SCALE AND MODEL INTERFACES IN THE CONTEXT OF INTEGRATED WATER RESOURCES MANAGEMENT FOR THE RIVERS OF THE KRUGER NATIONAL PARK

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Report to the Water Research Commission on the Project

AN INTEGRATED MODELLING SYSTEM FOR PREDICTING THE IMPACTS OF CHANGES IN WATER QUANTITY AND QUALITY BROUGHT ABOUT BY UPSTREAM DEVELOPMENT

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EXECUTIVE SUMMARY

This document is the final report of the Water Research Commission and Kruger National Park Rivers Research Programme (KNPRRP) project entitled;

AN INTEGRATED MODELLING SYSTEM FOR PREDICTING THE IMPACTS OF CHANGES IN WATER QUANTITY AND QUALITY BROUGHT ABOUT BY UPSTREAM DEVELOPMENT

The goal of the project was to develop a computer based system in which predictive models used by different scientific disciplines involved in the Kruger National Park Rivers Research Programme could be integrated.

The Kruger national Park is dependent upon several rivers for it's water supply, all of which rise outside of the Park's borders. Increasing development demands on these rivers has affected water quality and quantity in the KNP rivers and is placing its aquatic ecosystems under threat. Consequently, the project focused on the linking of models predicting changes in catchment hydrology, sedimentation and geomorphology to fish response in the Sabie River, one of the KNP's most important rivers. Model development has required successful interdisciplinary collaboration between scientists from hydrological, geomorphological and ecological disciplines and subsequent integration of their knowledge in the form of a suite of computer based predictive models.

The suite of models is structured to facilitate understanding of the systems under consideration rather than too produce definitive solutions. As such, they form an important means of communication between scientists and managers alike. Furthermore, it is envisaged that such an integrated system could become a useful to catchment planners and managers from whom decisions are required in the context of Integrated Catchment Management (ICM).

The final product of the project is an integrated system in which an hydrology model and three Qualitative Rule Based Models (QRBMs), known as the Abiotic-Biotic link (BLINK) models, which describe the geomorphic function, riparian vegetation and fish response of the Sabie River, are integrated with other catchment information within an Integrated Catchment Information System (ICIS). The critical problems faced in the course of the project were issues of modelling (prediction), scale and interdisciplinary collaboration.

The stated aims of the project were to:

i) Integrate existing predictive capabilities in hydrology, hydraulics, sediment production and transport, water quality, channel morphology and ecological functioning to form a modelling system appropriate to the aims of the KNPRRP.

ii) Test and refine this modelling system in a case study on the Sabie River.

iii) Demonstrate the utility of such a modelling system in a multi-criteria decision support role in a case study on the Sabie River, linking "what-if" catchment development scenarios to protocols for evaluating the acceptability of predicted changes.

iv) Formulate the operational framework for transfer of the modelling system to other KNP rivers.

During the course of the project, aims i) to iii) were all satisfied to a lesser or greater extent. Aim iv), however, did not receive attention due to the additional work load that the Abiotic-Biotic Links Project, described in Section 7 below, carried by the project team.

A brief summary of the report follows.

1. INTRODUCTION

The development of models, which provide the ability to predict responses to different development scenarios, is required to provide managers, and stakeholders alike, with some means of assessing the impact of potential change on a component of a natural system. The development of such systems has been the focus of many research programmes world-wide.

The Kruger National Park Rivers Research Programme (KNPRRP) is one such programme. The research reported in this document was performed under the auspices of the KNPRRP using the Sabie River, one of six important rivers flowing through the Kruger National Park (KNP), as the pilot study area. Much of the research in KNPRRP has focused on the flow requirements of aquatic ecosystems, in particular fish and riparian vegetation, the effect that changing hydrology and geomorphology have on them and the development of models to predict this response. A great challenge lies in linking these models to the complex interrelationships between abiotic (physical/chemical) and biotic (biological), processes.

2. INTEGRATED CATCHMENT MANAGEMENT AND THE KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

INTEGRATED CATCHMENT MANAGEMENT IN A SOUTH AFRICAN CONTEXT

The concept of a catchment as a basic management unit, implies certain geographical characteristics, such as topography, that delimit the area not only with respect to water, but also with respect to other media flows, such as energy, material and information. The flow of water serves as an indicator of the relief and landscape characteristics, on the one hand, and as an integrator of many of the processes occurring within the catchment, on the other.

Although the ultimate goal is ICM, it is recognised that catchment management in South Africa's immediate future will comprise mutual and sensitive dependence of water, land-use and aquatic ecology management, but with incomplete integration of natural resource management. River Management, Catchment Management, Integrated Water Resources Management and Integrated Catchment Management can be viewed as a hierarchy, the ultimate goal of which is to achieve Integrated Resource Management.

To support this sort of decision making process, methods of objectively quantifying responses of various resources to catchment planning scenarios are sought. The tools developed within the KNPRRP focus on the identification of the system characteristics and prediction of the behaviour of certain components, in the belief that they will be of assistance in the final step of management of the system.

THE KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

The KNPRRP embraces an ecosystem approach to river management. Streamflow forms the major connecting link between the various catchment components. Water, both its quality and quantity, is the common concern in all the disciplines involved in KNPRRP.

In Phase II of its development, the KNPRRP undertook to develop the necessary "*understanding of principles and methodologies required for effective management of our river systems*". It undertook to do this by attempting to "*develop, test and refine methods for predicting the responses of natural environments of rivers flowing through the Kruger National Park and in southern Africa to changing water quality and patterns of supply*".

ISSUES ARISING FROM AN INTEGRATED APPROACH TO CATCHMENT MANAGEMENT RELEVANT TO THE KNPRRP

The concept of ICM raises many issues, both technical and philosophical. These include;

Interdisciplinary Research

The holistic view of a catchment offered by ICM necessitates an interdisciplinary approach to the development of tools which may be of benefit to its implementation. Interdisciplinary research has the potential to produce results that exceed the sum of incremental disciplinary contributions, as more holistic understandings can emerge from such research. Furthermore, major environmental problems may arise from obscure interactions that would not be recognised without an interdisciplinary analysis.

Linking Abiotic and Biotic Components of Catchments

An ecosystem approach to catchment management implies that meaningful cognisance of biotic components of the system, and the abiotic influences upon these, must be made.

Issues of Integration of Models and Modelling Tools

It has been recognised by many researchers that full analysis of many problems faced in the course of water resources management requires an extensive set of capabilities. Most people involved in water resources simulation and management programmes have found that these exercises involve the use of a great many tools, and different data and information formats.

Scale Issues

The essence of environmental sciences consists of dealing with nested systems across spatial and temporal scales and the linkages and intricacies among and between the various components. The issue of scale has been identified as an important issue in each of the scientific disciplines directly involved in the KNPRRP, viz. ecology, geomorphology and hydrology, as has the problem of the "management scale", the spatial and temporal scale at which managers are most comfortable making decisions or which is the current practical limit of management effectiveness.

3. SCALE ISSUES AND THEIR SIGNIFICANCE IN THE DEVELOPMENT OF AN INTEGRATED CATCHMENT INFORMATION SYSTEM

Much of the lack of progress in resolving scale issues can be attributed to confusing terminology and inconsistent use of scale-related concepts. In this chapter, the terminology pertaining to scale, especially with regard to components that are affected in an interdisciplinary exercise such as the KNPRRP, is clarified, some effects of scale are identified and some common methods of accommodating scale issues are described.

WHAT IS SCALE

This section includes the definition of scale in terms of process scale, observation scale, operational scale and management scale. For the purposes of this document, scale is something that "pertains to size in both time and space" and to "the spatial or temporal dimension of an object or process, characterised by both grain and extent". The term "grain" usually refers to the size of the individual units of observation and "extent" to the total area or time covered by a study.

EFFECTS OF SCALE

Some examples of the effect of scale are presented. Heterogeneity and variability are two aspects closely related to and influenced by scale. The term "heterogeneity" is most often used to describe properties which vary with space (e.g. soil characteristics over a catchment), while "variability" is usually used to describe fluxes (e.g. runoff) or state variables (e.g. soil moisture) that vary in space and/or time.

The ease with which the response of a system may be estimated is commonly referred to as the predictability of that system. Predictability is inextricably intertwined with variability, and with the temporal and spatial scales of interest

Generalisations across spatial scales and units of aggregation may generate various types of errors and these are discussed.

A number of methods have been used to resolve problems arising from issues of scale in environmental systems. These include hierarchies, various scaling rules and laws, the use of representative units and GIS

4. MODELS AS TOOLS TO ASSIST INTEGRATED CATCHMENT MANAGEMENT

In this chapter, the significant role of simulation models, both as decision support tools, and as aids to effective communication between scientists is discussed.

A model is effectively a simplified representation of some part of the real world. A model predicts effects from causes. Any description of the causes and effects in a system by means of symbolic logic can be considered to be a model of that system.

TYPES OF MODELS AND MODELLING TERMINOLOGY

Typically, models are divided into deterministic and stochastic sub-categories. Essentially, the differentiation between classes of deterministic models is one based on the level of complexity used to represent the real world process to be simulated. This ranges from the complex mathematics of partial differential equations (PDE) to the simple IF-THEN rules included in what are known as qualitative rule-based models (QRBMs).

Models can also be classified as discrete or continuous. Discrete models are those that do not specifically account for time. Continuous or dynamic models are those that accommodate changes with time and often reflect an average response to average inputs and conditions. Models may also be referred to as distributed or lumped parameter models.

There are instances where the intricate and complex nature of the process may defy manageable mathematical description. In these cases, qualitative models may be formulated. The simplest form of a qualitative model is the "rule-based" model. In recognition of this qualitative way of handling relationships between variables, this approach has become known as Qualitative Rule Based Modelling and the models developed are known as Qualitative Rule Based Models (QRBM).

MODELS AS INTEGRATIVE COMMUNICATION TOOLS

The integrative power of model development has often been noted. The model development work presented in this document is based on the following recognition: That, in order to adequately tap into the level of scientific understanding of the different disciplines involved in the development of computer models to simulate biotic responses to abiotic processes, the models need to be easy to use, and should be engageable by participants with limited modelling experience, and should have an interface accessible to water resources managers.

MODEL INTEGRATION

It is recognised that in order for an integrated modelling system to adequately represent catchment components and processes, it must include an integrated suite of simulation models which represent these. The term "model integration" is often misunderstood. In this document, "model integration" is used as a generic term for linking models by both simple and complex means.

Models can be integrated either in series or in parallel. Series type integration is most common and involves taking the output from one model and using it as input for the next once the first model has completed its run. Parallel linking of models or model components involves using, in the same time step, the output from one component as input to the next and thus has the potential to accommodate feedback between the models.

ACCOMMODATING MULTIPLE SPATIAL SCALES AND ASYNCHRONOUS TIMING IN MODELS

A modelling system that is both able to integrate a variety of models, and provide useful management information must be able to operate at asynchronous time steps, and at multiple spatial scales.

In the KNPRRP, it was accepted that methods for matching these apparently disparate spatial scales in modelling are needed. It should be noted that serial integration, may provide a practical method of scaling smaller spatial scale models to accept input from larger systems.

5. AN INTEGRATED CATCHMENT INFORMATION SYSTEM

It has been recognised by many practitioners that full analysis of the many catchment problems faced by those attempting ICM requires an extensive set of capabilities. Computer based information systems in which the tools representing these capabilities are integrated to provide decision support to managers and stakeholders, play an increasingly important role in ICM initiatives, both internationally and locally.

Decision Support Systems (DSS) in this context are software systems that facilitate such management through integration of three types of information;

i) information on the state of the environmental system (in the case of ICM, the catchment),

ii) modelling (simulation) of the system, and

iii) evaluation of different scenarios/plans.

A number of local and internationally available DSSs were reviewed and decision to further develop a local system known as WDMGuide was taken. The system became known the Sabie Integrated Catchment Information System. ICIS is effectively part of a decision support system that makes use of ARCVIEW and a range of other software on a PC and larger host computers at remote sites. The ICIS is not a static system, but one which is under constant development. This is in line with the evolving needs of the user community who are intimately involved in its use and feedback as its development progresses.

6. THE SABIE RIVER CATCHMENT

PHYSICAL CHARACTERISTICS OF THE SABIE RIVER CATCHMENT

The Sabie River drains a catchment area of over 6000km2 at the international border between South Africa and Mozambique on the eastern boundary of the Kruger National Park. The river flows throughout the year and is fed by two major tributaries in the Lowveld zone, viz., the perennial Marite River and the seasonal Sand River.

Vegetation and landuse are varied, with much of the upper reaches of the catchment afforested with exotic tree species. Large-scale irrigation, chiefly of citrus crops, is found in the mid-regions of the catchment. The catchment also contains six game or nature reserves, several small towns and a number of rural settlements.

Flow in the Sabie River is subject to discharge extremes similar to other semi-arid systems in the area. The Sand River contributes significant amounts of sediment to the Sabie River. The Sabie River Catchment is typical of many in South Africa in that the quality of available

CATCHMENT MANAGEMENT ISSUES IN THE SABIE CATCHMENT

Catchment management has been identified as an important need in all of the rivers of the KNP, however, it is generally felt that it is in the Sabie-Sand system that this is most critical. The Sabie catchment is unique in that it has no serious water quality problems, and it is, prior to the construction of the Injaka Dam, the only perennial river, of the six flowing through the KNP, that is unregulated by any dam.

It has been recognised in the KNPRRP that over 90% of the water flowing through the park rises in the catchments to the west of the reserve and that it is imperative to develop modelling systems to aid in understanding the hydrological system dynamics outside of, as well as inside the KNP. The KNPRRP has also recognised that the management of the environmental reserve is going to require ongoing and dynamic systems to assist the process of day-to-day management of the river systems in the catchment and the conflicts that will inevitably arise over environmental allocations of water.

7. PREDICTIVE MODELS IN THE SABIE RIVER CATCHMENT

REQUIREMENTS OF A MODELLING SYSTEM FOR THE KNPRRP

Given the dependence of aquatic habitat on flow and sediment conditions, the simulation of catchment hydrology and sediment production on a daily basis were considered critical to the success of the project. Thus, the required modelling system should include robust physically meaningful hydrological modules to provide information for all other predictive models incorporated in the system.

REVIEW OF AVAILABLE CATCHMENT HYDROLOGY MODELS

The following hydrology models, readily available in South Africa and which operate on a daily or finer time step, were considered for use in the KNPRRP: ACRU, HSPF and VTI

Simulation of water quality outputs from the surface area of the catchment, in particular sediment, is a major function of this project. The ACRU model has the ability to generate daily sediment output and is therefore preferred to the VTI model. One of the HSPF model developers, Prof. R. Johannson (pers. comm., 1995) suggested that runoff components, such as quickflow, baseflow, etc. simulated by ACRU, could be used to "drive" water quality simulations in HSPF. A demonstration in this regard has been completed by Van Rensburg and Dent (1997).

Given the apparent unavailability of an appropriate integrated modelling system from international sources, and following the potential benefits of an ACRU-HSPF link evident in the implementation of the HSPF model by Van Rensburg and Dent (1997), and especially in the light of the support of the HSPF model offered by the CCWR, an ACRU-HSPF linkage for the KNPRRP was accepted by the Project Management and Development Committee. The focus of this integration is the interface between catchment and river channel, with ACRU simulating the land surface processes, and HSPF the in-channel hydraulic and water quality processes.

IMPLEMENTATION OF AN ACRU-HSPF LINK IN THE SABIE RIVER

The ACRU model was used to simulate the catchment hydrology for the period 1937 to 1995 inclusive. Due to a lack of data, the channel hydraulics were only simulated for the period 1967 to 1995 with HSPF.

Hydrological simulations of surface runoff and sediment yield were performed by the School of Bioresources Engineering and Environmental Hydrology and are fully reported by Pike *et al.*, 1997, reproduced in this document as Appendix I.

The link between ACRU and HSPF is made in series. Daily streamflow and sediment values computed at each subcatchment are produced by the ACRU model in it's native binary time series storage format and then converted into the WDM format for use by HSPF. A HSPF User Control Input (UCI) file was then created for the HSPF components of the simulation. A reach of river was established for each of the 56 ACRU subcatchments to represent the channel component of each subcatchment.

The HSPF model was used to simulate hydraulic properties of the river represented by the reaches as well water temperature and the transport of sediment in each reach.

Simulation Results

Only occasional water temperature readings are available from the DWAFs national water quality monitoring database and therefore, the temperature simulation cannot be verified. However, typical results of the water temperature simulation are judged to be poor as large and rapid fluctuations in water temperature associated with flow variability are simulated.

No time series of sediment data is available for calibration of the HSPF simulations. As expected, there is a strong relationship between streamflow and estimated sediment transport through the reaches. The ACRU-HSPF link does seem to fulfil the requirement of routing peripheral ACRU generated sediment input downstream.

Issues and Concerns

Despite the many apparent merits of linking two models so that the best features of either serve the objective at hand, it remains somewhat of a "forced marriage". Consequently, the simulation represents a river that is "Sabie-like" in many respects, but cannot be considered a true representation of the Sabie River.

It is recommended that future linkages of hydrology and hydraulic components of models follow the embedded option described in Chapter 4 and that a single appropriate hydrodynamic component is included in the ACRU model by its developers. Alternatively, where suitable input and calibration data are available, the HSPF model could be used in its entirety, but there seems to be little advantage in pursuing an ACRU-HSPF serial link any further for the Sabie River.

