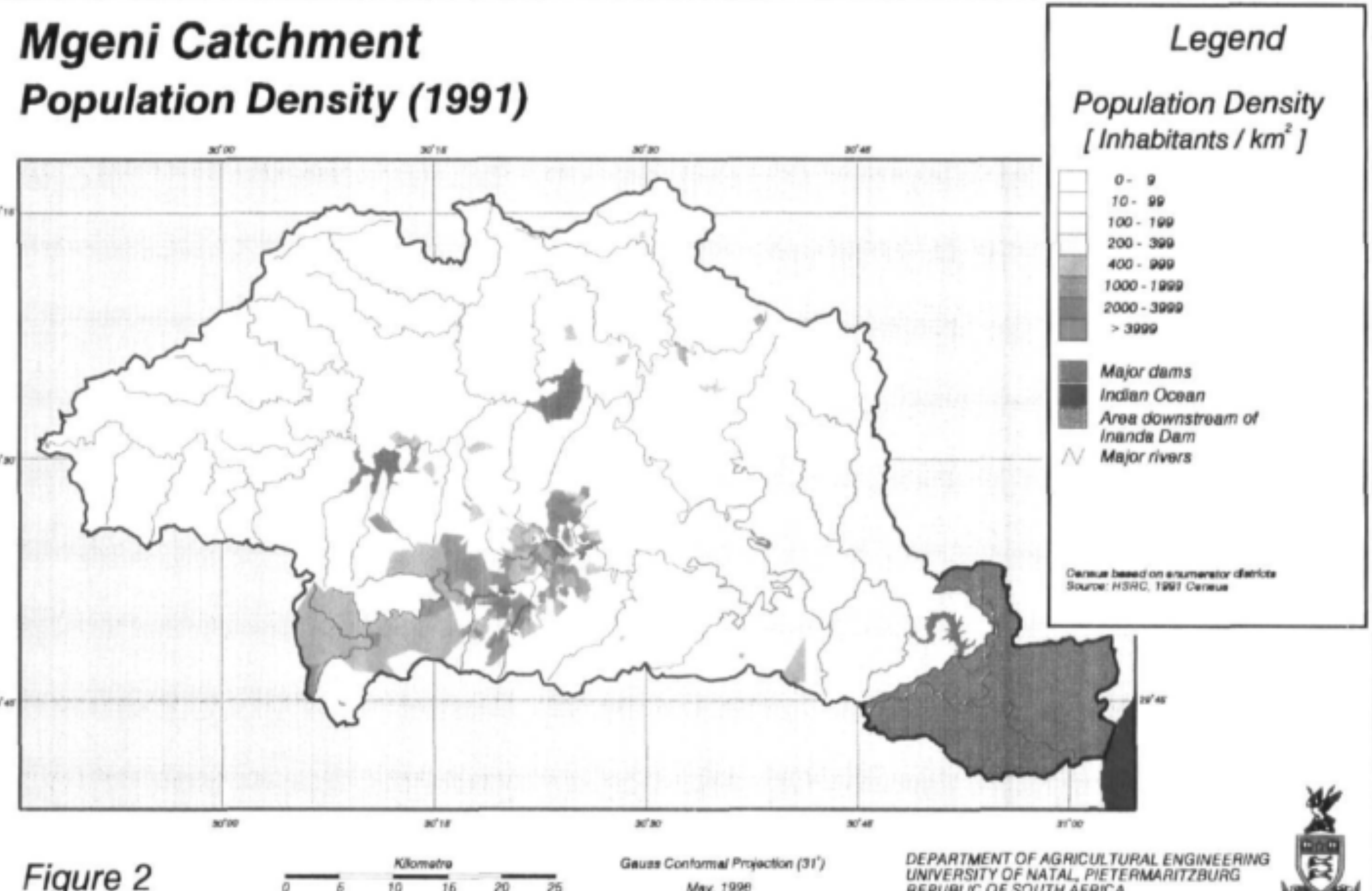

Figure 2

Gauss Conformal Projection (31°)
May, 1996

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Mgeni Catchment

Monitoring Network and ACRU Subcatchments

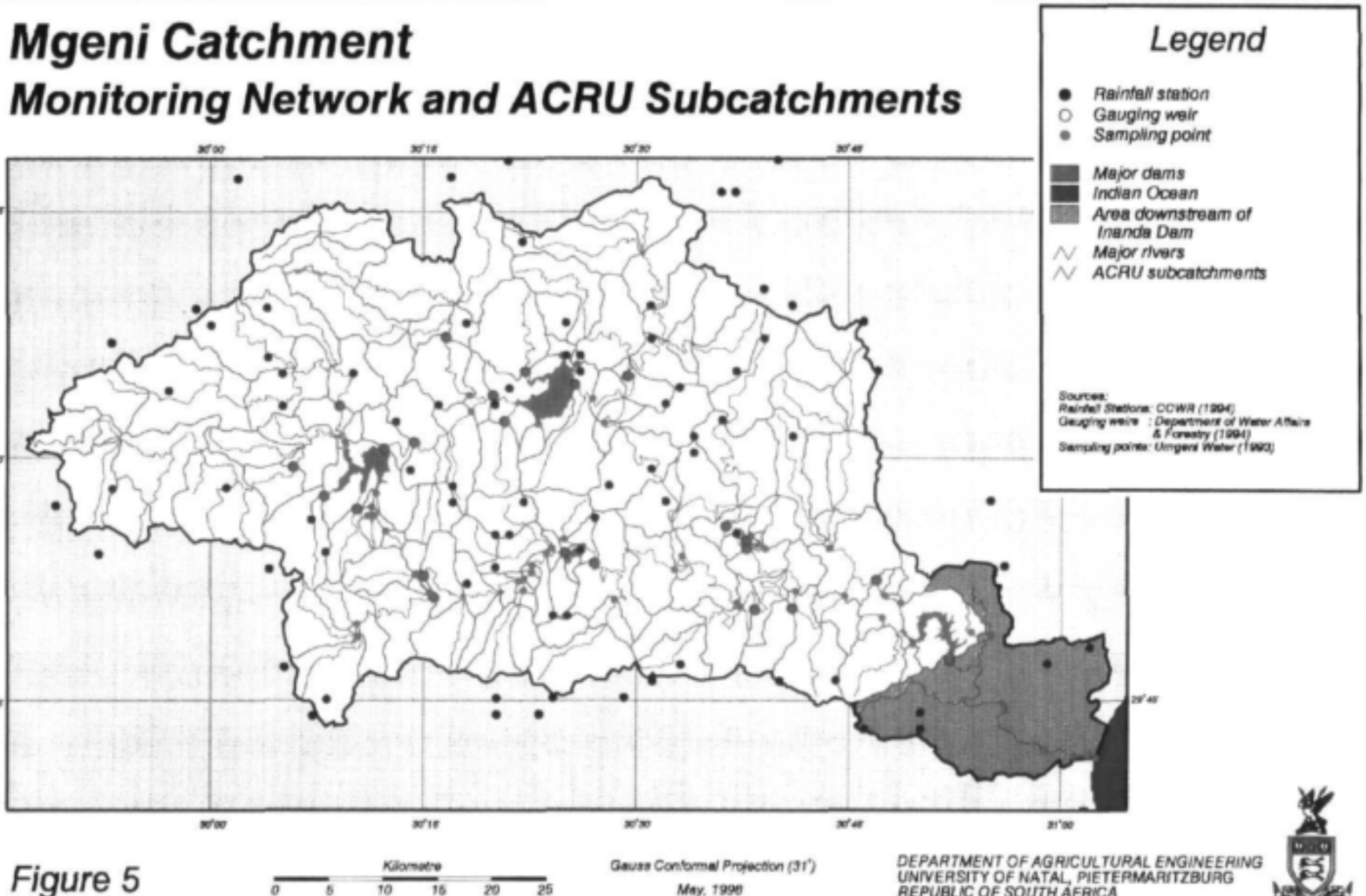

Figure 5

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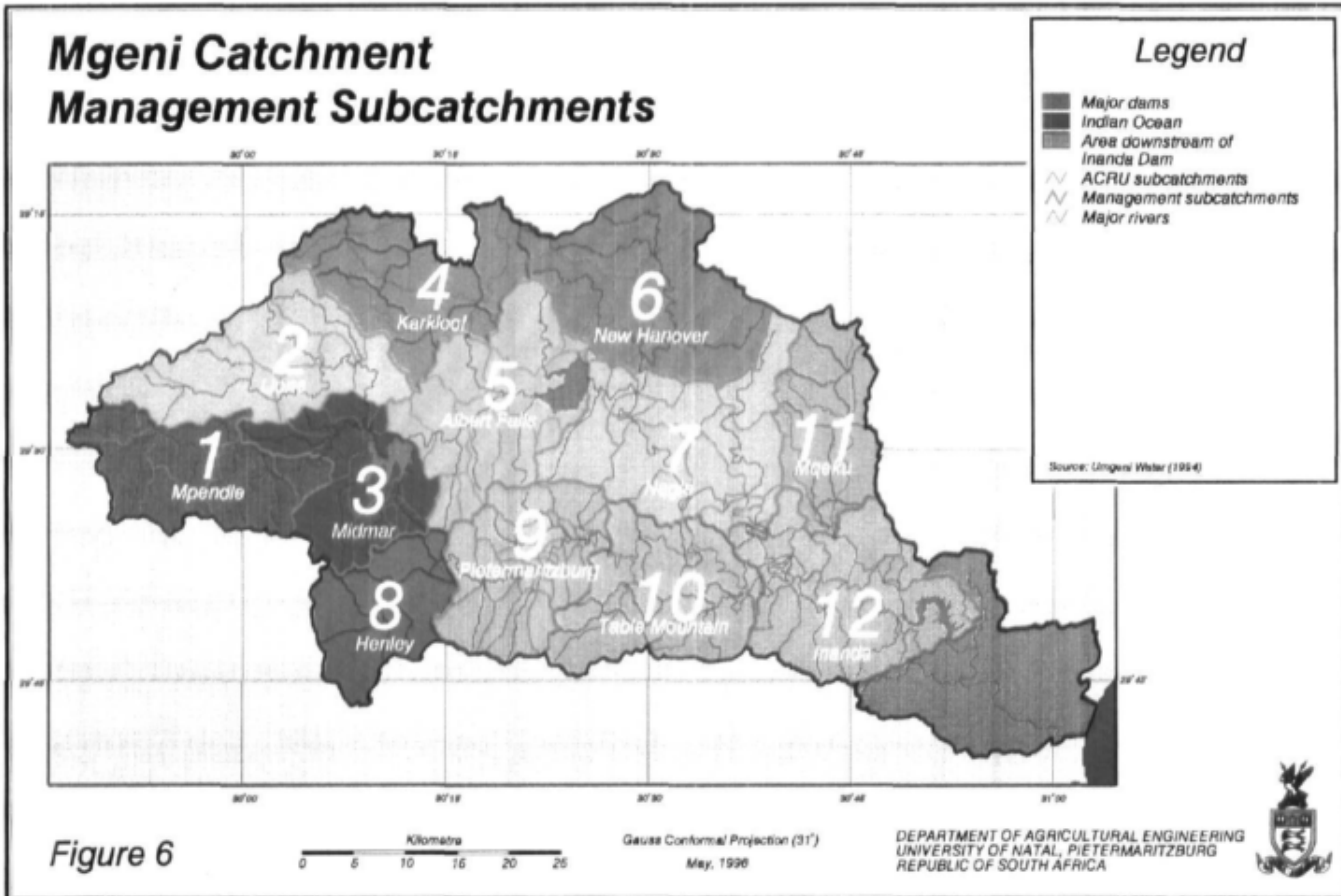

Mgeni Catchment
Management Subcatchments
Legend
Major dams
Indian Ocean
Area downstream of Inanda Dam
ACRU subcatchments
Management subcatchments
Major rivers
Source: Umgeni Water (1994)
1
Mpendle
2
3
Midmar
4
Karkloof
5
Albert Falls
6
New Hanover
7
8
Henley
9
Pietermaritzburg
10
Table Mountain
11
Mqeku
12
Inanda
Kilometre
0 5 10 15 20 25
Gauss Conformal Projection (31°)
May, 1996
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Figure 6