THE BLINK MODELS

QRBMs representing the change in geomorphology, riparian vegetation and fish of the Sabie River have been developed and are driven by input simulated by the ACRU model. These models form an important component of the Integrated Modelling System and their development is described in detail by Jewitt *et al.* (1998).

PRESENTATION OF MODEL OUTPUT AND MODEL VERIFICATION

The models are all operated from the Sabie ICIS. Several new tools for the display and presentation of data in colourful, user-friendly format were developed during the course of the project.

8. RESOLVING SCALE AND INTEGRATION ISSUES IN MODEL DEVELOPMENT FOR THE KNPRRP

MODEL INTEGRATION

The models developed in the Abiotic-Biotic links project have become known as the **B**iotic **LINK** or BLINK models. With the addition of the ACRU, VTI and HSPF model output, these models form an Integrated Modelling System for the Sabie River.

Integration of the models into the KNPRRP ICIS follows a combination of the series and parallel linking methods.

RESOLVING SCALE ISSUES IN THE BLINK MODELS

All of these models focus on a sacrifice of detail in order to reveal broader scale spatial and temporal ecological patterns. The broad operational scales used have been selected to optimally integrate the various process and observation scales involved. Therefore, much of the work done in this project involves the development of methodologies to scale up information from the observation scale to the operational scales selected for the purposes of modelling.

The modelling system utilises the concepts of "discrete event analysis" and "asynchronous timing", in order to adequately accommodate the complexities of the models as no single temporal scale is appropriate.

In addition, the models used and developed in this project effectively act as mechanisms for scaling the information they assimilate in different directions, both spatially and temporally.

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The modelling system developed in this project incorporates both "traditional" rainfall-runoff modelling techniques, in the form of the ACRU, VTI and HSPF models and knowledge based systems represented by the fish, geomorphology and riparian vegetation models. These have been integrated into a single modelling system forming part of the KNPRRP ICIS.

A number of difficulties have been encountered with the use of the large multi-component models in this project, both HSPF and to a lesser extent ACRU. These difficulties may arise as a result of using large complex modelling systems as interdisciplinary communication tools (Section 4.2), in trying to obtain adequate data to implement and calibrate them (Section 7.2) and finally in the procedures related to linking them.

RECOMMENDATIONS

It is recommended that future integrated catchment modelling exercises adopt the idea of a core catchment hydrology model with basic water quality functions, which may be coupled with a suite of pragmatic models, governed by some form of filter representing management needs. "Traditional" modelling paradigms are not always appropriate to this approach. Thus the use of Qualitative Rule Based Models is recommended where appropriate.

The following recommendations are made for further research:

i) The suite of models developed in this project is only partially verified. Further refinement of these models and verification over a wider range of conditions is required.

ii) The work reported in this document is of a scientific nature. Consequently, the manner of the transfer or use of these models, or their results, for ICM support is, another area in which further research is required.

iii) The participants in this project have all benefited from their exposure to the paradigms, work ethics, thought processes, methodologies and personalities involved in scientific disciplines other than their own. Although scientists are increasingly seeing the need for collaboration, this is a process that requires careful nurturing and proactive development. Such development should be the subject of planned programmes by South Africa's research funding institutions.

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Computing equipment, software and networking support was supplied by the Computing Centre for Water Research. The staff of the Computing Centre for Water Research. Mike Horn and later Rajesh Nundlall were the chief programmers of the ICIS system and Karl Wortmann produced the software for display of the BLINK model output. The CCWR also assisted by providing a WWW and FTP site for participants.

Mr. Reinier de Vos assisted greatly with the data gathering, configuration and later trouble-shooting of HSPF for the Sabie River.

Mr Andy Pike of the School of Bioresources Engineering and Environmental Hydrology, University of Natal performed the ACRU modelling tasks required for the Sabie Catchment.

The University of Stellenbosch provided office space and logistical support from 1994-1997.

Umgeni Water provided office space and computing facilities in 1997.

The University of Natal. PMB provided office space and computing facilities in 1998.

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ABBREVIATIONS USED

ACRU	Agricultural catchments Research Unit model
CCWR	Computing Centre for Water Research
DSS	Decision Support System
DWAF	Department of Water Affairs and Forestry
GUI	Graphical User Interface
HSPF	Hydrological Simulation Program - FORTRAN
ICIS	Integrated Catchment Information System
ICM	Integrated Catchment Management
IFR	Instream Flow Requirement
IWRM	Integrated Water Resources Management
KNP	Kruger National Park
VTI	Variable Time Interval model
WDM	Watershed Data Management file

Chapter One

INTRODUCTION

1.1 MOTIVATION FOR THIS STUDY

During the past two decades, the world has seen an increasing emphasis on the need to conserve natural systems in such a manner that they may yield the greatest sustained benefit to present generations, whilst maintaining their potential to meet the needs of future generations (IUCN, 1980). This has led to a change in the way that natural systems are managed worldwide.

The most important outcome of these evolving approaches to management of natural resources, is the belief that these systems must be managed in a holistic manner. In other words, the "interconnectedness" of all components of natural systems, including the anthropogenic effects, is recognised. The result of this is the recognition that changes in one component may bring about changes in a range of others. Components of natural systems should not be managed in isolation. Thus, in order to manage any component of the natural system, an understanding of how changes in other components will affect the components under consideration is required. The management of water is no exception, and often the catchment presents a sensible boundary within which to attempt to manage a water-related natural system. One product of this transition is the concept of Integrated Catchment Management (ICM). (In Chapter 2, the development of the ICM concept is described, as are the allied concepts of Integrated Water Resources Management (IWRM) and River Management.)

The implication of understanding how change of one component may bring about changes in another, is that some form of predictive capacity may be generated. The development of models which provide the ability to predict the response, for example, to different development scenarios, is required to provide managers, and stakeholders alike, with some means of assessing the impact of potential change in a component of a natural system, and has been the focus of many research programmes world-wide.

The Kruger National Park Rivers Research Programme (KNPRRP) is one such programme. "The KNPRRP is an interdisciplinary and co-operative endeavour aimed at contributing to the conservation of the natural environment of rivers, through developing skills and methodologies required to ***predict*** responses of the systems to natural and anthropogenic influences, and to improve the quality of the advice to resource managers, researchers and stakeholders" (Breen, *et al.,* 1994). The research reported in this document was performed under the auspices of the KNPRRP using the Sabie River, one of six important rivers flowing through the Kruger National Park (KNP), as the pilot study area. Much of the research in KNPRRP has focused on the flow requirements of aquatic ecosystems, in particular fish and riparian vegetation, the effect that changing hydrology and geomorphology have on them and the development of models to predict this response. Universally, the ability to predict the impact of changes in catchment landuse on the flow in rivers is not a new skill; many models have been developed that have this ability. The challenge is in linking these models to the complex interrelationships between abiotic (physical/chemical) and biotic (biological), processes. The limited understanding of biological processes makes this an extremely difficult task which is further compounded by the fact that these processes have different rates of change and operate at different scales (Breen *et al.*, 1997). This need to be able to predict changes of both the abiotic and biotic components of the river system formed a core component of Phase II of the KNPRRP, by way of a research project known as the KNPRRP Biotic-Abiotic Links (BLINK) project, and is fully described by Jewitt *et al.* (1998).

1.2 OBJECTIVES OF THIS RESEARCH PROJECT

The aim of this research has been the development of a hydrologically driven computer based modelling system which will enable the *integration* of the predictive methods used by different water related disciplines. The word "integration" is used in a broad sense in this document and is used to describe both the linking of simulation models and their output as well as the generic process of scientists from different disciplines or stakeholders in a catchment linking their ideas.

An important focus of the study has been to answer the question; "How can one most efficiently link predictive models from various disciplines, when these may operate in differing and varying spatial and temporal dimensions?" The most difficult technical issue in developing and using these models has been the cross-scale linkage between physical/chemical and ecological processes. A methodology to assist in resolving this vexing problem is presented and an integrated modelling system which includes hydrology, hydraulics, geomorphology, fish and riparian vegetation components of the Lowveld section of the Sabie River is used as a case study.

In summary, the objectives of this research were:

- The development of an hydrologically driven integrated interdisciplinary system of models for the Sabie River.
- To develop a computer based framework (Decision Support System) in which these models are integrated.
- To assess the extent to which scale issues may impact on interdisciplinary research,

- To facilitate interdisciplinary collaboration amongst researchers of the KNPRRP and
- To make recommendations regarding the transfer of the framework to other KNP Rivers.

Chapter Two

INTEGRATED CATCHMENT MANAGEMENT AND THE KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

The recent review of the Water Law of South Africa and the discussion surrounding it has resulted in some fundamental conceptual adjustments amongst the country's water management community. Foremost amongst these, is the concept of Integrated Catchment Management (ICM). Although ICM is now topical, it is often poorly understood. Stakeholders in catchments seem to be able to relate to the promise of ICM, but it seems difficult to translate into operational terms.

2.1 INTEGRATED CATCHMENT MANAGEMENT IN A SOUTH AFRICAN CONTEXT

According to the South African Department of Water Affairs and Forestry (DWAF), the environment should not be regarded as a "user" of water in competition with other users, but as the base from which the resource is derived and without which no development is sustainable (DWAF, 1997). The DWAF have stated that protection and conservation of the natural resource base is imperative (DWAF, 1997). Management of these resources should then revolve around the issue of sustainability. In a speech to the 1996 Stockholm Water Conference, the South African Minister of Water Affairs and Forestry, Prof. Kader Asmal, argued that the environment must not be seen as one of the competing demands on water resources, but as the fundamental source of life and the other economic values we get from land and water. He stated that, in South Africa, the DWAF is aiming for three goals - equity, development and a sustainable environment. He continued that it is his belief that all three are intertwined and that society needs all three - less than this will not be sustainable. This is congruent with a worldwide acceptance that economic growth and development must take place, but should be complementary, rather than antagonistic to environmental protection (Niu *et al.*, 1993).

The concept of an integrated catchment management approach has made its way to the forefront of environmental research very much in conjunction with the concerns about sustainability (Voinov and Costanza, 1998). It has been recognised that sustainability requires economic concerns to be considered within the framework of ecological options available, and that values of the society be brought in harmony with the integrity of the environment. Consequently, it became clear that existing administrative and socio-geographic boundaries are not really well suited to account for both the socio-economic and ecological features of existing systems. It was recognised in the USA, that catchments (or watersheds, as they are known there) seemed to be a reasonable alternative to existing system boundaries, as they may account for both the ecological and socio-economic properties of an area (Reid and Ziemer, 1997; Voinov and Costanza, 1998).

The concept of a catchment as a basic management unit, implies certain geographical characteristics, such as topography, that delimit the area not only with respect to water, but also with respect to other media flows, such as energy, material and information. The catchment boundaries may influence local atmospheric transport and local climate, migration flows and the associated patterns of species distribution, as well as dispersion flows of pollution. The flow of water serves as an indicator of the relief and landscape characteristics, on the one hand, and as an integrator of many of the processes occurring within the catchment, on the other. The use of the catchment as a management unit may also account for other factors, both of ecological and social origin. Historically, human settlements have tended towards sources of water - in southern Africa, these are most often rivers. Consequently, much of the human population and the associated anthropogenic pollution, and other forms of environmental stress are often tied to the river network.

The role of resource managers is to implement and devise policies that fulfil the goal of sustainability, thus placing responsibility on the environmental scientist to gather knowledge and produce tools to assist these managers. For many, the principle of sustainability has become a rallying point for the potential resolution of the growing conflicts between environment and economy (Yin and Pierce, 1993). Ecological sustainability has been defined as the intersection of societal values and ecological capacity (Reynolds *et al.*, 1996). It thus reflects, on one hand, the recognition of increasing demands on a finite resource base and potentially rapid changes to the quality of natural resources and, on the other, political necessity to act in response to economic realities (Yin and Pierce, 1993). Integrated Resource Management may be defined as a comprehensive, systematic and co-ordinated approach aimed at achieving the sustainable use of natural resources (Mitchel, 1990). This implies that cognisance must be taken, in an integrated manner, of the complexities of the biophysical system under consideration and the social aspects they encompass. Water is essential for human survival and a critical component for economic development. In arid and semi-arid countries, a burgeoning population, pressing development needs and increasing environmental awareness are rapidly accelerating the demands for water (Kirmani and Le Moigne, 1996).

By the time of the so-called "Earth Summit", the UN Conference on Environment and Development held in Rio de Janeiro in 1992, environmental sustainability had moved from being a philosophical idea, to being a core commitment of governments (Clark and Gardiner, 1994). Two key paragraphs of the Agenda 21 document accepted at this conference relate to water resources:

- Water resources must be planned and managed in an integrated and holistic way to prevent shortage of water, or pollution of water sources, from impeding development. Satisfaction of basic human needs and preservation of ecosystems must be the priorities; after these, water users should be charged appropriately.

- By the year 2000, all states should have national action programmes for water management, based on catchment basins or sub-basins and efficient water use programmes. These could include integration of water resources planning with land use planning and other development and conservation activities, demand management through pricing or regulation, conservation, reuse and recycling of water.

Thus, ICM was moved to the forefront of international water resources management.

2.1.1. Integrated Catchment Management, Integrated Water Resources Management and River Management

Mitchell and Hollick (1993) suggested that the output of any ICM exercise should be a combination of philosophy, process and product. As a philosophy, ICM should result in a shift of organisational cultures and attitudes towards an acceptance and pursuit of co-operative approaches. As a process, ICM should foster co-operation between stakeholders, be they national, regional or local government or community groups. As a product, ICM should facilitate the development of a catchment management strategy. This view of ICM is one which is under discussion with regard to its applicability to South African catchments (DWAF, 1996). DWAF and WRC (1998) accepted the basic premise of Mitchell and Hollick's (1993) thoughts, but added that the product of an ICM should be an implementation strategy to achieve a sustainable balance between utilisation and protection of *all* environmental resources in a catchment, and to grow to a sustainable society. In other words, the perception that ICM concerns only the "water" component of a catchment is false.

Integrated Water Resources Management, on the other hand, is viewed as simultaneously a philosophy, a process and implementation strategy to achieve equitable access to, and sustainable use of, water resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits (DWAF and WRC, 1998).

River Management reflects the manner in which many rivers have been managed in the past, i.e. the rivers have been managed without the recognition that the flow in the river integrates many landscape and biological features. The water in the river was manipulated to ensure supply to users, most often for human, agricultural or livestock consumption, with little concern for the aquatic environment. Breen *et al.* (1997) suggested that a transformation is necessary so that the management of river systems and their resources is ecologically sustainable. More recently, it has been accepted that rivers form complex systems that are far more than the water they channel (Breen *et al.*, 1997) and that river management must reflect this recognition.

Although the ultimate goal is ICM, it is recognised by DWAF and WRC (1998) that catchment management in South Africa's immediate future will comprise mutual and sensitive dependence of water, land-use and aquatic ecology management, but with incomplete integration of natural resource management. In line with the thinking of DWAF and WRC (1998), it is recognised in this document, that "true" ICM is currently a very distant goal. However, ICM is a goal that has been set, and the theory, methodologies and tools reported in this document are aimed at achieving ICM, with the hope that they will aid the interim discussions, and later implementation, of catchment management and assist in the integration of water resources management.

River Management, Catchment Management, Integrated Water Resources Management and Integrated Catchment Management can be viewed as a hierarchy, the ultimate goal of which is to achieve Integrated Resource Management.

2.1.2. Future Water Resources Management in South Africa

It has been noted (DWAF, 1996), that sustainability of water resources implies the adoption, in an iterative manner, of three successive steps in water management;

i) identification of water resources system characteristics pertaining to different problems encountered; these consist of biophysical, economic, social and environmental characteristics of the system,

ii) prediction of the behaviour of the water resources system, and

iii) management of the water resources system.

In the past, aspects of the system where quantitative understanding is relatively poor, such as ecology, have largely been ignored in the decision-making processes. This may have been due no less to the ability of scientists to understand and predict such interactions, than the ability or willingness of policy makers and planners to accommodate ecosystem dynamics, especially, when expressed by non-quantitative means. Water resources management internationally and in South Africa has, in the past, been a prescriptive affair. However, the management of water resources solely to maximise consumptive use has been giving way to a realisation that management for environmental values, such as biodiversity, and social and cultural values is necessary (Cortner and Moote, 1994). As explained above, this has resulted in a change in the way that natural resources are managed, a paradigm shift from, in this case, water resources management performed by a single statutory organisation, possibly based on information from a large systems analysis type of model, to an approach to management that recognises the importance of the stakeholders, including the environment in the process. In line with the Rio declarations, the idea of a "water reserve" is one which is receiving much attention (DWAF, 1997). According to this concept, water necessary for basic ecological functioning, and water needed to meet basic human needs, will have first call on available reserves. Only once a decision pertaining to the amount of water representing the reserve is made, will water be made available for commercial and other needs.

To support this sort of decision making process, methods of objectively quantifying responses of various resources to catchment planning scenarios are sought. Models, which provide a quantifiable response to a given scenario, are sought within many disciplines in order to aid objectivity in planning exercises.

The development of models has been used as an effective means of ensuring the participation of stakeholders in catchment management (Grayson and Doolan, 1995). This mirrors the change in the way that land and water resources are managed. The scientific thinking on the subject may be undergoing a "scientific revolution" which is part of, and driven by a larger social revolution, visible in such projects as the Reconstruction and Development Programme

(RDP) of the SA Government (DWAF, 1997) and a perceived movement away from "command and control" (DWAF, 1996) type management. The tools developed within the KNPRRP and the focus of Chapters 5 and 7 of this document are a part of this process, and fall in the scope of Steps i and ii above, i.e. the identification of the system characteristics and prediction of the behaviour of certain components, in the belief that they will be of assistance in the final step of management of the system.

2.2. THE KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

The Kruger National Park (KNP) is South Africa's premier National Park and a major drawcard to local and foreign tourists. The biodiversity of the Park and water supplies for its facilities is dependent upon several rivers, all of which rise outside of the Park's borders (Figure 2.1). These catchments are increasingly affected by agricultural, forestry and industrial development, as well as an urgent need to develop water supplies for a burgeoning human population. This increasing demand has affected water quality and quantity in the KNP rivers and is placing its riparian ecosystems under threat (Breen *et al.*, 1994).

It has been noted in Chapter 1 that the KNPRRP is an interdisciplinary and co-operative endeavour aimed at contributing to the conservation of the natural environment of rivers, through developing skills and methodologies required to predict responses of the systems to natural and anthropogenic influences affecting water supply, and to improve the quality of the advice to resource managers, researchers and stakeholders (Breen, *et al.,* 1994). The KNPRRP embraces an ecosystem approach to river management. The catchment ecosystem is made up of abiotic components such as physiographic features, and biotic components such as aquatic organisms, wildlife and people that occupy it. Streamflow forms the major connecting link between the various catchment components as illustrated in Figure 2.2. Water, both its quality and quantity, is the common concern in all the disciplines involved in KNPRRP.

The KNPRRP comprises four sub-programmes:

Sub-programme 1: Information Systems Development and Management

The purpose of this sub-programme is to provide an information management system which enables the efficient capture, storage, retrieval and dissemination of information to serve the needs of researchers, decision-makers and stakeholders.

Sub-programme 2: Decision Support System Development and Management

The purpose of this sub-programme is to provide methodologies for integrating information and expert opinion into structured decision support systems directed at achieving the best possible answer at the time and at informing researchers of the information needs required to improve answers in the future.

Sub-programme 3: Research Development and Management

The purpose of this sub-programme is to provide in an efficient and cost-effective manner, the information and expert opinion required to improve the quality and usefulness of the response to enquiries from researchers, resource managers and stakeholders.

Sub-programme 4: Training, Information and Technology Transfer

The purpose of this sub-programme is to ensure that information and technology developed within the programme are transferred effectively to the appropriate users including researchers, managers and stakeholders.

In Phase II of its development, the KNPRRP undertook to develop the necessary "*understanding of principles and methodologies required for effective management of our river systems*". It undertook to do this by attempting to "*develop, test and refine methods for predicting the responses of natural environments of rivers flowing through the Kruger National Park and in southern Africa to changing water quality and patterns of supply*".

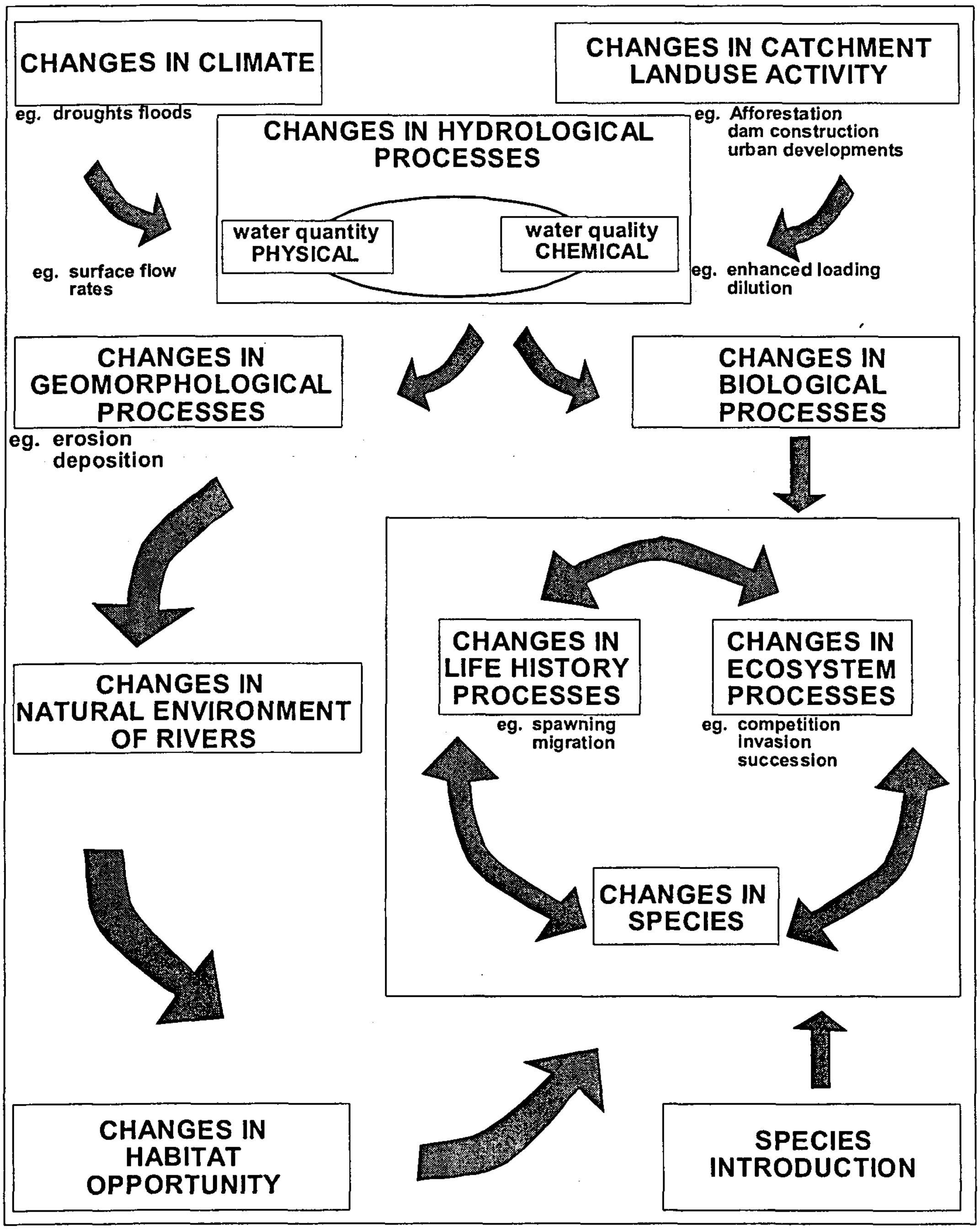


Figure 2.2 Understanding and predicting change in the natural environment of rivers (Breen *et al.*, 1994).

Thus the development of an hydrology-based catchment modelling system in which "modules" from other disciplines, such as geomorphology and aquatic ecology, may be incorporated could provide a particularly useful tool to bring together products from the different KNPRRP projects, as well as providing an aid to managers and planners when identifying effective sustainable management options for the rivers of the KNP. The development of such a system, with which the changes identified in Figure 2.2 could be assessed for the Sabie River became one of the aims of the DSS sub-programme, and is described in Chapters 7 and 8.

2.3. AN ECOSYSTEM APPROACH TO MANAGEMENT IN THE CONTEXT OF INTEGRATED CATCHMENT MANAGEMENT

The KNPRRP recognises that water is an integral part of any ecosystem and that a major connecting link in catchment ecosystems is the flow of water. The KNPRRP also adheres to the principles of ICM. However, the assumption that the catchment offers an optimal spatial scale for the management of ecosystems, may not necessarily be valid.

The term "ecosystem management" is commonly used, particularly in the USA literature. The term has generated much debate regarding whether an ecosystem can be managed, and, if it can, what the term "ecosystem management" might mean and "what is an ecosystem?" (e.g., Fitzsimmons, 1994; Fitzsimmons, 1996; Jensen *et al.*, 1996). More recently, there appears to be an acceptance that the terms an "ecological approach to management" or "ecosystem approach to management" are more appropriate terminology (Goodrich, 1996).

It has been noted by various researchers that ecosystems operate at many scales, both spatial and temporal. Therefore, an ecosystem approach to management should have a hierarchical context that views smaller ecosystems as nested within increasingly larger ecosystems. It should define the boundaries and scales of ecosystems which may change and evolve in response to both human and natural events (Kay, 1993; USDA, 1996; Haufler *et al.*, 1997). The USA National Parks Board Service (USNPS, 1994) warned that a common misconception is that an ecosystem approach to management entails simply drawing new maps and assigning new boundaries around broader ecological areas. This is not the case. Ecosystems do not have permanent or absolute boundaries and the structure and function of ecosystems change through space and time. Consequently, there is a need to address both spatial and temporal sources of variability when applying an ecosystem approach to management (USDA, 1996). Multiple factors need to be considered at multiple scales with multiple boundaries.

The United States National Parks Board Service (USNPS, 1994) decried debates about defining a definitive ecosystem boundary as being neither constructive nor useful. They concluded that no single boundary is best for every issue and it is better to ask what combination of boundaries is best to tackle the problems at hand. The USNPS give the examples of appropriate boundaries for water pollution, which will revolve around catchments and aquifers, while boundaries for wildlife management will involve the species, habitat and migration routes. A single boundary may not capture the relevant areas. Purely ecological patterns for defining useful management areas (ecoregions) may be patchy and discontinuous and often tend to disregard social factors (Voinov interdisciplinary analysis. An interdisciplinary approach can also simultaneously address the environmental, social, and economic impacts of policies or plans (USNPS, 1994).

Typically, however, interdisciplinary research efforts rapidly fragment into loosely related disciplinary studies, i.e. they become multi-disciplinary rather than interdisciplinary (Bella and Williamson, 1996). The development of interdisciplinary models, of which scientists from different disciplines feel ownership, may be a way in which disintegration of such interdisciplinary projects may be prevented. The integration of the understanding of different catchment components and processes, scientific disciplines and predictive models underlies much of the thinking in this document and is a theme that is common throughout. Interdisciplinary work is difficult! However, the development of such an integrated modelling system is dependent upon successful interdisciplinary co-operation. With the recognition of the different levels of detail, appropriate spatial and temporal scales and a common goal, many of the difficulties associated with interdisciplinary research may be overcome.

2.4.2. Linking Abiotic and Biotic Components of Catchments

An ecosystem approach to catchment management implies that meaningful cognisance of biotic components of the system, and the abiotic influences upon these, must be made. Since the inception of the KNPRRP, there has been an awareness of the need to relate aquatic biotic response to abiotic catchment conditions and this was an issue highlighted in the definition of KNPRRP Phase II. Figure 2.3 shows a conceptual view of the links between catchment abiotic processes and biotic responses. The ultimate aim of forging such links would be to establish the flow requirements of the aquatic ecosystem. In terms of the KNPRRP, it is the flow requirements of the aquatic ecosystem which are highlighted, though the important influences of other abiotic components are recognised.

For many years, attempts to predict the environmental flow requirements of riparian biota have concentrated on establishing the discharge regime which will maintain or enhance the habitat for riverine flora and fauna. Fundamentally, these approaches make the assumption that the channel is stable and does not respond to altered flow conditions by altering its morphology, thus affecting the physical habitat distribution in the river. Given the extent of documented river channel change following an alteration to one or more of the controlling catchment variables (Brooks, 1992), it would appear necessary to predict changes in habitat availability, given changes to the fluvial geomorphology. Thoms *et al.* (1990) recognised that fluvial geomorphology was the logical integrating discipline to link river response to ecological functioning, as it is the geomorphology that forms the physical template for habitat development.

and Costanza, 1998). This may hinder the application of management strategies that assume some common public understanding and behaviour. Economic, social and administrative divisions often take no account of ecological and geographical factors and therefore may tend to be unstable and disputable. Catchments seem to be a good compromise as a spatial unit on which to focus management strategies.

The hierarchical structure of catchments, sub-catchments and sub-sub-catchments is very useful for upgrading and downgrading, zooming in and out, changing resolution, depending upon the type and scale of the managerial problems to be resolved. (This concept of hierarchies and scaling is discussed in detail in Chapters 3 and 4.) Furthermore, the view of a catchment as a hierarchy of nested sub-catchments is compatible with the view of an ecosystem as a hierarchy of nested smaller ecosystems. The catchment has been used as a management unit in some important ecosystem management applications. The best known of these is the adoption of "watersheds" as the geographic unit for reporting the habitat of the spotted owl in the US Pacific North West (FEMAT, 1993).

Those involved in developing a process of integrated catchment management need to be aware that the catchment may not be an appropriate spatial scale for management of many, and, in particular, non-aquatic ecosystems. However, it does seem that the adoption of the view of a catchment and subcatchments as a hierarchy, is compatible with the hierarchical view of ecosystems, and may provide a useful basis for approaches to management.

2.4. ISSUES ARISING FROM AN INTEGRATED APPROACH TO CATCHMENT MANAGEMENT RELEVANT TO THE KNPRRP

The concept of ICM raises many issues, both technical and philosophical. Some of the more philosophical arguments have been dealt with above. A discussion of some of the more technical aspects of ICM follows.

2.4.1. Interdisciplinary Research

The holistic view of a catchment offered by ICM necessitates an interdisciplinary approach to the development of tools which may be of benefit to its implementation. Interdisciplinary research has the potential to produce results that exceed the sum of incremental disciplinary contributions, as more holistic understandings can emerge from such research. Furthermore, major environmental problems may arise from obscure interactions that would not be recognised without an

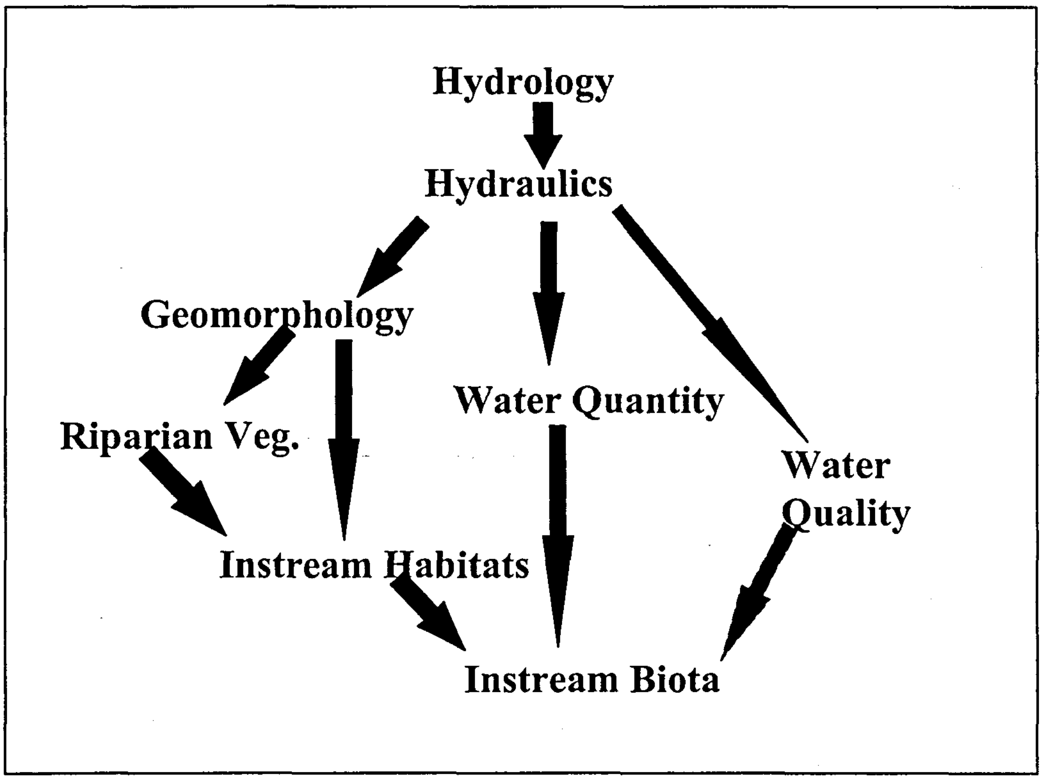


Figure 2.3 Conceptual diagram showing links between catchment abiotic and biotic components (O'Keeffe, 1995).

The form of river channels is primarily determined by the influence of flowing water and sediment, and any alteration to this balance will result in geomorphological change. However, well-known static ecological assessment techniques, such as PHABSIM (Bovee 1982), link ecological response to local channel hydraulics. As such their use is inappropriate on dynamic river systems, since a new hydrological regime will result in changes in geomorphology and hence habitat availability (Russell and Rogers, 1989). Thus, an important component of the KNPRRP has been the development of a model of geomorphic change. The development of such a model is fully reported by Heritage *et al.* (1998) and is discussed in Chapter 7.

KNPRRP participants realised only too well that predictions of changes in the flow regime or geomorphic template are often meaningless. To managers, it may mean little to present results such as, "flow will be reduced by x%". The final prediction must be one relating to the riparian ecosystem, i.e. "If flow is reduced by x%, species y will disappear from the river". Extensive discussions amongst KNPRRP scientists, culminated in a workshop to identify methods of forging and representing these links between abiotic and biotic components. Consequently, a research project aimed at developing computer tools to simulate biotic responses to abiotic stimuli in the Sabie River catchment was proposed. The ensuing project became known as the "BLINK Project" and is reported fully in Jewitt *et al.* (1998). Although the development of these models is referred to in this document, the focus is rather on their integration into an Integrated Modelling System for the rivers of the KNP.

2.4.3. Issues of Integration of Models and Modelling Tools

It has been recognised by many researchers (e.g. Lam and Swayne, 1993) that full analysis of many problems faced in the course of water resources management requires an extensive set of capabilities. Most people involved in water resources simulation and management programmes have found that these exercises involve the use of a great many tools, and different data and information formats. These include spreadsheets, graphics, time series analysis, GIS, statistical analyses, simulation, "expert system" capabilities and metadata queries. The development of a software system in which these tools are integrated will provide a powerful decision support tool to researchers and managers alike.