Mgeni Catchment
Mean Annual Precipitation per Subcatchment

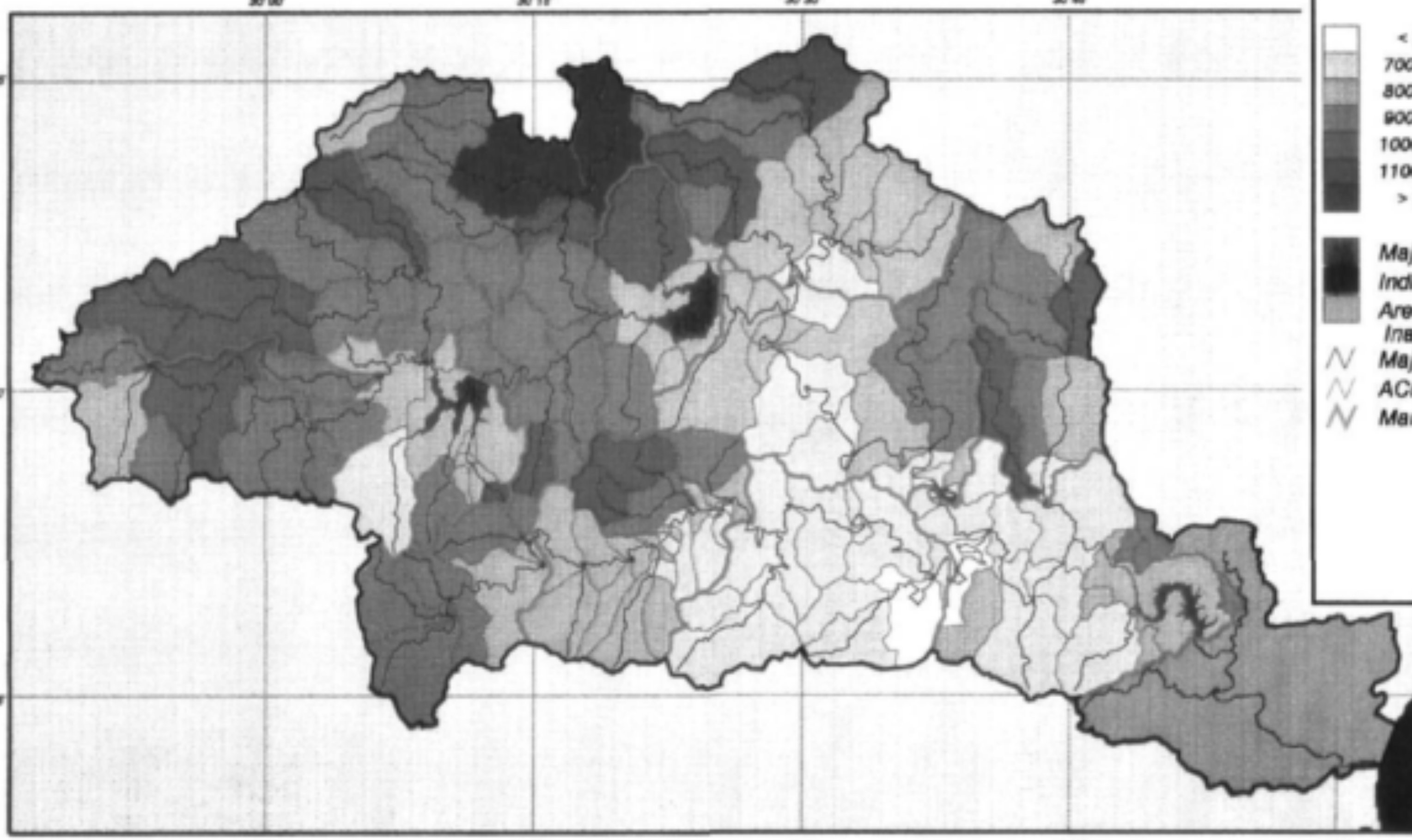

Figure 7

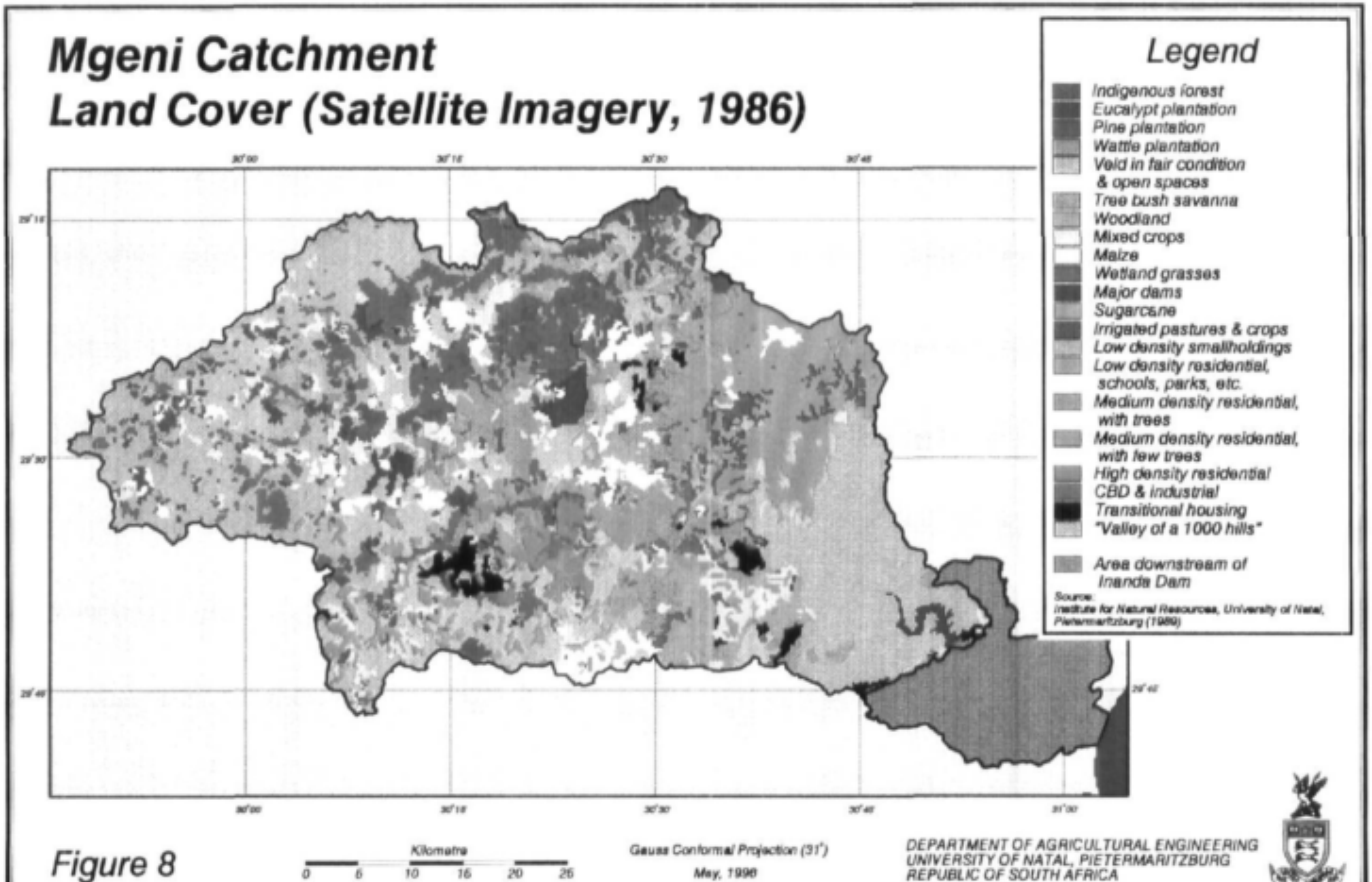

Figure 8

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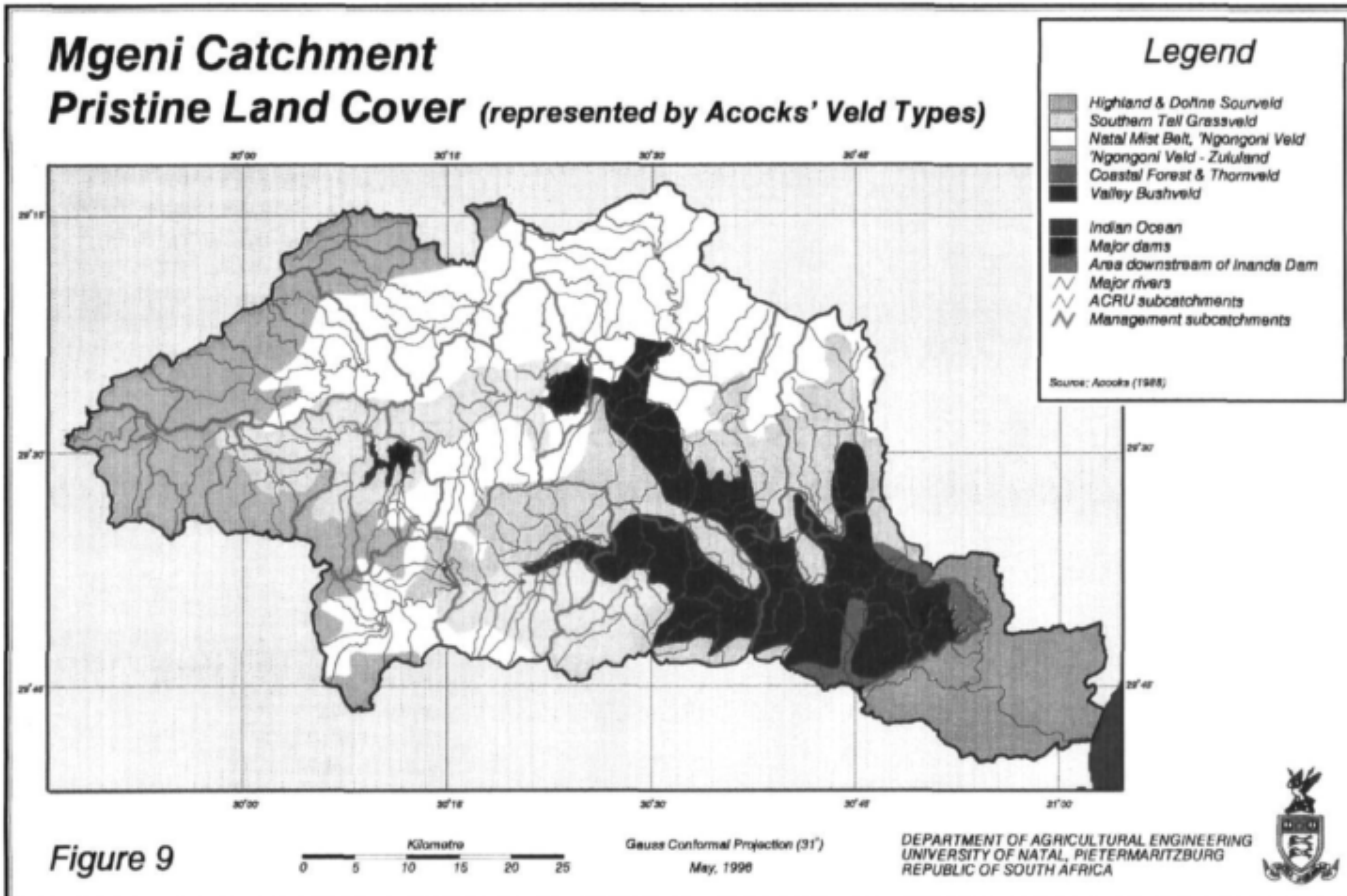
Mgeni Catchment
Pristine Land Cover (represented by Acocks' Veld Types)
Legend
Highland & Dohne Sourveld
Southern Tall Grassveld
Natal Mist Belt, 'Ngongoni Veld
'Ngongoni Veld - Zululand
Coastal Forest & Thornveld
Valley Bushveld
Indian Ocean
Major dams
Area downstream of Inanda Dam
Major rivers
ACRU subcatchments
Management subcatchments
Source: Acocks (1988)
Kilometre
0 5 10 15 20 25
Gauss Conformal Projection (31°)
May, 1996
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Figure 9