There are many definitions of decision support systems (DSSs). In the context of this document, and as discussed in Section 2.2, DSS refers to a software system in which several tools are integrated. This usage follows that of Reynolds *et al.* (1996), who stated that "a decision support system is a software application that provides an integrated environment in which a collection of tools can be efficiently used together to manage a larger portion of the overall decision process". These include the tools mentioned above, as well as information databases and simulation models. The key to useful computer based decision support is *integration* (Fedra, 1995). An Integrated Catchment Information System (ICIS) has been developed as part of the KNPRRP and is described more fully in Chapter 5. This system is developed with the recognition that in any given software system for real-world applications, several sources of information or data bases, more than one problem representation or model, and finally a multi-faceted and problem-oriented user interface, need to be combined in a common framework to provide a realistic and useful information system. Associated with this is an emerging view that such an information system may act as a living repository for the knowledge which the collective scientific community has about the catchment involved (Maaren and Dent, 1995).

At the level of data and background information, numerous and, often, incompatible, noncommensurate information from disparate sources has to be brought together. Some of the obstacles frequently encountered relate to institutional, conceptual, and seemingly simple technical and administrative problems, such as different units of measurement, different map projections, hard to trace paper files and missing documentation (Fedra, 1995). In addition, it is often assumed that different simulation models may be easily incorporated into such a system. This is not a trivial task, as illustrated in Section 4.5. Furthermore, many of the required prediction tools do not exist and may have to be developed. This is especially true of tools for linking catchment abiotic and biotic responses (Jewitt *et al*, 1998). In addition to the many issues associated with integration of useful tools, the vagaries of scale must also be dealt with.

2.4.4. Scale Issues

The essence of environmental sciences consists of dealing with nested systems across spatial and temporal scales and the linkages and intricacies among and between the various components. The issue of scale has been identified as an important issue in each of the scientific disciplines directly involved in the KNPRRP, *viz.* ecology, geomorphology and hydrology, as has the problem of the "management scale", the spatial and temporal scale at which managers are most comfortable making decisions or which is the current practical limit of management effectiveness.

"Scale Issues" have been the subject of at least two international hydrological conferences which have resulted in special issues of the *Journal of Hydrology* (Rodriguez-Iturbe and Gupta, 1983) and *Hydrological Processes* (Blöschl and Sivapalan, 1995) and have recently gained prominence as the "latest ecological buzzword" (Wiens, 1997). It has also been the subject of several meetings and workshops on ecological issues of scale held in Great Britain (Giller *et al.*, 1994), Australia in 1995 (Aust. Scales Workshop, 1995) and Sweden in 1996 (Norberg and Elgrim, 1996). In the geographic disciplines, scale has always been a major issue (Meentemeyer, 1989) and, certainly, geographers and hydrologists have identified scale problems and discussed solutions over a longer period than their colleagues in the biological disciplines (Klêmes, 1983; Wiens, 1989; Meentemeyer, 1989; Wiens, 1997). Indeed, until the 1990's, the level of discussion with regard to scale in ecology was largely at the level of problem identification (e.g. Lawton, 1987; Wiens, 1989), whilst geographers and hydrologists have been able to offer more detailed insights into, and some solutions to, various scale problems (Rodriguez-Iturbe and Gupta, 1983; Meentemeyer, 1989; Blöschl and Sivapalan, 1995). An explanation for this phenomenon may be that geographers and hydrologists have often used detailed research findings in the development of simulation tools, which are often used to provide solutions at scales different from that of the experimental unit. In hydrology, many experiments have been "model led" (Blöschl and Sivapalan, 1995, Schulze, 1995). Ecological research, on the other hand, has had description of species and the processes affecting them as its first and foremost consideration (Schrader-Frechette and McCoy, 1994). It is the need to provide ecological predictions that has driven ecologists to study and suggest solutions to some of the identified scale issues (e.g., Kolasa, 1989; O'Neill *et al.*, 1989; Waltho and Kolasa 1994; Levin, 1992).

Spokespersons for hydrologists (Klêmes, 1983), as well as ecologists (Wiens, 1989) have identified the problem that humans appear to have the best grasp of things which are within anthropocentric scales and, thus, for which humans have an "intuitive feel". Klêmes (1983) suggested that hydrologists have made slow progress in understanding the processes occurring at the "hydrological scale", as it is largely outside our direct sensory perception or beyond what Gould (1994) refers to as "the measuring rods of our own world". On the other hand, Wiens (1989), suggested that ecologists have been dealing with phenomena that are intuitively familiar because of their accessibility, and have thus been slow to recognise the "influence of scaling". Figure 2.4 shows "Human" scale in the context of various physical processes as defined by Klêmes (1983).

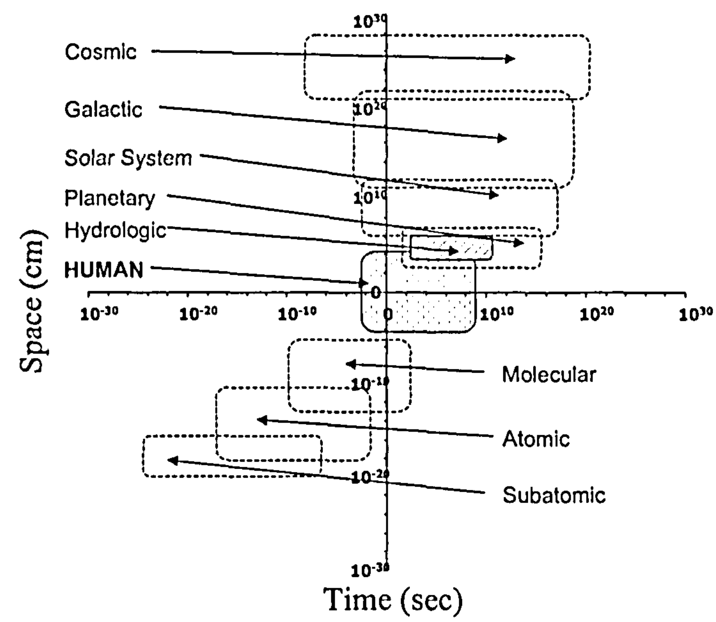


Figure 2.4 "Human" scale in the context of hydrological scale (Klêmes, 1983).

The question of appropriate scale for integration of simulation of ecology, geomorphology and hydrology is a problematic one and has been formulated by Loucks *et al.* (1985) as "How can one most efficiently link predictive models from various disciplines, when these may operate on differing and varying spatial and temporal dimensions?" The relevant scale is primarily dependent upon the spatial and temporal response of the system being modelled and the planning or operational decision to be made at each spatial increment. These scales may in fact vary during the period of simulation as various processes become dominant in the system and may then have different importance for planners and managers. This question is especially important in the link between biotic and abiotic processes and is addressed more fully in Section 3.2.

Traditionally, physical geographers and hydrologists have close links and tend to approach problems in a similar way - they are aware of each others' work and these scientists are often housed in the same departments or organisations. The scale problem is thus not so much a problem at the phase of linking processes within a modelling system, but more at the phase of deciding which is an appropriate scale at which to work, i.e. at what scale does one need to simulate processes affecting the river channel and (being aware of the inputs) at what scale is this possible.

In terms of an integrated modelling system, it has been mentioned that a problem in forging a link between hydrology and biotic responses, is that research in the abiotic and biotic fields experienced, until recently, little integration (King and Tharme, 1993a). There are of course more obvious problems, such as the habitat of an invertebrate being a physically small area subject to great flow variations. The predictive tools of the hydrologist and the ecologist have not been designed with each other in mind and often seem to operate at opposite ends of the spectrum of catchment spatial scales. Figure 2.5 illustrates a hierarchy of the decreasing spatial scale apparently applicable to various catchment components, both abiotic and biotic, relevant to the KNPRRP and the integrative role of streamflow in these (Jewitt and Görgens, 1995). The catchment nodes identified in this figure represent spatially preferred scales for scientists involved in the KNPRRP. In the case of river ecology, the scale which is attractive to the ecologist is that of the habitat of the organism under study (King and Tharme, 1993b). The need is to know, for example, the velocity or depth of water at a particular habitat unit and a prediction regarding the suitability of the habitat and a response of its biota can then be made. However, the scale of the habitat unit, is typically tens of centimetres to metres (Wadeson, 1994). To the hydrologist or civil engineer typically operating at the scale of the sub-catchment or larger, and the geomorphologist typically operating at the scale of a section or reach of river channel, this is too fine to be able to make a prediction regarding velocity and depth of flow with a high degree of confidence. When attempts at small-scale predictions of flow depth and velocity have been attempted, the input requirements and complexities of the models involved have effectively made them unusable (Gan and McMahon, 1990; King and Tharme, 1993b). This link is, however, critical to many environmental management systems, such as those of the Murray Darling Basin (Young and Davies, 1995) and the KNPRRP (Breen *et al.*, 1994) and needs to be made.

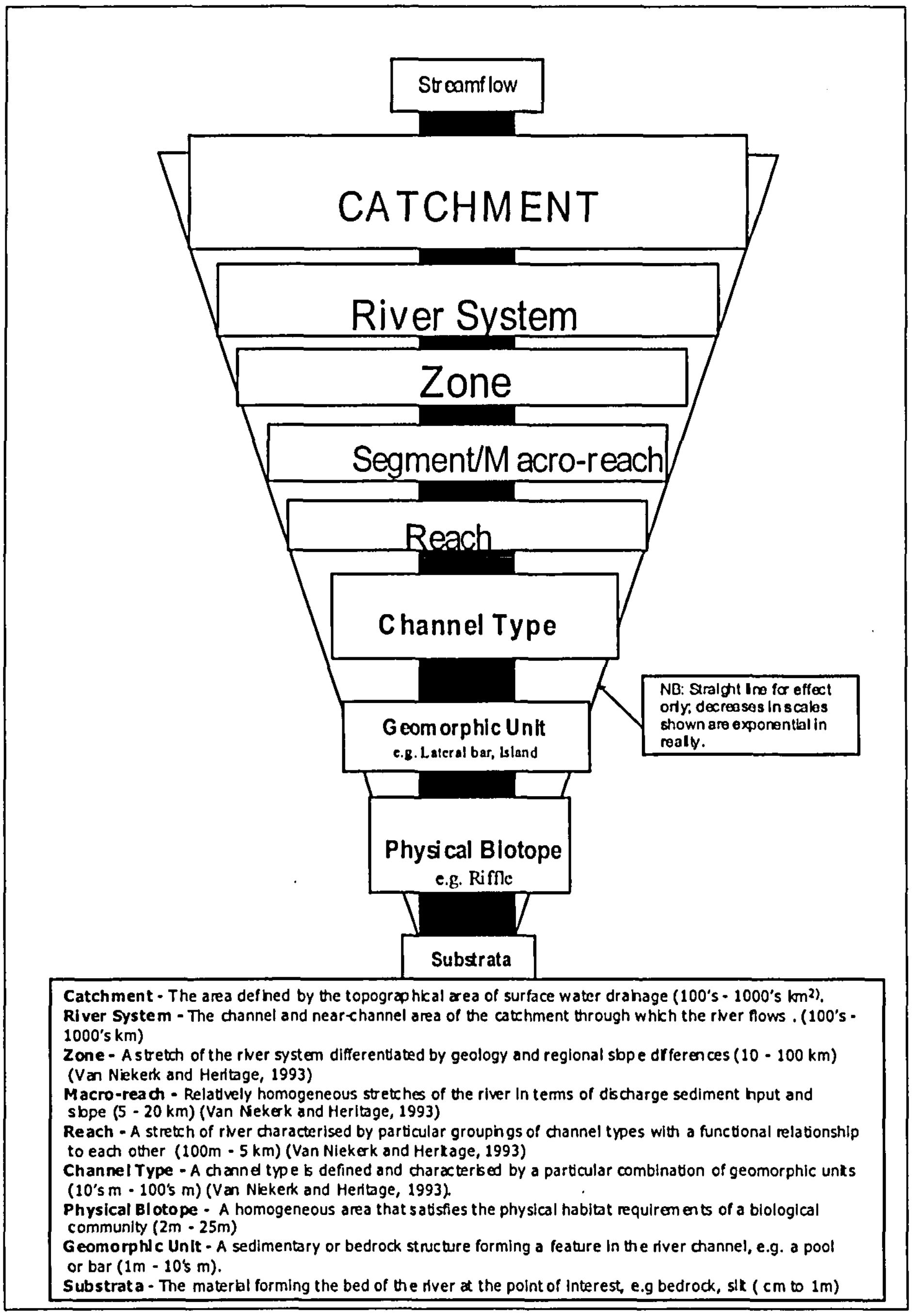


Figure 2.5 Decreasing spatial scales of catchment components represented by preferred spatial scales or catchment nodes utilised by different scientific disciplines of the KNPRRP.

The terminology surrounding scale is less intuitive than it first appears (Haufler *et al.*, 1997). The understanding of scale issues will be aided by consistent terminology. Confusion is created by the inconsistent and overlapping common usage within and between disciplines, of related concepts such as scale, hierarchy, resolution, grain, and extent. Before attempting to identify an appropriate scale for linking these components, it is necessary to explore the concept of scale further. These aspects are discussed in the following chapter.

Chapter Three

SCALE ISSUES AND THEIR SIGNIFICANCE IN THE DEVELOPMENT OF AN INTEGRATED CATCHMENT INFORMATION SYSTEM

Much of the lack of progress in resolving scale issues can be attributed to confusing terminology and inconsistent use of scale-related concepts. In this chapter, the terminology pertaining to scale, especially with regard to components that are affected in an interdisciplinary exercise such as the KNPRRP, is clarified, some effects of scale are identified and some common methods of accommodating scale issues are described.

3.1. WHAT IS SCALE?

The term "scale" refers to a characteristic temporal (time) or spatial dimension of a process, observation or model of that process that encapsulates either a discrete state or a transition between states of that process. Commonly, "scale" is intuitively used as an indication of the order of magnitude, rather than as a specific value. For the purposes of this document, scale is something that "pertains to size in both time and space" (Allen and Hoekstra, 1992); and to "the spatial or temporal dimension of an object or process, characterised by both grain and extent" (Turner and Gardner, 1991). The term "grain" usually refers to the size of the individual units of observation and "extent" to the total area or time covered by a study (Wiens, 1989) (see Section 3.1.2).

It has been stated that "scale has become a questionable item with the advent of GIS" (Ramsey *et al.*, 1995), as layers may be zoomed in or out. There is often a false perception that GIS may provide a panacea to scale problems. Similarly, models that can operate at time steps from minutes upwards effectively give a continuum of "scales", increasing from the selected baseline unit, whatever that might be. However, it has been noted that, in nature, scales of phenomena are not arbitrary. Rather, they arise as a function of their material substance and the balance between the forces interacting with them. In a particular process, the spectrum of preferred scales tends to be concentrated around discrete nodes, which may seem to be far apart (Klêmes, 1983; Meentemeyer, 1989; Blöschl and Sivapalan, 1995) and may often be organised in a hierarchical structure. Study of Figure 2.5, in the previous chapter, shows several potential nodes, which have been identified by the various disciplines involved in the KNPRRP as having distinct qualities. Klêmes (1983) stated that once such a node has been discovered, the rewards have been great, as the scientists involved then have a firm basis for conceptualisation. Consequently, rapid advances have been made through the development of workable theories and models at that scale. He stated further, that progress has been slower in disciplines attempting to work at scales between these nodes. An example of such a node is the recognition that relatively small catchments in temperate zones display a very peaked response to discharge. However, in larger catchments with an area of approximately 300 km^2, the peak flattens as catchments of this size may maintain a floodplain (Beven *et al.*, 1980).

In order to identify a common scale that may be used to integrate processes important to different scientific disciplines within the KNPRRP and the natural systems they study, it is necessary to define more clearly the concept of "scale". In essence, we deal with three different scale types in both spatial and temporal nodes, i.e. *process, observation* and *operation.*

3.1.1. Process Scale

The process scale is the scale that natural phenomena exhibit. This scale is effectively beyond our control. These scales are not fixed, and may in fact vary according to the process involved, as will be discussed more fully in later sections.

It should be noted that there is an intrinsic relationship between time and space scales. Figure 3.1 is a scope diagram representing hydrological processes at a range of characteristic space-time scales. Scope diagrams are a commonly used form for representing various scales in a graphical way. It is apparent from Figure 3.1 that events covering small spatial scale tend to be associated with small temporal scales. For example, thunderstorms usually cover smaller areas and do not last as long as frontal rainfall events. Processes operating at smaller spatial scales operate at higher frequencies, while processes occurring over larger spatial scales operate at lower frequencies. Furthermore, smaller scale events tend to show more variability. For instance, thunderstorms exhibit rapid transitions between different "states" (e.g. rain intensity levels). With reference to the catchment nodes identified in Figure 2.5, when studying typical catchment processes in more detail, it may be noted that, for example, stability of a geomorphic unit may be associated with stable flows ranging from hours to weeks. Typically, abiotic factors are more influential at larger scales, while both biotic and abiotic factors occur at finer scales.