Mgeni Catchment
Distribution of Farm Dams

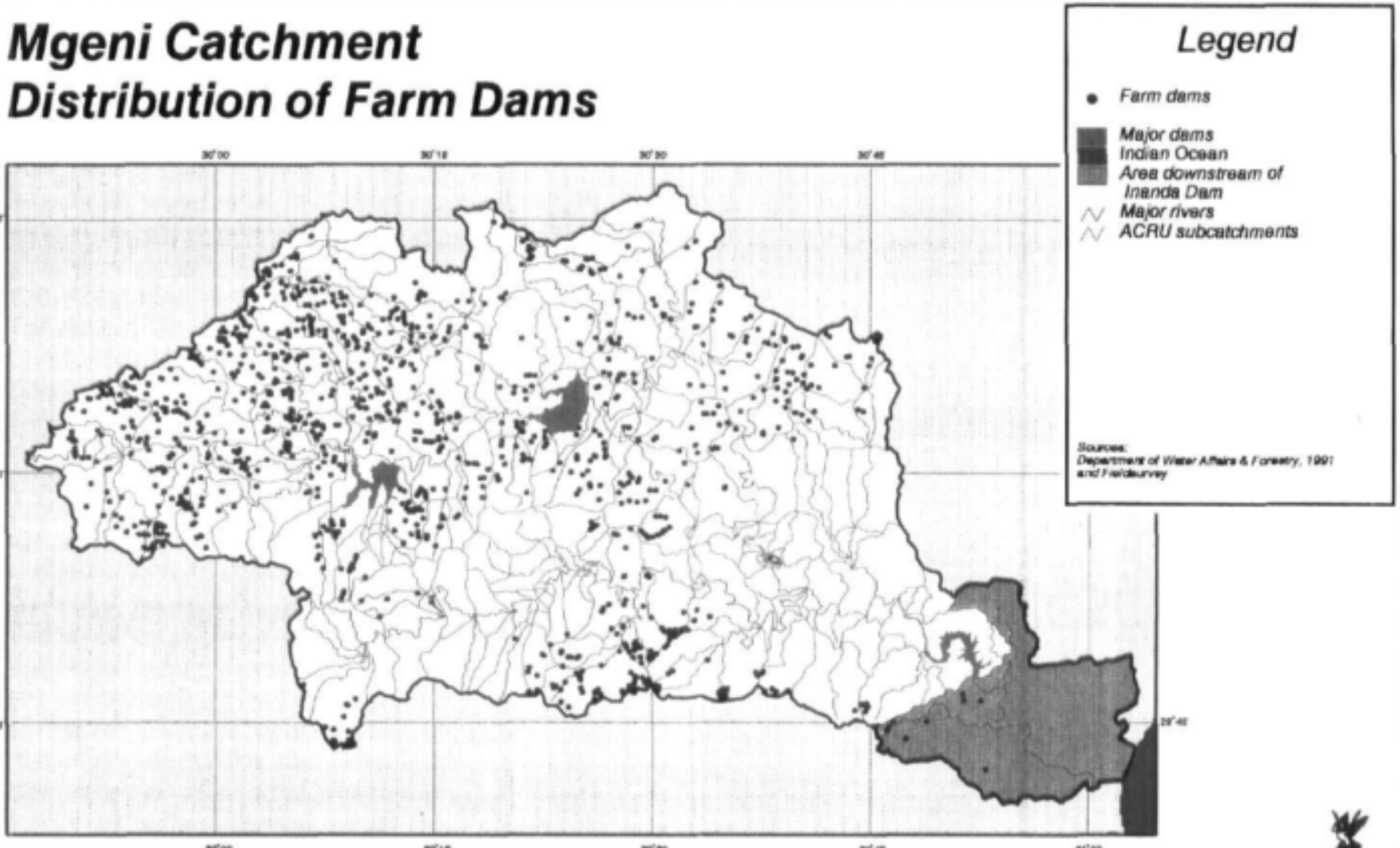

Figure 10

Kilometre
0 5 10 15 20 25

Gauss Conformal Projection (31°)
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Mgeni Catchment