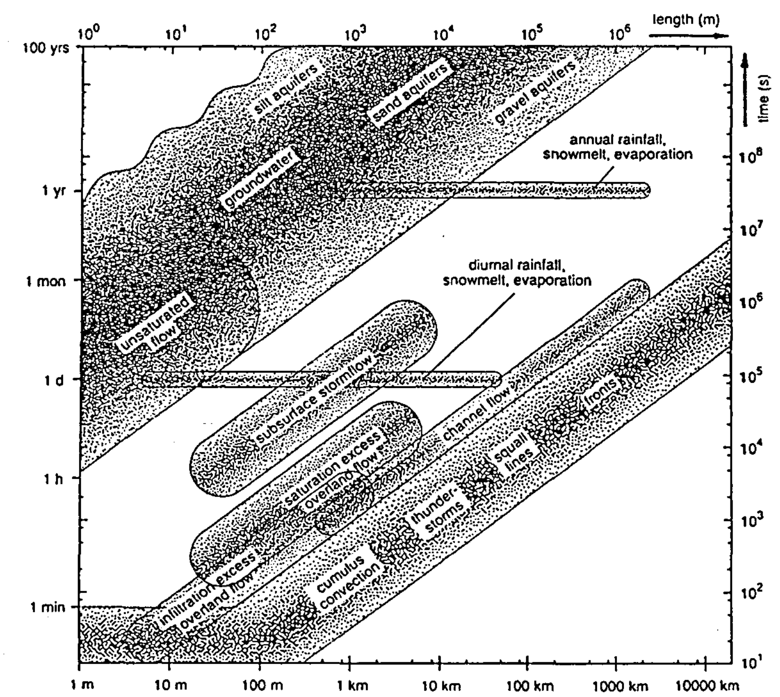


Figure 3.1 Scope diagram showing typical spatial and temporal scales of typical hydrological events (Blöschl and Sivapalan, 1995).

Typically, three types of process scale are identified, as illustrated in Figure 3.2. Characteristic time scales of hydrological processes are described by Blöschl and Sivapalan (1995) as;

i) the lifetime (or duration) of intermittent processes (or events), e.g. a flood,

ii) the period (or cycle) of periodic processes, e.g. snowmelt, and

iii) the correlation length (or integral scale) of a stochastic process showing some sort of correlation, e.g. whether or not wet years tend to follow wet years.

Similarly, characteristic spatial scales may be described in terms of spatial extent, period and integral scale depending upon the nature of the process.

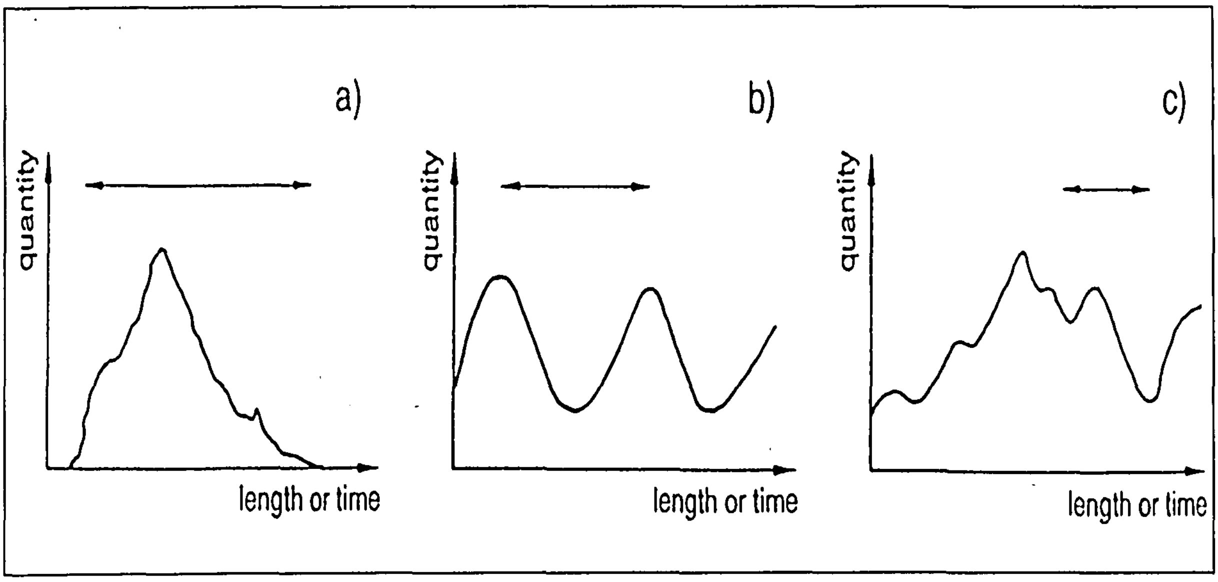


Figure 3.2 Three alternative definitions of process scale in space (or time). (a) Spatial extent (or duration); (b) space (time) period (cycle); (c) correlation scale in space (or time) (after Blöschl, 1996).

Many processes in natural systems exhibit one or more preferred scales and may lead to the identification of a "separation of scales". Separation of scales usually refers to a process consisting of a small scale component which is superimposed upon a larger component, but separated by what is termed a "spectral gap" (Blöschl and Sivapalan, 1995). For example, some hydrological processes exhibit preferred time scales of one day and one year with a spectral gap between them, e.g. snowmelt often occurs only during the day as the snow freezes again at night, and this process only occurs when snow has fallen. Thus, in the case of snowmelt, this spectral gap is caused by the periodicity of solar radiation.

3.1.2. Observation Scale

This is the scale at which humans choose to study natural phenomena. This scale the observer is free to choose, though these scales are usually imposed by perceptual capabilities, or by technological or logistical constraints. Observation of the environment can only take place at a limited range of scales. Consequently, these constraints limit us to a "low-dimensional slice through a high-dimensional cake" (Levin, 1992). The definition of an observation scale is characterised by the collection of a finite number of samples (Blöschl and Sivapalan, 1995). Consequently, observation scale can be defined in terms of;

i) the spatial/temporal *extent* of a dataset,

ii) the temporal spacing between samples, often regarded as the *resolution*, and

iii) area of, and time spent taking each sample, also called the integration volume of the sample, the experimental unit, or most commonly, the *grain*.

These concepts form the so-called "scale triplet" (Blöschl, 1996) and are illustrated in Figure 3.3.

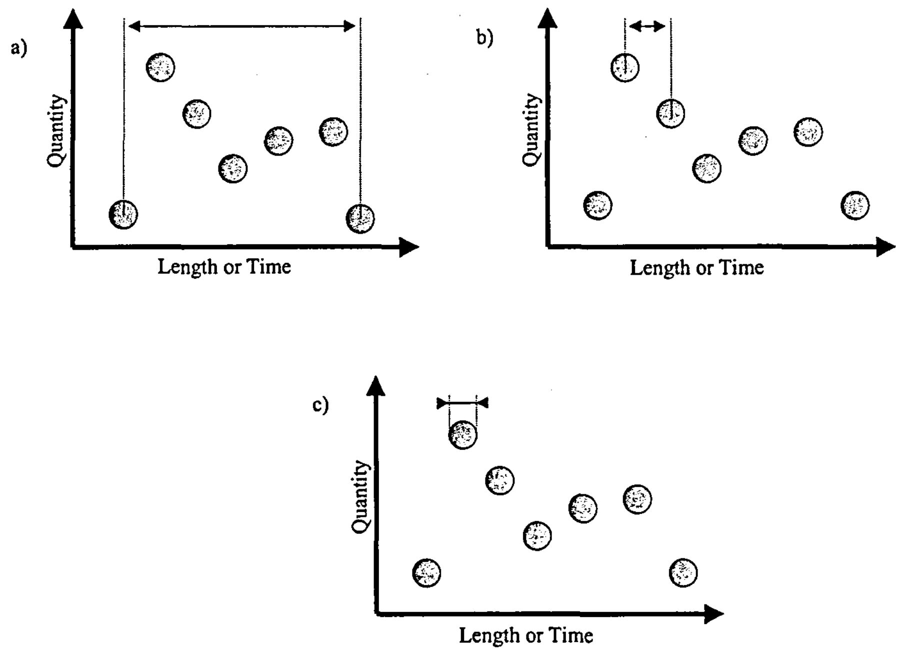


Figure 3.3 Three alternative definitions of observation scale in space and time: a) spatial or temporal extent; b) spacing or resolution, and c) grain (or integration volume).

Ecologists tend to concentrate on *grain* and *extent* as two distinct spatial scales in their experimental design. Grain refers to the finest spatial or temporal entity discernible at a given scale of analysis (Allen and Hoekstra 1992; Turner and Gardner 1991), and determines the lowest or smallest level in a hierarchy that is visible. Grain has also been defined as the size of the individual units of observation (Wiens, 1989). Typically, for the fish ecologist, it represents a scale of 1mx1m. Resolution is another term that has been used in this context and refers to the precision of measurement, and is usually defined by specifying a grain size (Turner and Gardner, 1991). Extent refers to the total size of the area or time encompassed by a study, and is also referred to as the scope or size of the study. In general, larger extents are represented by larger minimum grain sizes and coarser resolutions in order to have a manageable number of units and relationships to analyse. Ideally, a study should be performed over the largest possible extent with high resolutions, i.e. high frequency of sampling. However, this is often not practicable nor affordable.

The extent and grain define the upper and lower limits of resolution of a study (Wiens, 1989), as shown in Figure 3.3. Moving beyond these boundaries requires some form of extrapolation.

The nodes shown in Figure 2.5 represent the spatially "preferred scales" for the hydrological, geomorphological and ecological disciplines involved in the rivers of the KNPRRP. Figure 3.4 is a scope diagram showing the immediately apparent scales identified in Figure 2.5, but including both the grain and extent applicable to the various disciplines in such an interdisciplinary exercise.

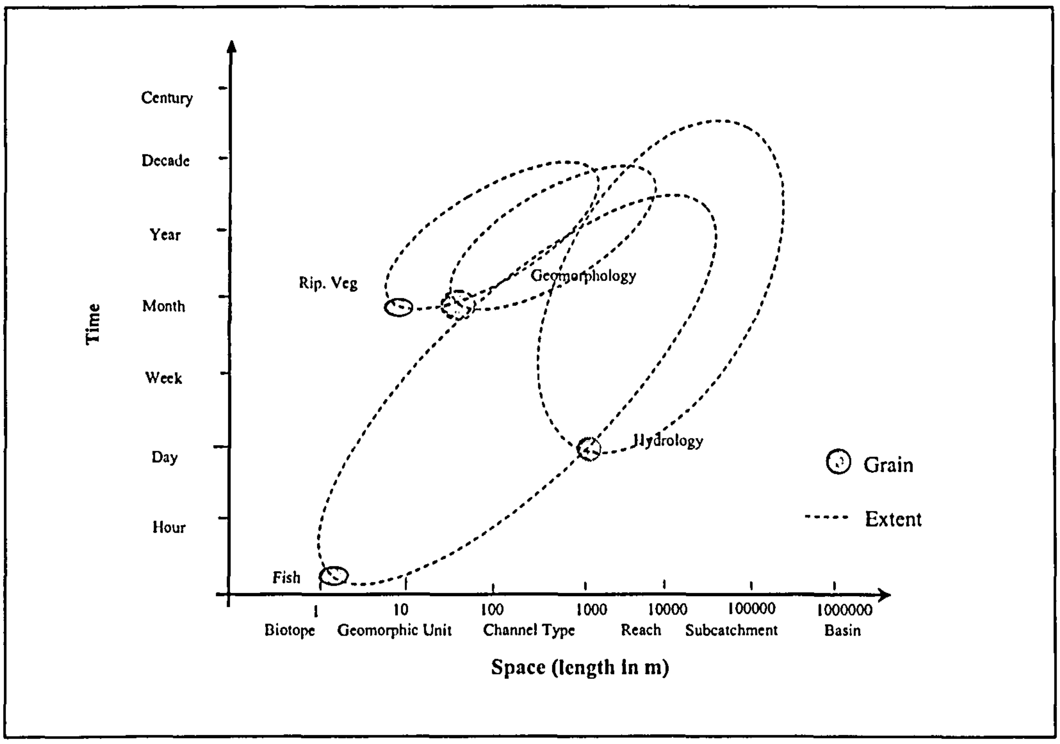


Figure 3.4 Scope diagram showing *grain* and *extent* of components of interest in interdisciplinary predictions for the KNPRRP.

3.1.3. Operational Scale

The operational scale is the scale at which the study or the management actions focus and is also referred to as the working scale. The operational scale is governed partly by the applications of the study, and partly by the process scale. If the goal of the project at hand is the management of, for example, a catchment or component thereof, the operational scale may be synonymous with the so-called "Management Scale". The "management scale" is generally accepted to be the scale at which managers focus their operations. However, this is not a particularly useful concept.

In order to gain a proper understanding of the processes affecting an entity being studied, those processes should be studied at the scale at which they occur. However, these scales may not be relevant to the goal of a project.

Until recently, ecological research has had description of species and the local biological interaction processes affecting them as its first and foremost consideration (Schrader-Frechette and McCoy, 1994). It is evident, particularly in the biological disciplines, and to a lesser extent in geomorphology and hydrology, that the scales at which information is available, tend to focus on identifying the mechanisms directly affecting the entity being studied. For example, the focus of ecological research at the scale of the biotope may result in a large amount of data pertaining to point measurements of flow depth and velocity. Attempts to identify organism responses to measured flow depth or velocity may not be particularly relevant to the broader scale hydrological processes at work. Studies to explore characteristics of fish assemblages of the Sabie-Sand system offer an example of this. Ecological studies of fish were designed in order to identify and describe the fish present in the Sabie System (Weeks *et al.*, 1996), whilst simultaneous geomorphological studies, were largely aimed at the development of a predictive capability of potential geomorphic change in the Sabie System (Heritage *et al.*, 1994, Van Niekerk *et al.*, 1995). Furthermore, in the KNPRRP, hydrological, and to a lesser extent, geomorphological research is related to catchment processes, whilst ecological research is focused on the micro-habitat conditions affecting the organism being studied.

The operational scale is the scale at which, in the context of this work, the link between catchment abiotic and biotic processes is made. It effectively includes the integrative modelling scale - and, ideally, should be compatible with the management scale. However, there is unlikely to be any single preferred operational scale.

3.1.4. Scale, Scope and Resolution

Although these terms have been introduced in 3.1.2, it is necessary to clarify further their use in this document. The scope of an exercise usually refers to the level of "completeness" of the exercise (Pegram *et al.*, 1997) and is encompassed by the range between the grain and extent of the study.

The term "resolution" is most commonly used to refer to the level of disaggregation of the study and is usually measured by the "space" between the units forming the grain of the study. In continuous time studies and regular spatial grid based studies, the resolution equals the grain. Although a large scale often includes a relatively coarse grain size, this is not necessarily true. In this context, the term resolution can be used to refer to the spacing between entities forming the grain (Figure 3.3.b). When a question involves structures and processes with a coarse grain size, a large-scale perspective is usually required simply to encompass all the relevant variables. In a large-scale analysis with relatively coarse grained variables, gathering data and doing analysis at too fine a grain size may actually obscure the processes relevant to the question at hand. This issue is discussed with examples in a description of the errors associated with scale in Section 3.2.4.

The term resolution may also be used when describing a model and, apart from time and space increments, may refer to the number of parameters in a model and the number of variables forming its input and output. Often, models that have very few input variables and low detail output are said to be "coarse resolution" models.

3.1.5. Large versus Small Scale

It should be noted that the accepted hydrological and ecological use of the term "large scale" is the opposite of approaches in cartography or photography (Meentemeyer, 1989; Wiens, 1989; Blöschl and Sivapalan, 1995; Haufler *et al.*, 1997). In this document, the hydrological usage of the term "scale" is followed, with large or broad scale referring to something with a large extent, and small or fine scale referring to something with a small extent. By necessity, a fine scale view of things needs a relatively fine grain size in order to be able to view objects or processes within its extent.

3.1.6. Process versus Observation Scale

Ideally, processes should be observed at the scale at which they manifest changes in state (Blöschl and Sivapalan, 1995; Aust. Scales Workshop, 1995). However, this is not always possible, as many processes simultaneously operate at a variety of scales and often only small scale (e.g. point) measurements are available. Many researchers have noted that making observations at incorrect scales may result in a variety of errors. These are discussed in more detail in Section 3.2.4.

There is a difference between process and observation scale, which is essentially a problem of whether scale is viewed as absolute or relative in terms of both space and time. If space is viewed as absolute, its boundaries are absolute and clearly defined. In this case, space is defined by an area of a fixed size, which may be further divided into equal sub-areas, i.e. an Euclidean point of view. According to Meentemeyer (1989), when referring to geographical studies, defining space as absolute, is the appropriate approach for most mapping and descriptive studies. Ecological studies with the aim of identifying and describing species have followed a similar approach, where sampling is performed on a fixed spatial grid, and provide a temporal parallel to absolute space, for a fixed time period (Wiens, 1989; Weeks *et al.*, 1996; Tharme, 1997).

If space is viewed as relative, it is defined by the spatially based processes under consideration and may be described in non-Euclidean terms. A catchment, for example, is a spatial unit defined relative to the processes affecting it, and its hydrological extent is not explicit. Consequently, spatially-based processes may be difficult to map in terms of absolute space (Meentemeyer, 1989). Thus, if spatially-based processes and mechanisms are the focus of a study, it is necessary to view space in relative terms.

Similar arguments can be put forward in terms of time, i.e. temporal scale. Klêmes (1983), distinguishes between administrative (e.g. week, month) and physical (e.g. season) time scales. These can be compared to absolute and relative space respectively, where physical processes define physical time scales, such as the season, and administrative time scales are arbitrary and absolute. However, it should be noted that these suggestions ignore the deeper argument that surrounds the assumption that the units used to measure space and time are themselves absolute, whilst space and time are in fact defined as relative measures.