Mean Annual Runoff (mm) per Subcatchment

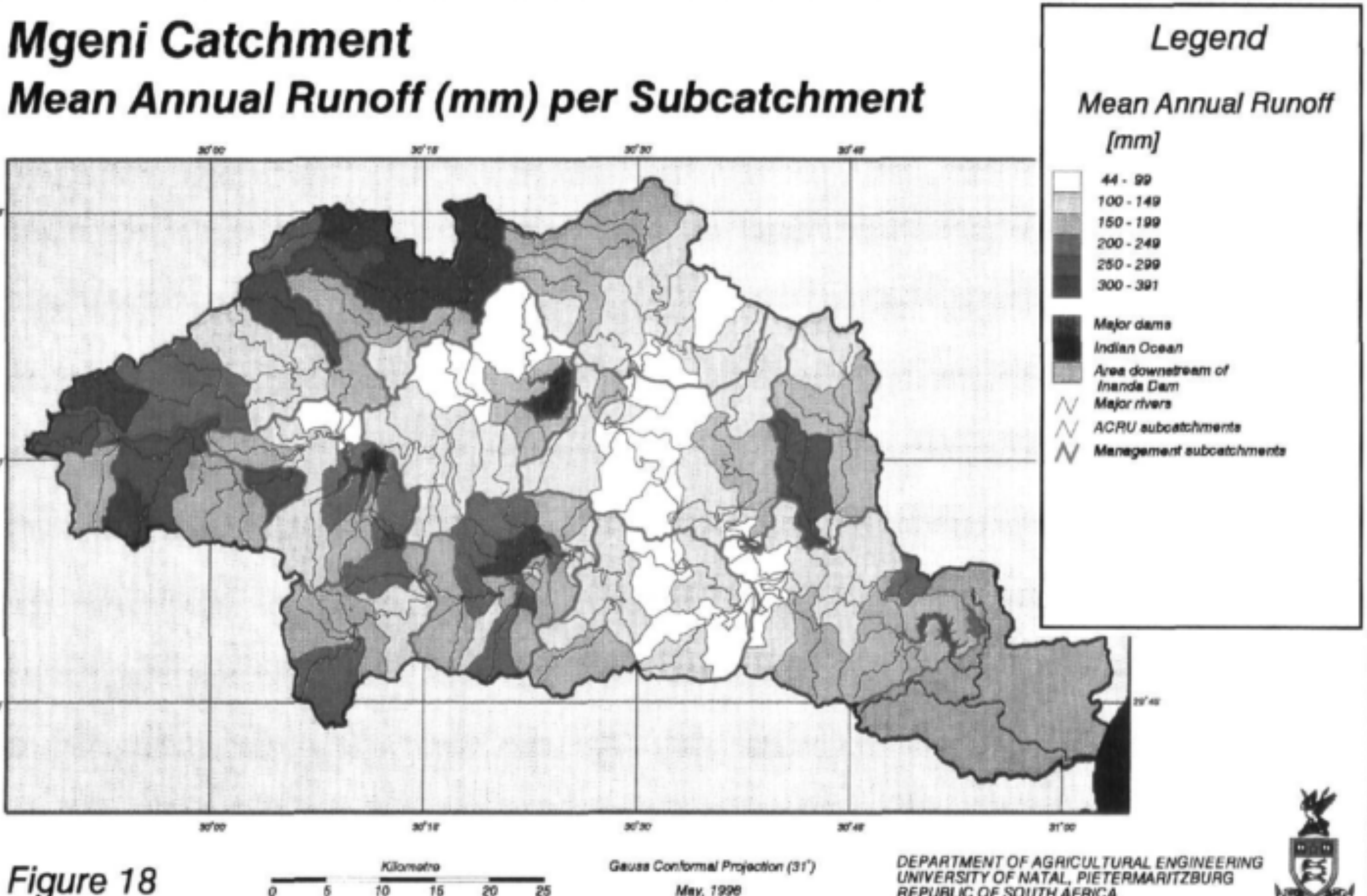

Figure 18

Gauss Conformal Projection (31°)
May, 1998

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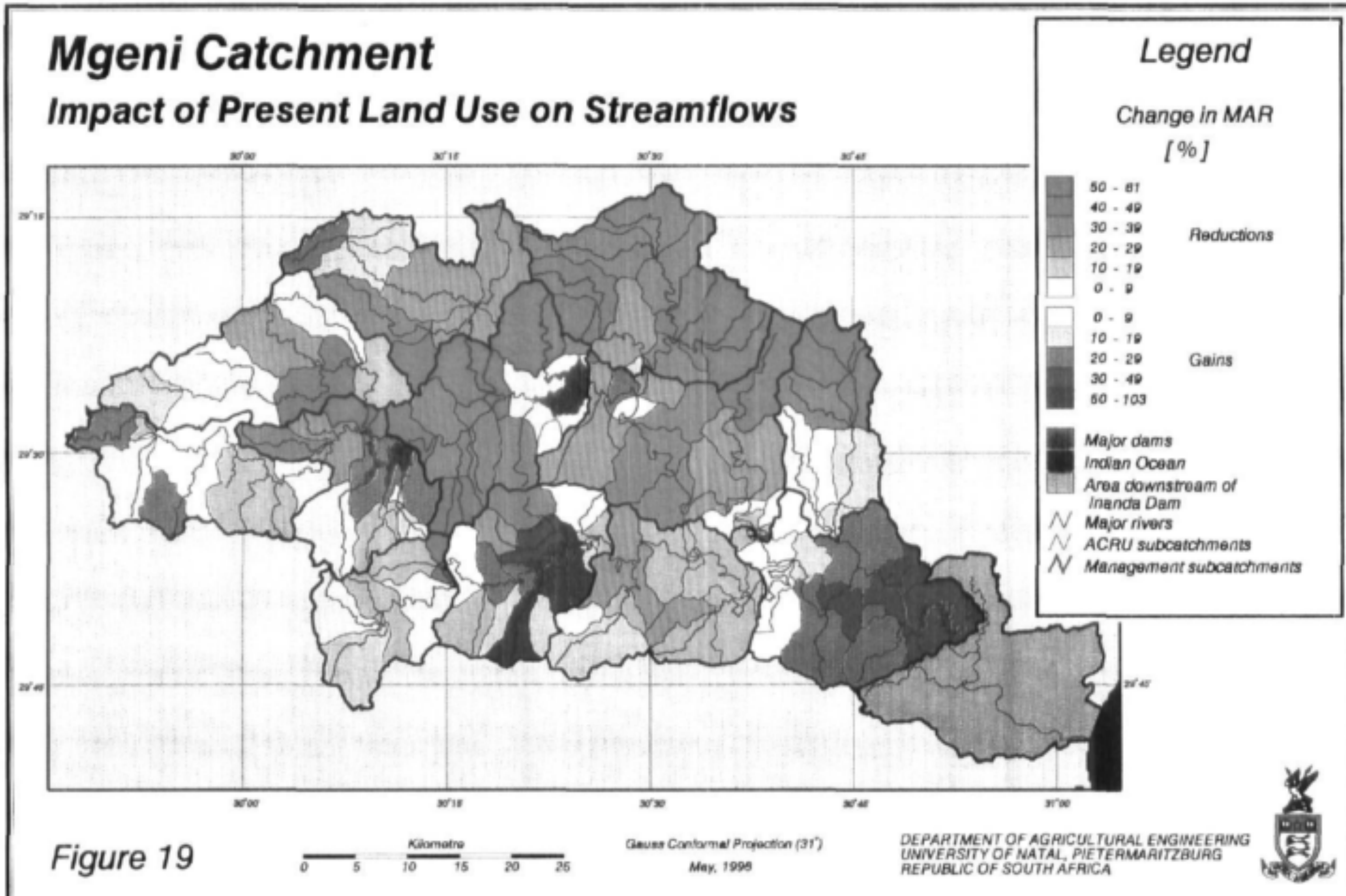
Mgeni Catchment
Impact of Present Land Use on Streamflows
Legend
Change in MAR
[%]
50 - 61
40 - 49
30 - 39
20 - 29
10 - 19
0 - 9
Reductions
0 - 9
10 - 19
20 - 29
30 - 49
50 - 103
Gains
Major dams
Indian Ocean
Area downstream of Inanda Dam
Major rivers
ACRU subcatchments
Management subcatchments
Kilometre
0 5 10 15 20 25
Gauss Conformal Projection (31°)
May, 1998
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Figure 19

Mgeni Catchment
Mean Annual Soil Loss Potential

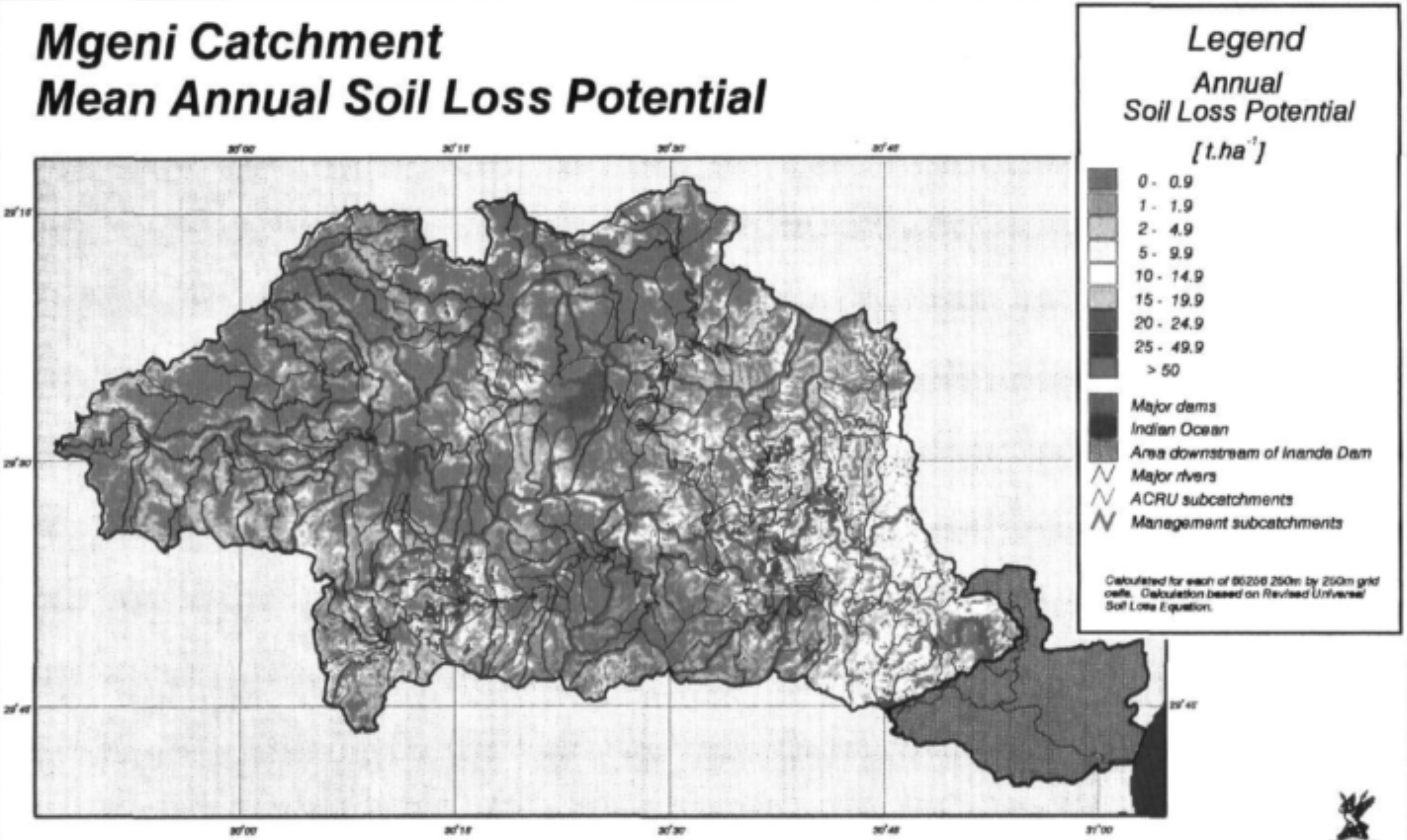

Figure 22

Gauss Conformal Projection (31°)