Wiens (1989) suggested that linking catchment abiotic and biotic processes depends upon identifying the abiotic processes which determine biotic responses, and the spatial scale at which these abiotic processes become the dominant component governing biotic response. Linking of hydrological, geomorphological and ecological models involves the linking of abiotic processes with biological responses.

Hydrological processes, such as streamflow, and their hydraulic characteristics such as depth and velocity of flow, affect the geomorphological dynamics of a river channel, both of which affect fish. Clearly, if the processes are of overriding concern, linking of catchment abiotic and biotic processes should involve a relativistic view of time and space. However, the processes influencing biotic response to abiotic conditions are not always identified. Consequently, forging this link requires the use of an approach that utilises both absolute and relative concepts of scale, both spatially and temporally.

In the ecological field, the view is held that grain and extent are defined purely by the organism (see section 3.1.2). According to this view, grain is the smallest scale at which an organism responds to its habitat and extent the largest scale of heterogeneity to which an organism responds (Kotliar and Wiens, 1990). Ecologists have held the view that, in order to relate changes in landscape ecological pattern to processes affecting the distributions and abundance of species, it is essential that an organism-centred view of space is accepted (Gardner *et al.*, 1991, Wiens *et al.*, 1985). However, this approach ignores the fact that many abiotic processes affecting ecological patterns are neither observable nor modellable at these organism-centred scales. Wiens (1989) modified his use of grain and extent from being organism-defined to being observer-defined; in effect a top-down rather than bottom-up approach. This interpretation of grain and extent is used in this document.

It has been noted that sciences dealing with processes and mechanisms are better able to switch scales than those whose emphasis is descriptive and thus deal mainly with observed phenomena (Meentemeyer, 1989; Levin, 1992). This is because the scale of observation is determined by the observer and the phenomenon being observed, and is most likely expressed in absolute terms. Dealing with processes, however, necessitates the observation of the process at a scale appropriate to it, i.e. a relative view of space. It has already been noted that processes should be studied at the scale at which they occur. Obviously, this is not always possible - large scale processes may often only be studied using aggregations of small scale (absolute) measurements, or, more likely, the aggregated and integrated effects of these processes are measured. For example, streamflow which, although measured at a point (absolute), is an integrator of processes occurring at scales far larger than the point at which it is measured. Thus, process scale actually refers to a relative view of scale, whilst observation scale is most often absolute.

In an ideal field experiment, processes should be observed over a large extent with a high resolution and a small grain. This would allow any "signal" measured to be close to the true "signal" produced by the process being observed. However, such a situation is rarely possible. In reality, some form of compromise in the experiment design is made. This may have a variety of effects on the interpretations of observations made.

If the experiment is designed with a large spacing (resolution) compared to the scale of the process being observed, the true process may not be resolved by the sampling and will appear as noise, as illustrated by Figure 3.5a. In the example illustrated by Figure 3.5a, the frequencies that do appear in the data are larger than those of the true process. This effect is known as "aliasing" (Blöschl, 1996). This also results in a tendency to underestimate the variance of the natural process as the sampling does not pick up part of its variance, as it lies between the sampling points.

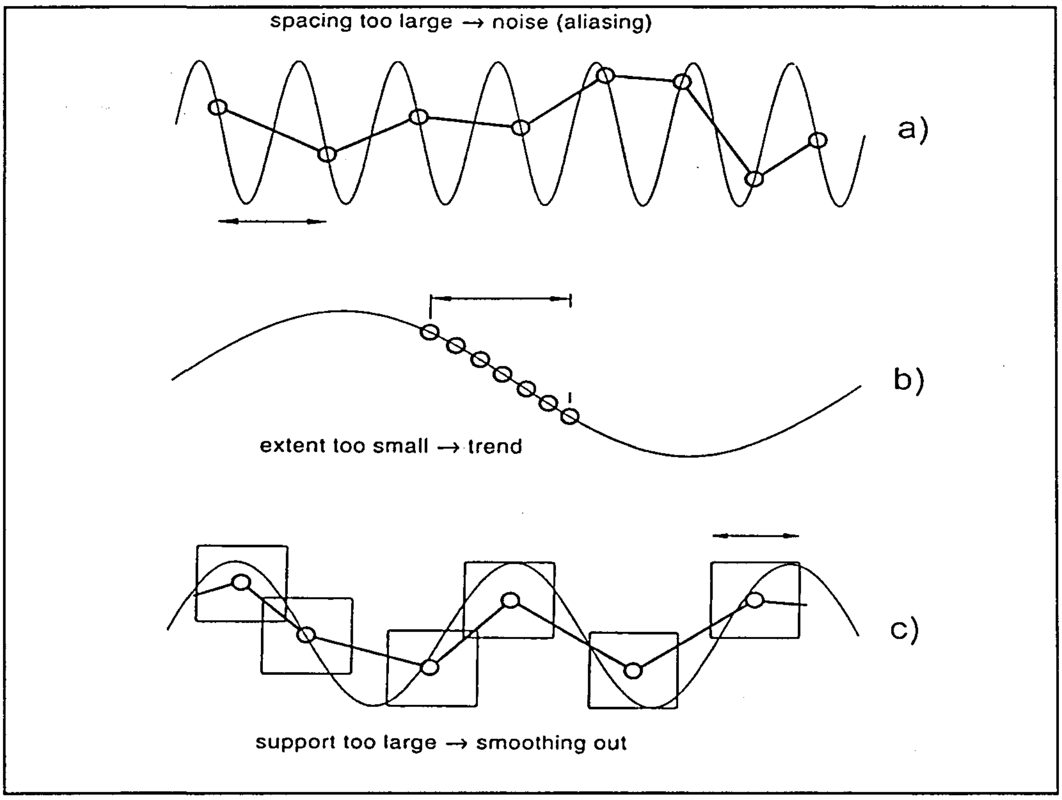


Figure 3.5 The effect of sampling for observation scales not commensurate with the process scale. (a) Resolution (spacing) larger than the process scale cause aliasing in the data; (b) Extents smaller than the process scale cause a trend in the data; (c) Grains larger than the process scale cause excessive smoothing. The process scale is the period (Blöschl, 1996).

If the extent of the observation is small compared to the process scale (Figure 3.5b), the true process will also not be properly identified and will appear as a trend in the data. This indicates that the underlying process exhibits a large scale component which is larger than the extent of the observations, i.e. the process scale is larger than the observation scale in terms of extent (Blöschl, 1996). Trends in data are often considered to be evidence that the underlying process is non-stationary. Most statistical methods are based on the assumption of stationarity. Thus, in many fields, trends (non-stationarities) are removed from the observed data before processing. This has the effect of removing the large-scale component of variability. Blöschl (1996) concluded that correlation scales that are estimated from "detrended" data would always be smaller than those estimated from the original data. Furthermore, Figure 3.5(b) illustrates that the effect of a small extent in the observation scale compared to that of the process scale, will result in the variance of the process being underestimated.

If the grain of an observation is too large (Figure 3.5c), excessive smoothing of the true process may occur. However, in the disciplines involved in the KNPRRP, excessively large observational grains are not a problem. Rather, the problem is that the grain of the observations is too small, and the resolution too coarse. As a result, there are gaps between the data points from which no information is available. For a given resolution, data with a large grain contain more aggregated information about the underlying process than with a small grain. Large grain sizes have the effect of smoothing out variability, resulting in the underestimation of the variance of the process, as explained in more detail in Section 3.2.1.

Figure 3.6 summarises the discussion above and illustrates that processes operating at scales larger than the scale of the observation extent appear as trends in the data, processes occurring at scales smaller than the observation grain appear as noise. It must be noted that the effect of observation scale (grain, resolution and extent) should always be viewed as relative to the process scale.

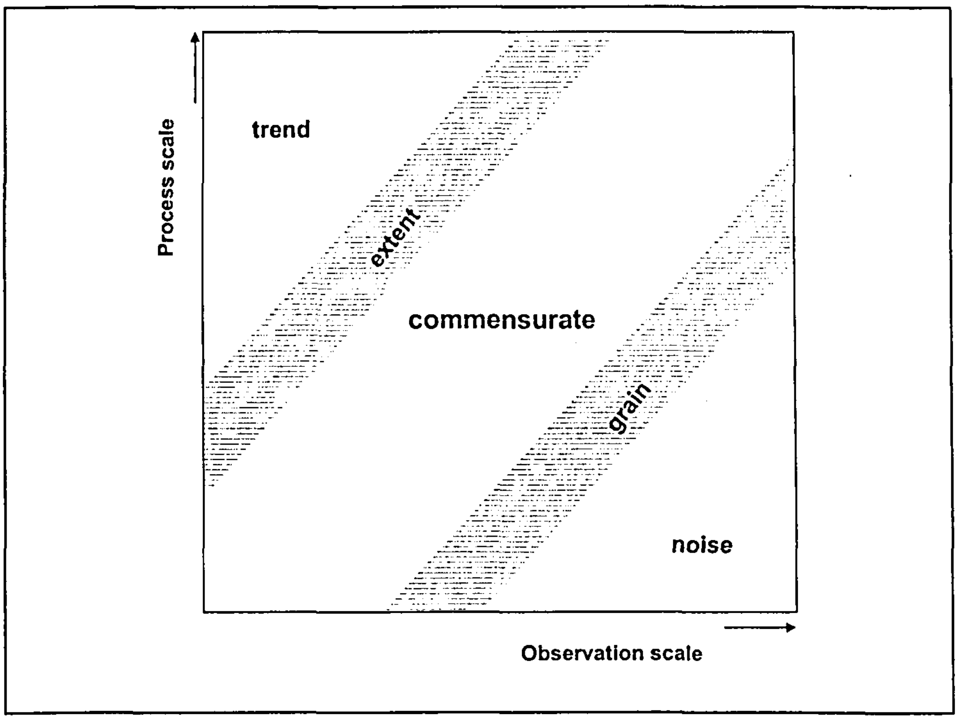


Figure 3.6. The effect of sampling as a function of process scale and observation scale (with grain small) (Blöschl, 1996)

3.1.7. Commonly Used Scale-Related Terms

Many terms are used in the literature, often with very little explanation, when referring to spatial or temporal scale. A brief description of the usage of some of these terms in this document follows.

Point Scale – measurement at a point ($<1m^2$), e.g. measurement of rainfall in a gauge.

Local Scale - usually refers to small ($<10m^2$) area of measurement.

Hillslope Scale - also referred to as field scale, especially in hydrology experiments. Typically an area of approximately $1000m^2$ in extent.

Landscape Scale - refers to a relatively homogeneous group of physiographic, geomorphic or vegetation characteristics.

Catchment Scale - a relative measure applied to the drainage area of a particular tributary of a primary river channel. Typically ranging in size from $1km^2$ to $1000km^2$.

Basin Scale - usually refers to the primary river catchment, e.g. the Sabie River catchment forms part of the Nkomati Basin.

Regional Scale - refers to a climatic region, e.g. The Lowveld or the Winter Rainfall Zone are often referred to as regions of South Africa.

Diurnal - temporal measurement referring to changes between day and night.

Event Scale – the length of time an event, such as a flood, is discernible.

Daily, weekly, monthly, seasonal and annual - commonly used temporal measurements.

Long-term scale – usually used to refer to a period of many decades, or even centuries.

3.2. EFFECTS OF SCALE

Much of the terminology associated with the issue of scale has been clarified in the previous section. Before exploring some of the more specific scale influences, some examples of the effect of scale are presented. Table 3.1 is a summary of some general characteristics of various attributes of ecological systems and investigations at "fine" and "coarse" scales.

Table 3.1 General characteristics of various attributes of ecological systems and investigations at "fine" and "broad" spatial and temporal scales. "Fine" and "broad" vary as they are defined relative to this study (after Wiens, 1989).

Attribute	Fine Scale	Broad Scale
Number of variables important in correlation	Many	Few
Rate of processes or system change	Fast	Slow
Effects of individual movements on patterns	Large	Small
Factors affecting species distribution	Habitat, Species Interaction	Barriers, climate
Resolution of detail	High	Low
Sampling adequacy	Good	Poor
Effects of sampling error	Large	Small
Experimental manipulations	Possible	Difficult
Replication	Possible	Difficult
Empirical rigour	High	Low
Potential for deriving generalisations	Low	High
Form of models	Mechanistic/ Conceptual	Correlative/ Conceptual/ qualitative
Testability of hypotheses	High	Low

The largely qualitative effects of scale listed in Table 3.1 have several implications. Different sets of physical laws prevail at different scales. This arises from the important feature that one "element" at a particular scale arises from the interaction of a vast number of "elements" at a lower level. Consequently, the laws at the higher level may express the "averages" of those that are dominant at lower levels. The fact that different forces tend to dominate at different levels, puts severe limitations on the validity of mathematical relationships between components formulated on the basis of empirical evidence at a given scale (Klêmes, 1983; Wiens, 1989). Consequently, empirical results are usually scale dependent (Meentemeyer, 1989). This enforces the importance of considering the relationship between observation and process scale as discussed in Section 3.1.6.

3.2.1. Heterogeneity and Variability

Heterogeneity and variability are two aspects closely related to and influenced by scale. The term "heterogeneity" is most often used to describe properties which vary with space (e.g. soil characteristics over a catchment), while "variability" is usually used to describe fluxes (e.g. runoff) or state variables (e.g. soil moisture) that vary in space and/or time (Blöschl and Sivapalan, 1995). Variability and heterogeneity are absolute and only have meaning relative to a particular scale of observation, i.e. their definition requires an implicit spatial or temporal scale. Figure 3.7 illustrates subsurface heterogeneity in a catchment. At the local scale, soils may exhibit macro-pores and cracks, at the hillslope scale, high conductivity layers and "pipes" may be identifiable. Heterogeneity at the catchment scale may relate to different soil types and their properties. At the regional scale, geology may be the dominant effect on soil formation.

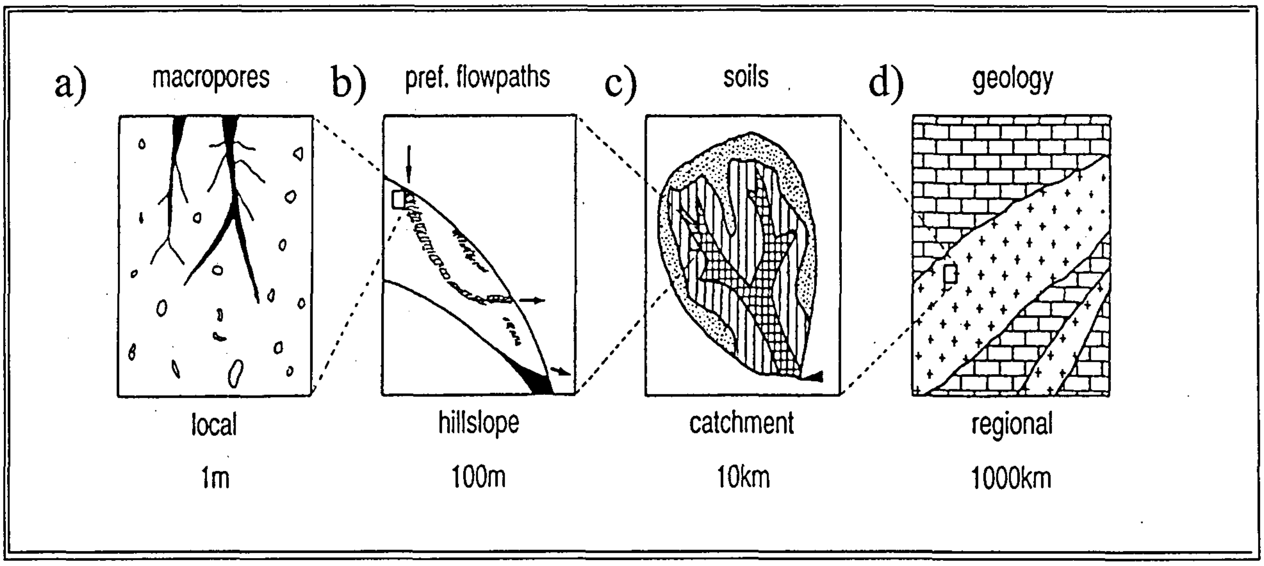


Figure 3.7 At the local scale (a), soils may exhibit macro-pores and cracks, at the hillslope scale (b), high conductivity layers and pipes may be identifiable. Heterogeneity at the catchment scale (c) may relate to different soil types and their properties. At the regional scale (d), geology may be the dominant effect on soil formation (after Blöschl and Sivapalan, 1995).

Figure 3.8 illustrates variability present in a runoff record at a range of scales.

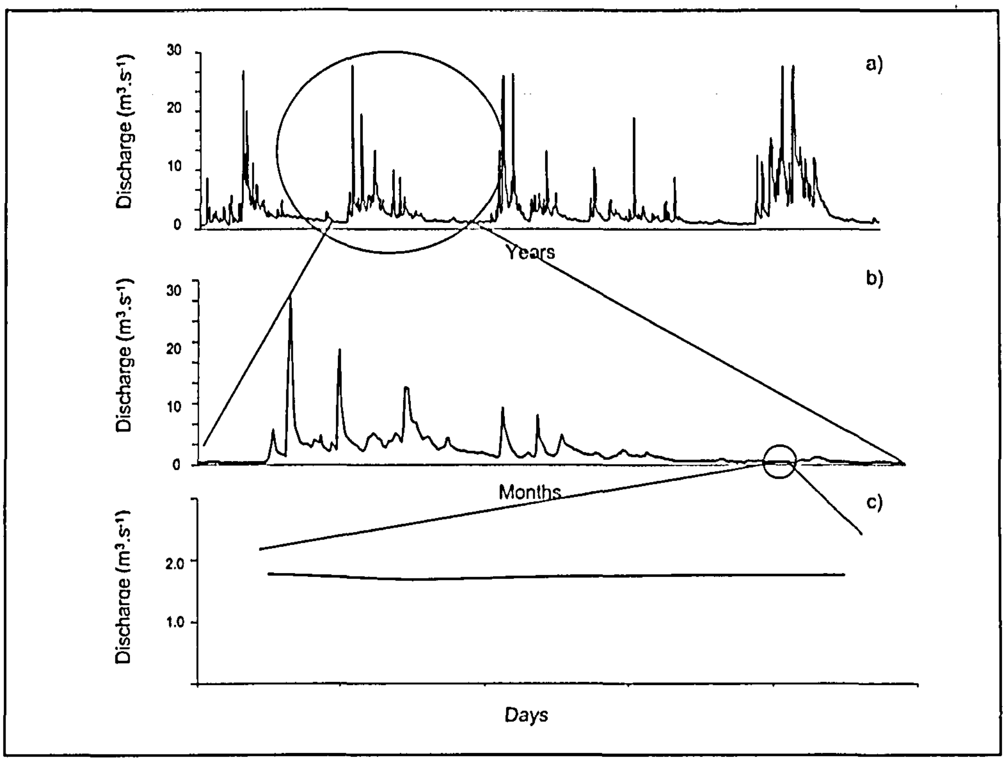


Figure 3.8 (a) shows year-to-year variation in annual precipitation and resulting streamflow (in the Sabie River); The number and intensity of storms is driven by regional climatic cycles; (b) illustrates that the strong wet summer/dry winter precipitation pattern imposes a variance of several orders of magnitude on streamflow between seasons; over 80% of precipitation in this case falls between October and April, with few or no storms and minimum flows in late August/September; (c) shows that during the winter streamflow recession period, diurnal changes in streamflow appear to be driven by evapotranspiration demands.

Figure 3.9 illustrates the effect of changing the spatial extent of a study area. It can be noted that as the extent of the study is increased (large squares), elements of the landscape that were not present in the original extent are included. As the grain of the samples is increased (small squares), small patches that were previously differentiated are now included in the sample and the differences between them averaged out. Consequently, the quantification of variation requires the determination of relevant scales (Levin, 1992).

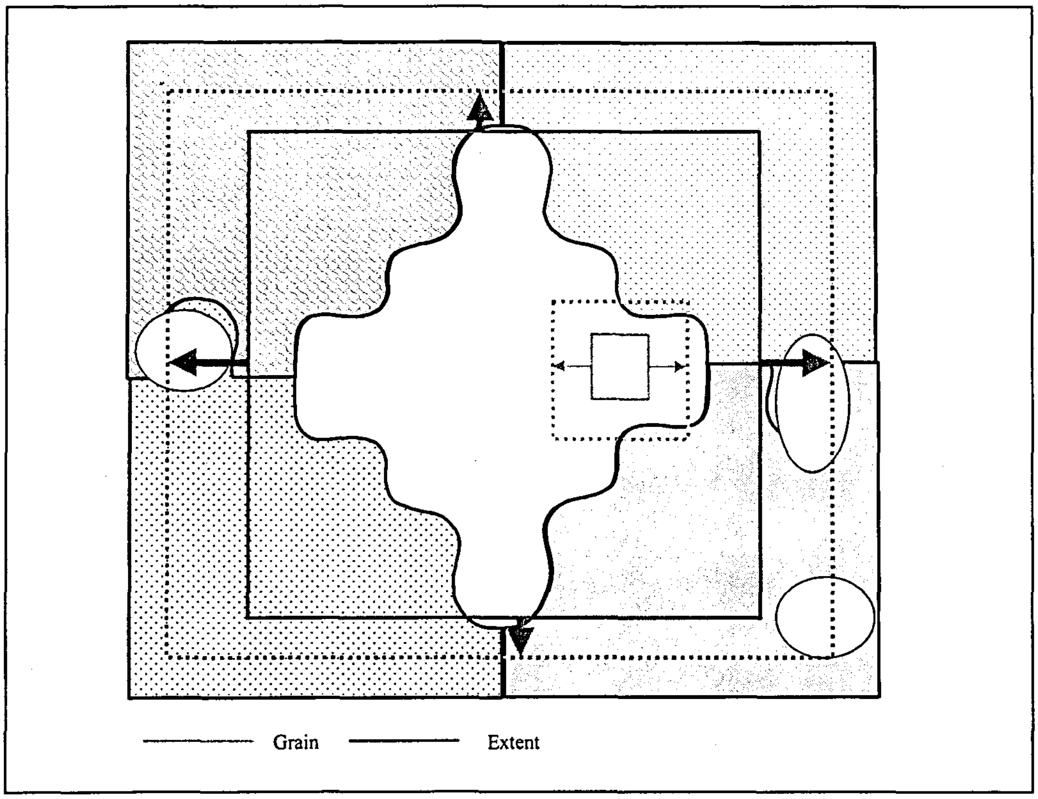


Figure 3.9 The effects of changing grain and extent on a study (after Wiens, 1989).

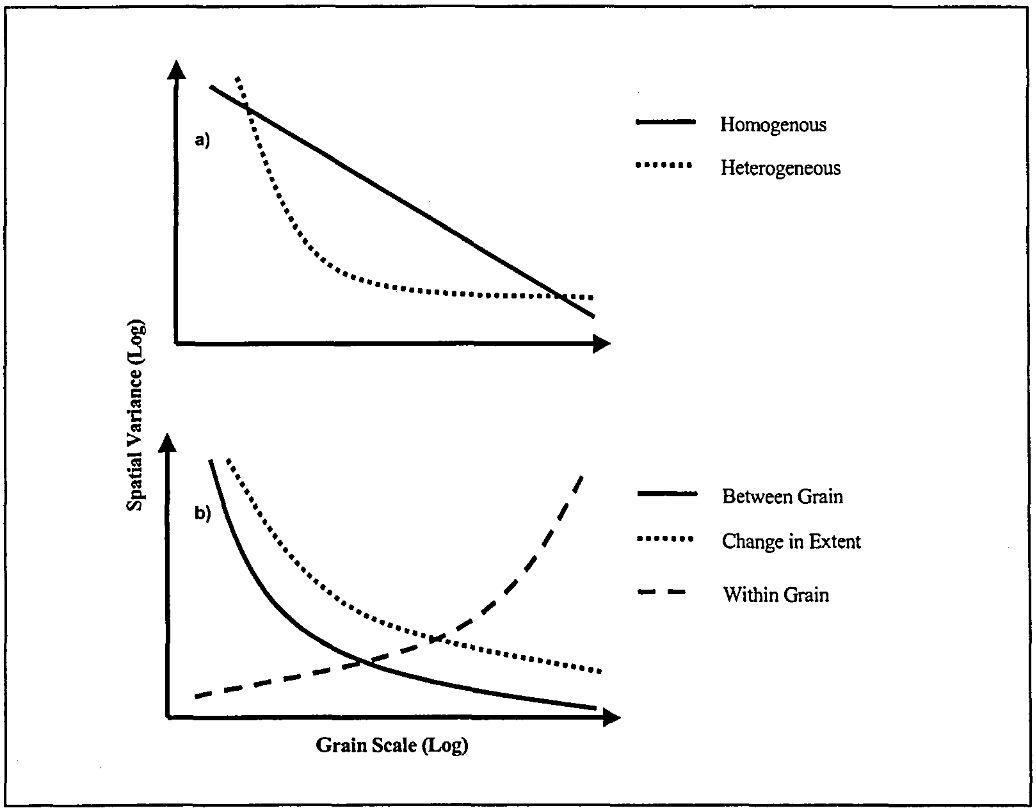


Figure 3.10 The effect of heterogeneity and changing grain and extent on variance (after Wiens, 1989).

A commonly used statistical index of variability is variance, σ^2, which is calculated as;

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(Z_i - m)^2$$

Equation 3.1

In homogeneous environments, spatial and temporal variability will be a function of the size of the grain (*n* in Eqn. 3.1). As the grain increases, so variability decreases. Thus, in a perfectly homogeneous area, a log-log plot of variance, σ^2, versus grain, *n*, has a slope of -1 (Figure 3.10a). However, in a heterogeneous area, as grain size increases, more spatial heterogeneity is contained within the sample, averaged out, and is lost to the study. If, on the other hand, the extent of the study is increased and grain remains constant, elements of the study that were not present in the original extent are included and greater spatial heterogeneity is included in the sample (Figure 3.9). Variability of the sample, according to Eqn. 3.1 above, must then decrease with increasing extent *n*, i.e. decreasing grain, or increasing extent, as illustrated in Figure 3.10b. This is related to within- and between- grain components of variation as explained further by the example below, developed by Isaacs and Srivastava (1989) and modified by Blöschl (1996).

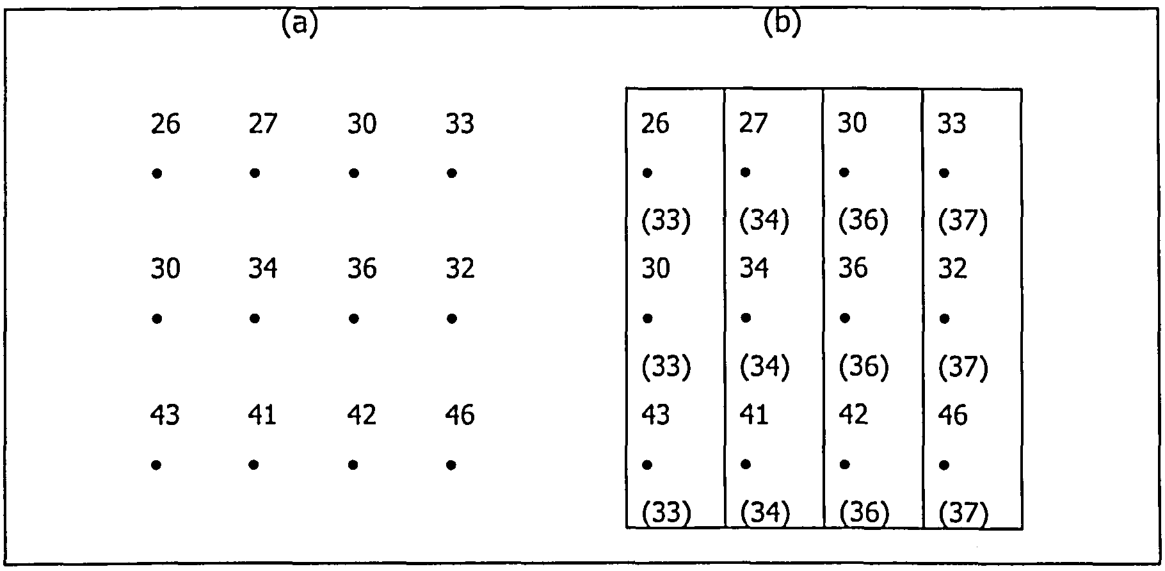


Figure 3.11 A representation of a hypothetical regular rainguage grid with 12 gauges. The point values are shown in (a) and grouped into 1x3 blocks in (b), with the average block values shown beneath each sample location.

Figure 3.11 shows 12 examples of, say, rainfall on a regular grid. The mean of these samples is 35mm.

The variance can be calculated as follows:

Variance of point values $= 1/12\ [(26-35)^2 + (30-35)^2 + (43-35)^2 +$

$(27-35)^2 + (34-35)^2 + (41-35)^2 +$

$(30-35)^2 + (36-35)^2 + (42-35)^2 +$

$(33-35)^2 + (32-35)^2 + (46-35)^2\ ]$

$= 40.0\ mm^2$

In Figure 3.11b, the grain has been extended to form four 1x3 blocks while the extent is kept constant. Beneath each sample, the value of the corresponding block (grain) average is shown in parentheses. The variance of the four block averages may be calculated as:

Variance of block values $= 1/4\ [(33-35)^2 + (34-35)^2$

$(36-35)^2 + (37-35)^2\ ]$

$= 2.5\ mm^2$

A further source of variance is represented by the variability of the point values within their corresponding block:

Within blocks (grain)

variance of point values $= 1/12\ [(26-33)^2 + (30-33)^2 + (43-33)^2 +$

$(27-34)^2 + (34-34)^2 + (41-34)^2 +$

$(30-36)^2 + (36-36)^2 + (42-36)^2 +$

$(33-37)^2 + (32-37)^2 + (46-37)^2\ ]$

$= 37.5\ mm^2$

The three calculations above are similar in that they are all calculations of some average squared deviation. They differ only in the grain size of the individual values and in the mean that is subtracted from each individual value. It can also be noted from the example above, that total variance can be calculated as the variance of the point values within the block forming the grain plus the variance between block averages within the extent, i.e.:

σ^2 (total) = σ^2 (within grain) + σ^2 (between grain)

Thus, with increasing grain scale, less of the variance is due to differences between the samples and more of the overall variation is included in the samples and averaged away (Figure 3.10b). Increasing the extent of the study may increase the between-grain component of variance but within-grain variance is not noticeably affected (Wiens, 1989).

Thus, as the scale, here meaning grain, of description and observation increases, variability decreases, and the ability to predict merely average conditions increases. In biological systems, Levin (1992) attributes this effect to moving beyond the scale of individual disturbances.

3.2.2. Scale and Predictability

The ease with which the response of a system may be estimated is commonly referred to as the predictability of that system. Predictability is inextricably intertwined with variability, and with the temporal and spatial scales of interest (Levin, 1992). The effects of local heterogeneity are averaged out at broad scales, consequently, patterns appear to be more predictable at broader scales (Wiens, 1989; Levin, 1992; Harris, 1996). However, models of broader-scale patterns must then result in less predictive accuracy at specific points in space and time (Meentemeyer, 1989; Levin, 1992).

As mentioned previously, in the context of observation of natural processes, there is an intrinsic relationship between time and space. As the spatial scaling of a system increases, so too does its temporal scaling, although these relationships will differ between systems (Wiens, 1989). Figure 3.12 shows that studies conducted at a coarse time scale at fine spatial scales have a low predictive capacity. Fine temporal scale studies conducted at coarse spatial scales may appear to have high predictive capacity, however, they may be only "pseudopredictions", as the time resolution of the natural dynamics of the system under consideration are longer than the study period. This relationship between spatial resolution and predictability has also been analysed by Costanza and Maxwell (1993). They found that while increasing scale provides more descriptive information about the aggregate patterns in the data, it also increases the difficulty of accurately modelling those patterns. Allied to this, Wiens (1989) and Levin (1992), both concluded that fine-scale studies may reveal greater detail about biological mechanisms, but that generalisations are more likely to be identifiable at broader scales. In other words, processes operating at scales larger than the scale of the observation extent appear as trends in the data, processes occurring at scales smaller than the observation grain appear as noise (as discussed in Section 3.1.6).

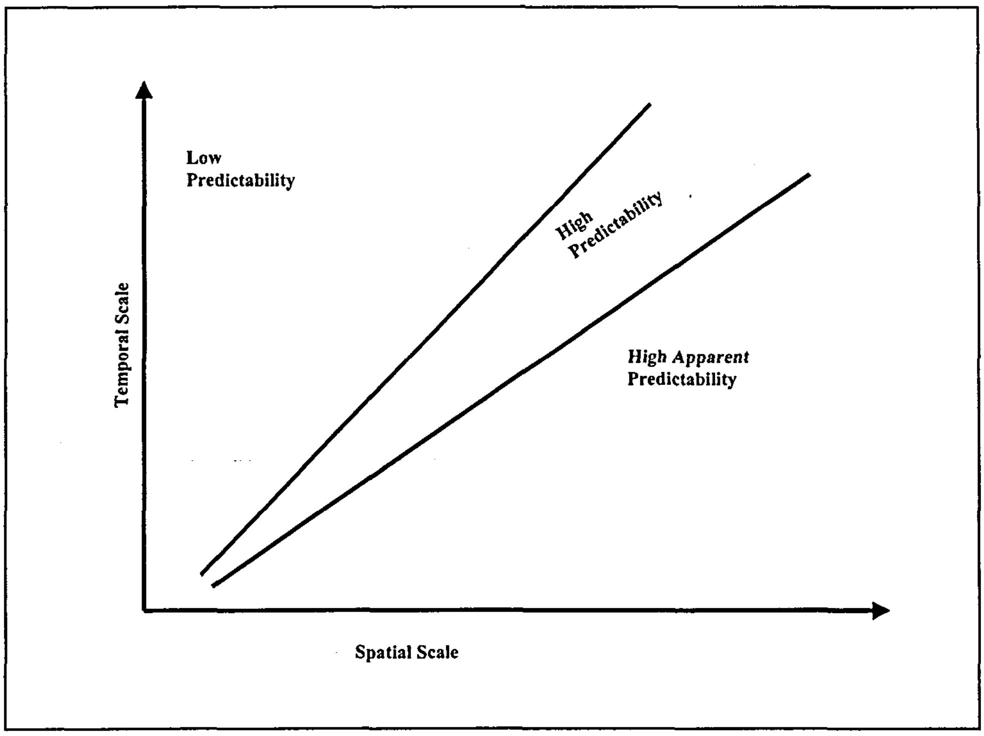


Figure 3.12 The effects of scale on predictability (after Wiens, 1989).