May, 1996

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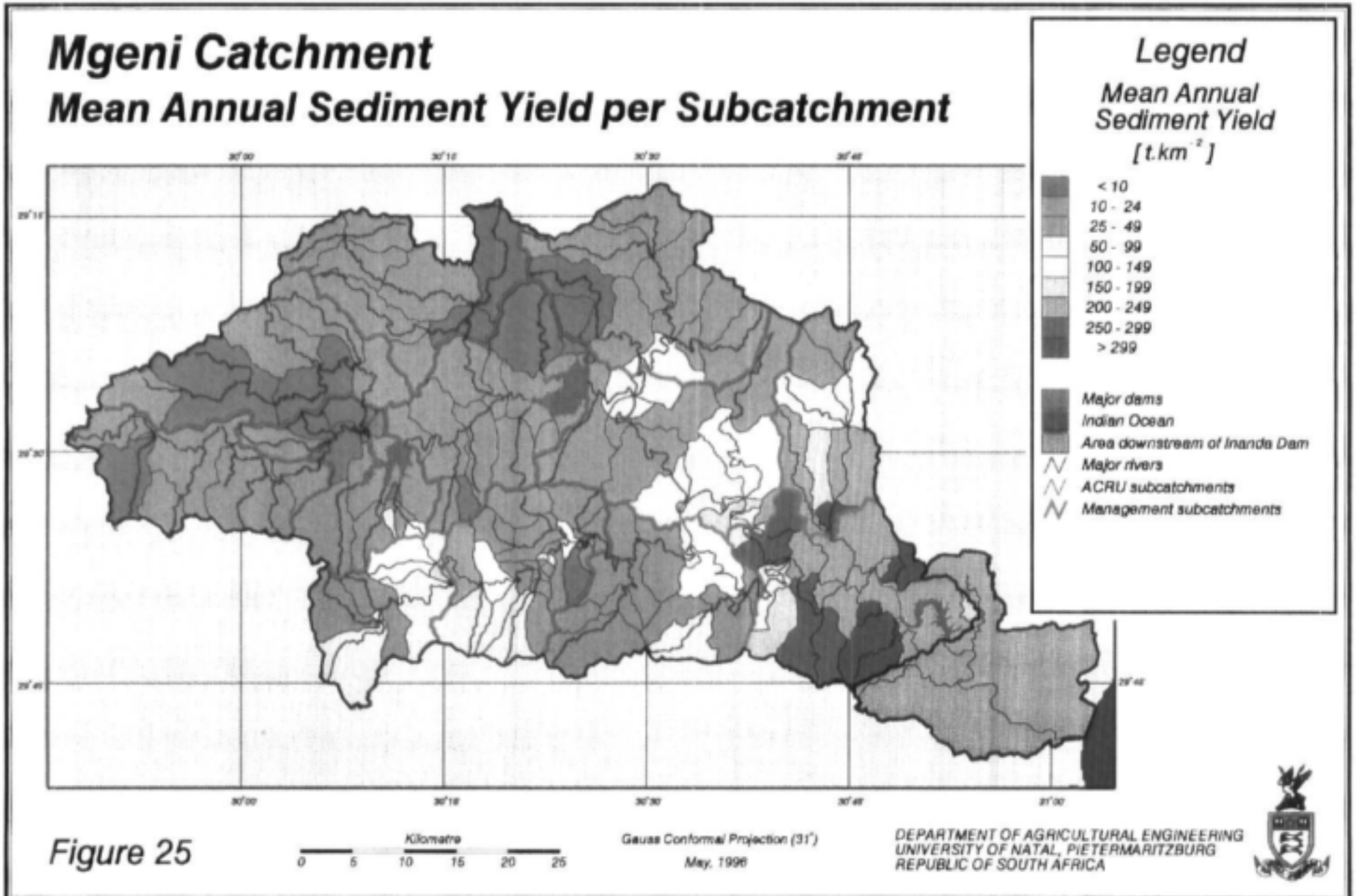
Mgeni Catchment
Mean Annual Sediment Yield per Subcatchment
Legend
Mean Annual Sediment Yield [t.km⁻²]
< 10
10 - 24
25 - 49
50 - 99
100 - 149
150 - 199
200 - 249
250 - 299
> 299
Major dams
Indian Ocean
Area downstream of Inanda Dam
Major rivers
ACRU subcatchments
Management subcatchments
Kilometre
0 5 10 15 20 25
Gauss Conformal Projection (31°)
May, 1996
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Figure 25

Mgeni Catchment
Phosphorus Pollution Potential

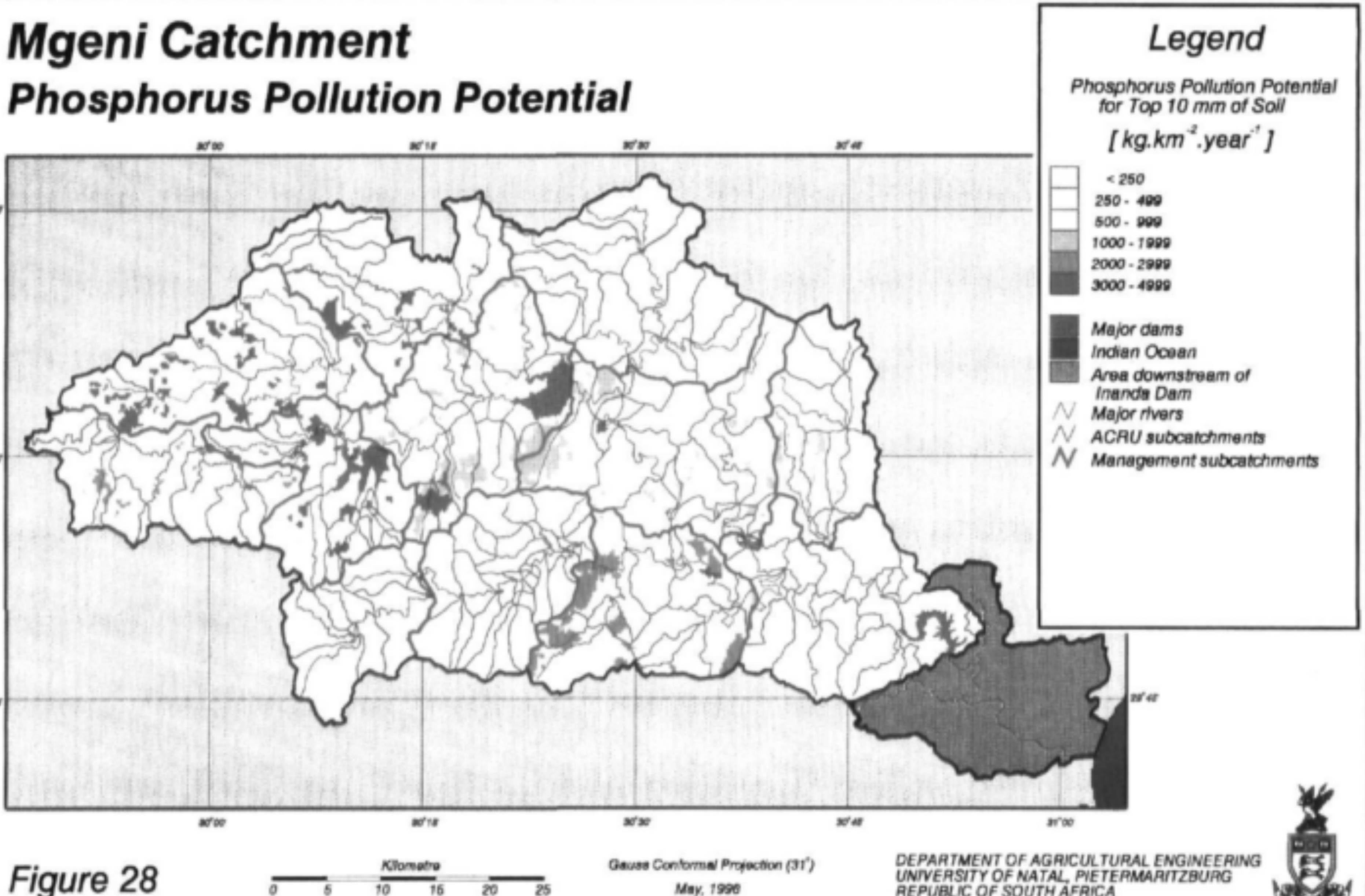

Figure 28

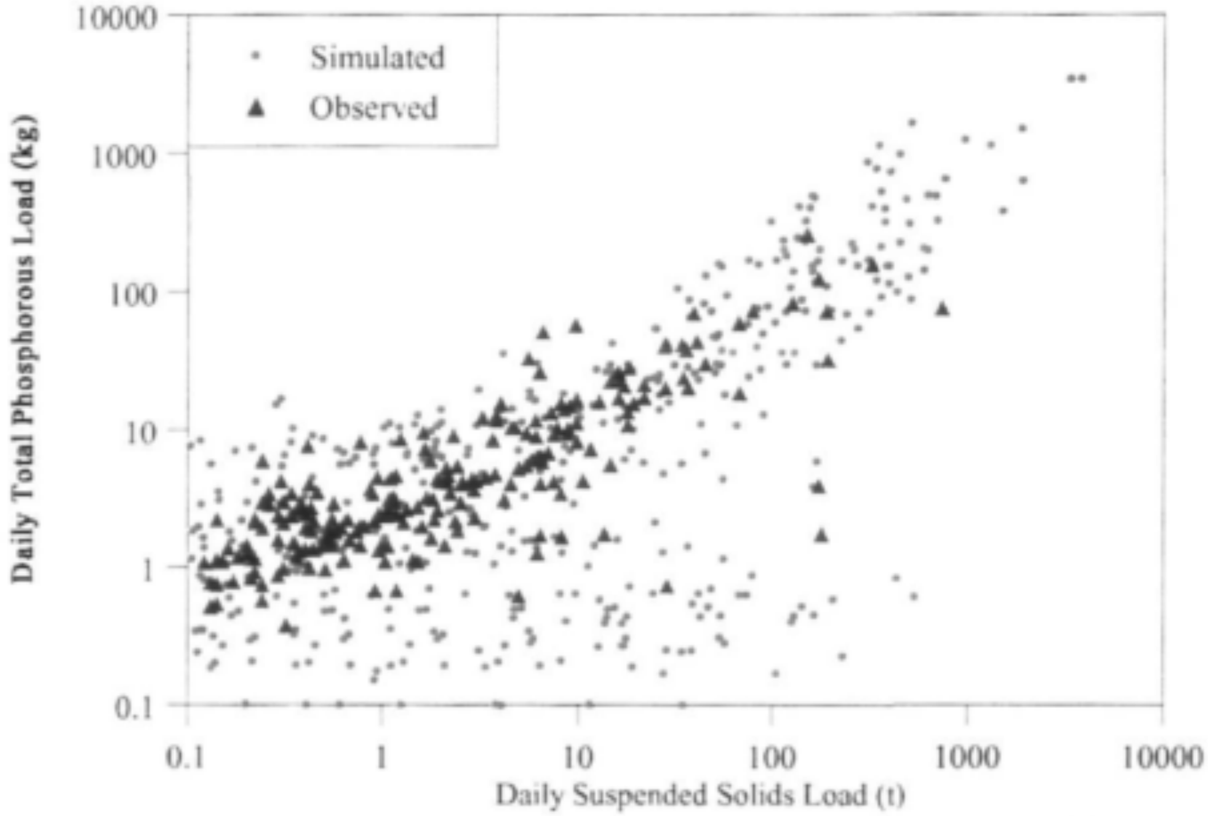

Figure 30 Simulated and observed sediment : total phosphorous load relationships for 1989 to 1993 at gauging station 57 (U2H011)

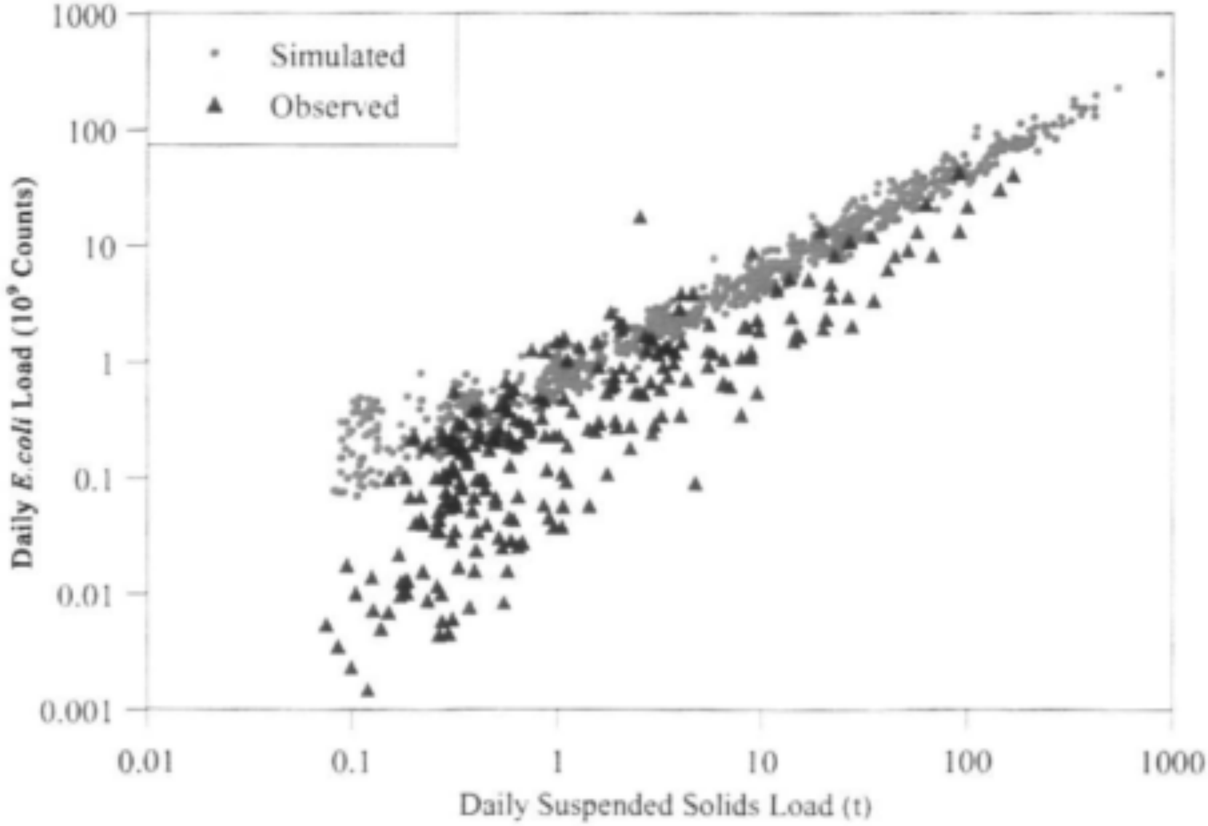

Figure 31 Simulated and observed sediment : *E.* coli load relationships for 1989 to 1993 at gauging station 5.1 (U2H006)

Mgeni Catchment

Mean Annual Phosphorus Yield per Subcatchment

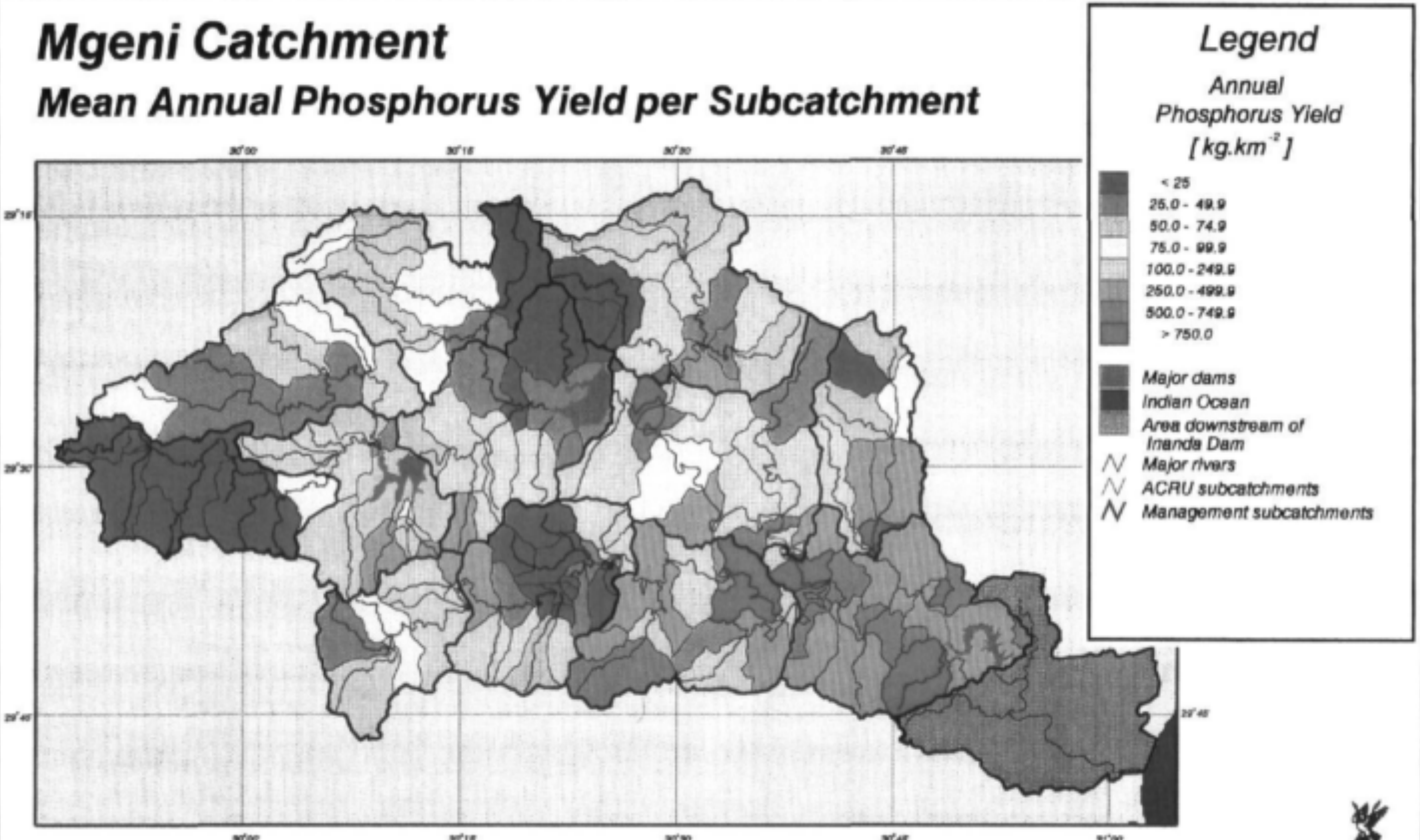

Figure 33

Kilometre
0 5 10 15 20 25

Gauss Conformal Projection (31°)
May, 1996

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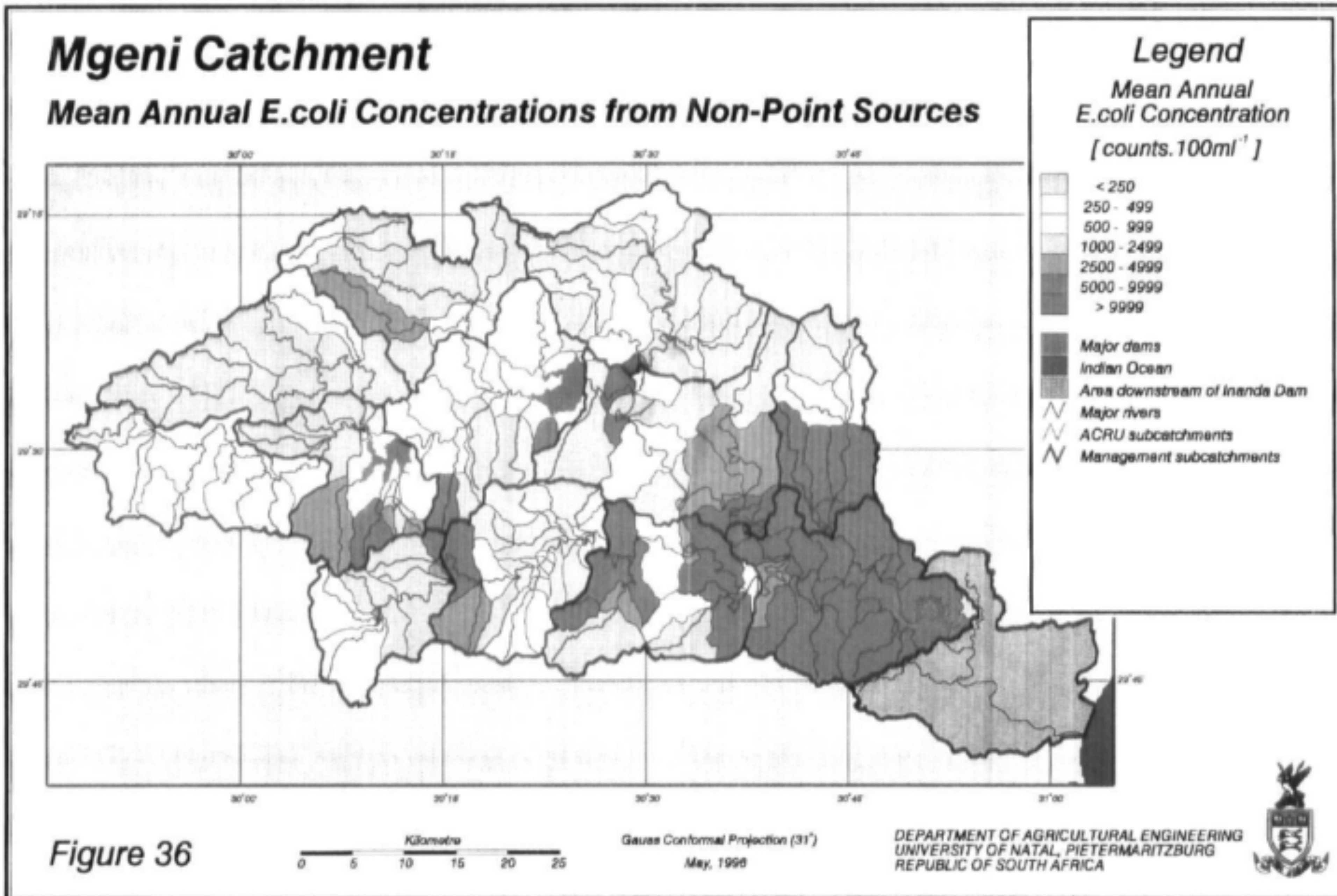
Mgeni Catchment
Mean Annual E.coli Concentrations from Non-Point Sources
Legend
Mean Annual
E.coli Concentration
[counts.100ml⁻¹]
< 250
250 - 499
500 - 999
1000 - 2499
2500 - 4999
5000 - 9999
> 9999
Major dams
Indian Ocean
Area downstream of Inanda Dam
Major rivers
ACRU subcatchments
Management subcatchments
Kilometre
0 5 10 15 20 25
Gauss Conformal Projection (31°)
May, 1996
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Figure 36