Because many researchers have found that local interactions, be they ecological, hydrological or hydraulic, are more pronounced at smaller than at larger scales (Wiens, 1989; Blöschl and Sivapalan, 1995), they avoid the confusing picture presented by local interactions by focussing on processes and phenomena which involve broad spatial scales. These appear to be changing at rates which require long time scales to observe and model (Meentemeyer, 1989; Blöschl and Sivapalan, 1995). This is a basic technique of scientific enquiry (Levin, 1992): i.e. by changing the scale of prediction, it is possible to move from apparently unpredictable, unrepeatable individual cases to collections of cases whose behaviour is regular enough to allow generalisations to be made.

The effects of components which do not react linearly to aggregation raise some significant points with regard to the influence of spatial and temporal scale on the performance of models, in particular their predictability (Costanza *et al.*, 1993). For example, a complication with using aggregate models, which integrate over many details of fine resolution, is that the aggregate models may not be able to represent biological processes at the space and time scales necessary.

3.2.3. Changing Dependencies with Scale Variability of Dependent and Independent Variables

As indicated previously, different sets of apparent physical laws tend to dominate at different scales. Consequently, dependent and independent variables may vary with the processes being observed, or when viewed with absolute measures, with changing scale.

With an absolute perspective of time, at a time scale of months to years, the geomorphic units found in a channel type are dependent on the hydrological conditions, i.e. flood, drought and their associated geomorphological effects - such as sediment scouring or deposition. At a more immediate time-scale, the local hydraulic conditions are dependent upon the geomorphic units present at a point in the river, because they determine the instantaneous cross-sectional flow area and slope which in turn determine the instantaneous discharge, i.e. the independent and dependent variables switch. Thus, at certain temporal scales, hydraulic conditions are dependent upon the geomorphic units present in the river. However, if a significant flow event occurs, the geomorphic units are then altered by hydraulic conditions and the dependent variables switch. At certain spatial scales this is also true. The microhabitat of an organism within 1 m^2 is dependent upon the local hydraulic conditions irrespective of the time scale. At any spatial scale larger than that, e.g. the *geomorphic unit* and *channel type* (Figure 2.5), some components of discharge become dependent upon the unit of study, for any time scale, providing it is not during an extreme, or "formative" event such as a flood (when there is a switch in dependent and independent variables).

However, with a relativistic view of time and space, the geomorphic units making up a channel are dependent on, or a function of, *inter alia*, the "equilibrium" catchment hydrology, whilst the local hydraulic conditions are dependent upon those geomorphic units. Thus, the geomorphic units reflect the processes associated with medium to long-term "regional" hydrology of the river at scales larger than the channel.

The changing dependency with scale may cause much confusion in interdisciplinary research. The use of relative definitions of scale may circumvent some of this confusion. For example, the matrix in Table 3.2 depicts fluvial geomorphic components (spatial scale) which are dependent upon hydraulic conditions (flow depth and velocity) for a range of temporal scales. The matrix below assumes steady state hydrological conditions prevailing in the catchment and is developed assuming absolute measurements of time and space.

Table 3.2 Matrix of fluvial geomorphic components (spatial scale) the altering of which is dependent upon steady-state hydraulic conditions (flow depth and velocity) for a range of temporal scales.

"1" = "dependent upon hydraulic conditions of flow".

	Sec.	Min.	Hr.	Day	Wk	Mnth	Seas	Yr.	Dec.	Cent
Substratum	1	1	1	1	1	1	1	1	1	1
Geom. Unit	0	0	1	1	1	1	1	1	1	1
Channel Type	0	0	0	0	0	1	1	1	1	1
Reach	0	0	0	0	0	0	1	1	1	1
Segment	0	0	0	0	0	0	0	0	1	1
System	0	0	0	0	0	0	0	0	0	1

However, if the matrix is altered to reflect which geomorphic units are dependent upon hydraulic conditions during say, a 1:10 year flood, the matrix changes its appearance. A flood is likely to last less than a month, thus, at temporal scales larger than a month, the geomorphic units cannot be directly dependent upon a flood. Secondly, a 1:10 year flood may be relatively localised and will probably not affect the whole river system.

Table 3.3 Matrix of geomorphic components which are dependent upon hydraulic conditions during a 1:10 year flood at a single point in time.

	Sec.	Min.	Hr.	Day	Wk	Mnth.	Seas.	Year	Dec.	Cen.
Substratum	1	1	1	1	1	0	0	0	0	0
Geom. Unit	1	1	1	1	1	0	0	0	0	0
Channel Type	1	1	1	1	1	0	0	0	0	0
Reach	1	1	1	1	1	0	0	0	0	0
Segment	1	1	1	1	1	0	0	0	0	0
System	0	0	0	0	0	0	0	0	0	0

3.2.4. Errors Associated with Scale

Generalisations across spatial scales and units of aggregation may generate various types of errors. It has already been noted in Section 3.1.6 that processes operating at scales larger than the scale of the observation extent appear as trends in the data, processes occurring at scales smaller than the observation grain appear as noise. Thus, it is not possible to generalise beyond the extent without assuming patterns and processes to be scale-independent (which is false), and impossible to determine patterns below the grain (Wiens, 1989; Blöschl and Sivapalan, 1995).

According to Haufler *et al.* (1997), inappropriate treatment of scale-related issues can be classified into two types of errors;

- Errors of Commission - the occurrence of a process/category/species is erroneously predicted in an area where it is absent, and
- Errors of Omission - when a model/method/analysis fails to predict the occurrence of a process/category/species that is actually present in an area.

Errors of Commission

The most common scale-related error of commission is asking a question, or attempting a solution to a problem, on a scale that is too small. Examples of scale-related errors of commission include questions asked, or an analysis framed, at a scale at which meaningful answers to the question cannot be provided.

For example, the afforestation of an area within a catchment may lead to questions about the impact of afforestation on the catchment runoff. However, without a broader spatial and temporal scale to provide context for these actions, there is no way of assessing the significance of changes emanating from a single plantation within a catchment. Broader scales are required to put this single action in the spatial context of the local and larger catchments, right up to the whole basin. Assuming that the catchment level response will be the same as the plot level of response is an error of commission, or what is referred to as an individualistic error by Meentemeyer (1989), i.e. calculating the outcome of macrolevel (aggregate) relationships based upon microlevel (individual) relationships.

Another form of scale-related error of commission may occur if it is assumed that the appropriate scale for a given issue is the same for all components of an ecosystem. Almost every natural resource issue has a biological, physical, social, and organisational dimension. Each of these dimensions has its own hierarchy, and it is quite possible that, when attempting to deal with a specific issue, the relevant questions may be at different scales in different categories of hierarchies (Haufler *et al.*, 1997). For example, in attempting to maintain the presence of a single fish species in a river downstream of a dam construction, the biological questions may be confined to the management of the river system where the fish breed and migrate. However, in the physical, social, and organisational hierarchies, the relevant scales are larger and more complex. Scales of the physical hierarchy that directly affect the fish may be very broad. For example, water quality changes, which may affect the fish, could be associated with acid precipitation which can have its source outside of the catchment, or even country, under consideration.

Errors of Omission

A scale-related error of omission (Haufler *et al.*, 1997) may occur when a relevant question is not asked, because it is not obvious at the limited scale or scales being considered. Focus on a single scale commonly obscures important related processes or issues that only become obvious at larger or finer scales. An example of a scale-related error of omission is the failure to consider cumulative impacts of an activity at a broader scale. For example, afforestation of a small area in a catchment may not have a significant effect on catchment runoff. However, repeating such an action over and over again, or across the catchment, requires the consideration of impacts at temporal and spatial scales larger than the single action. Failure to ask questions about cumulative impacts on broader scales is a scale-related error of omission (Haufler *et al.*, 1997).

A second common error of omission identified by Haufler *et al.*(1997) is the failure to examine impacts of a given action at a smaller scale. For example, an analysis within a predetermined boundary at a broad scale may attempt to analyse fine-scale features and processes. Haufler *et al.* (1997) cite the example of ecosystem analyses, performed at a catchment scale, attempting to answer questions regarding individual biotic species or specific silvicultural practices. The information required to answer these questions must be developed at a much finer scale than the catchment. Meentemeyer (1989) described such errors of omission, which he referred to as "ecological fallacy", a term obtained from the field of economic geography. Ecological fallacy involves making inferences about the individual or lower levels from higher levels of aggregation. These usually arise when the grain of an experiment is large and the estimate of variation for the observed phenomenon is low, as the mean values vary less than the values on which they are based.

3.3. RESOLUTION OF SCALE ISSUES

A number of methods have been used to resolve problems arising from issues of scale in environmental systems. Attempts have been made to develop relationships through which the dynamics at one scale can be understood as the collective behaviour of the components at a different scale. Levin (1992) believed that the key to understanding how information is transferred across scales is to determine what information is preserved and what information is lost as one moves from one scale to another. Attempts to understand this have included the development of scaling rules (or laws), the use of hierarchies to reflect the range of scales being dealt with and the selection of units that are representative of and characteristic of a larger unit. It is always preferable to scale up from fine resolution data to coarse scales, than vice versa, as the loss of resolution can be monitored and evaluated. The use of Geographic Information Systems (GIS) provides some useful methods of accommodating some scale issues.

3.3.1. Scale and Hierarchies

A hierarchy is a formal organisation of various spatial or temporal sizes or levels graded from small to large (Haufler *et al.*, 1997). Hierarchies are useful devices for organising information, analysis, and management across multiple scales. According to Hierarchy Theory, nature can be partitioned into "naturally occurring" levels that share similar time and space scales, and that interact with higher and lower levels in systematic ways. One end of the spectrum is characterised by high perspective and low detail, and the other end, by high detail and low perspective. Movement towards a lower level results in details becoming clearer, while assemblages, patterns, and relationships formed by these become less discernible. Movement in the opposite direction, towards a higher perspective region, results in the opposite effect; assemblages, patterns and relationships emerge while the detailed processes that form them become more obscure. In other words, look one level down a hierarchy for more detail and one level up for more context. Moving up the hierarchy also results in higher predictability (Levin, 1992). Viewing the system from several vantage points over the entire spectrum provides complementary understandings of real-world systems whose complete nature is beyond human perception.

It was recognised in Section 3.1.2 that one observational element at a particular scale arises from the interaction of a vast number of elements at a lower level. Consequently, the laws at the higher level may express the averages of those dominant at lower levels. Hierarchy Theory embraces this idea, as many hierarchies developed for natural systems are spatially nested, i.e. a system at one level forms the environment or context for systems making up the lower levels of the hierarchy.

Allen (1987) believed that it is a mistake to believe that any levels of a hierarchy are any more (or less) arbitrary than any others. He is supported by the opinion of Wiens (1989) that scales chosen for analysis are arbitrary in that they tend to reflect hierarchies of spatial scales that are "based on our own perception of nature". In nature, scales of things are not arbitrary, but arise as a function of their material substance and of the balance between the interacting forces (Klêmes, 1983). Many systems, such as the hydrological system and ecosystems and their various components, may change gradually, forming continua on the Earth's surface, which traverse administrative and political boundaries. Based on their understanding of these systems, scientists and managers, *inter alia*, form boundaries by using physical, biological, and social considerations. Wiens (1989) has called for non-arbitrary methods of defining and detecting scales.

As explained previously, the evidence of a "spectral gap" may form the basis for definition of a hierarchy of scales that is less arbitrary than those commonly used. O'Neill *et al.* (1986) recognised that variance increases as transitions are approached in hierarchical systems. However, this seems to be putting the chicken before the egg. The evidence of increased variance should indicate a transitional zone, not vice versa. A variety of methods have been used in attempts to define natural scales of apparent patterns. In addition to analyses of variance, these include spectral analysis and the application of fractal geometry.

In reality some hierarchies will be based on naturally occurring scales as they grow out of functional and/or structural boundaries that exist in the physical world, most likely associated with the "preferred nodes" identified by Klêmes (1983) and discussed previously in Section 3.1.1. Some physical hierarchies (e.g. substratum to geomorphic unit to channel type to reach) are examples of largely natural hierarchies. On the other hand, some hierarchies are largely human-created systems and depend upon administrative, not natural or physical boundaries, and many of these will remain this way, especially where multi-disciplinary projects are concerned.

At each level in the hierarchy the higher levels may appear as constraints and the lower levels as noise. It is necessary to note that what appears to be "noise" at a lower level could be turned into significant perturbations on the higher level. This could happen when a critical mass of components form a pattern, which affects the slower processes at the higher level. The rapid and extensive human uses of fossil fuels could be seen as such a pattern, causing perturbations at the global atmospheric level, which might feed back and radically alter the framework of action at the lower level.

The simplifying assumptions inherent in Hierarchy Theory may ease the problem of scaling by providing a common (but generalised) set of rules that could be applied at any scale in the identified hierarchy.

3.3.2. Scaling Rules and Laws

The process of "scaling" refers to the application of information or models, developed at one scale, to problems at other scales. Upscaling refers to transferring information from one scale to a broader scale. Downscaling refers to transferring information to a finer scale.

In many disciplines, including hydrology, geomorphology and ecology, primary information and measurements are generally collected at relatively small scales (e.g. small runoff plots in hydrology, 1m x 1m quadrants in ecology) and that information is then used to build models at very different scales (e.g. catchment, river basin). There is a need to know which properties change and which are invariant when scale changes. The process of scaling is directly tied to the problem of aggregation, (the process of adding or otherwise combining components) which in complex, non-linear, discontinuous systems is a far from trivial problem.

Most commonly, the mode of scaling has been to obtain data at fine scales, aggregate and compare these with results obtained at coarse scales, in the hope that either linear or otherwise parameterisable relationships may be found. If the data do not scale linearly, the model must operate at the scale of the data collection - regardless of its practicality. This has been termed the "tyranny of scale" (Dubayah, 1996). The focus of research into scaling has been the search to discover the most relevant macroscopic statistics that may inform the broader scales about the behaviour of the finer scales (Levin, 1992).

The major reason for errors in aggregation in scaling complex systems is the non-linear variability in the fine-scale phenomenon. An example of this is given by Rastetter *et al.* (1992), who developed a scaling relationship for individual leaf photosynthesis as a function of radiation and leaf efficiency, and used this to estimate the productivity of the entire forest canopy. Rastetter *et al.* (1992) noted that, because of non-linear variability in the way that individual leaves process light energy, one cannot simply use the fine-scale relationships between photosynthesis, radiation, and efficiency along with the average values for the entire forest to get total forest productivity without introducing a significant aggregation error. They believed it necessary to somehow understand and incorporate this non-linear fine-scale variability into the coarse-scale equations developed.

Three basic methods for scaling that are applicable to complex systems are described and compared by Rastetter *et al.* (1992). All the methods are attempts to utilise information relevant to non-linear small-scale variability in large-scale models.

Rastetter *et al.* (1992) described the following methods of scaling:

- Partial transformation of the fine-scale mathematical relationships to coarse-scale using a statistical expectations operator that incorporates the fine-scale variability. This implies deriving new coarse-scale equations that incorporate the fine-scale variability. The incorporation of this variability leads to equations that are extremely complex and cumbersome.

- Subdividing the system into smaller, more homogeneous parts (i.e. spatially explicit modelling). The implication of this method for their forest productivity study is that the forest must be subdivided into many relatively more homogeneous levels or zones and the basic fine-scale equations applied to each one. This requires a method for adjusting the parameters for each partition, a choice of the number of partitions (the resolution) and an understanding of the effects of the choice of resolution and parameters on the results.

- Calibration of the fine scale relationships to coarse scale data, when these data are available. This method requires that coarse-scale data are available (i.e. not simply the aggregation of fine-scale data). In many cases, however, these coarse-scale data are either extremely limited or not available. This is a method commonly used in hydrological simulations where measured runoff provides a coarse scale measurement for calibration of simulation models.

Rastetter *et al.* (1992) concluded that a combination of these methods is the most effective overall method of scaling in complex systems.

Scaling Laws and Fractals

Similarity is central to the concept of scaling and is based on the fundamental principle of "self-similarity" between scales, i.e. the recognition that variability of a particular process or observation exists at a range of scales (Wiens, 1989; Levin, 1992; Costanza *et al.,* 1993; Blöschl and Sivapalan, 1995). This concept implies a regular and predictable relationship between the scale of measurement (here meaning the grain) and the measured phenomenon. If a system is self-similar, i.e., there is some feature that is constant at all scales, it can be represented by something called a scaling law or power law. A scaling law is a simple description of how a system's features change in proportion to the scale of the system. For organisms or individuals differing in size, scaling relationships among them are known as allometric laws. A power law describes a system in a simple way over a range of scales and can be expressed as:

$$y = cx^a$$ Equation 3.2

where c is a system-specific constant and a is the power that describes the relationship. When viewed on a log-log plot the relationship is linear. Unlike arithmetic or geometric relationships, scaling laws tend to be very well behaved with little variance (i.e. R^2 values are close to 1.0).

Scaling laws are sought in many disciplines in order to explain, quantify and identify phenomena that may be scale-independent. For example, it has been noted that differently sized piles of sand have a critical slope. If the slope is greater than the critical value, an unstable situation arises in which avalanches occur to reduce the slope, until it reverts to the critical value (Gell-Man, 1994). The slope and size of laboratory induced avalanches from sand piles have been shown to follow a power relationship that may be used as a scaling law.

The concept of fractals is another related approach to the problem of scaling. The best known example of this is the Mandelbrot equation (Mandelbrot, 1977) which describes the measured length of a coastline as an increasing function of the resolution at which it is measured. At smaller spatial scales, more of the small-scale bays and indentations of the coast are noted and the total measured length increases.

The relationship between length and resolution usually follows a regular pattern that can be summarised in the following equation:

$$L = k\,s\,(1\text{-}D)$$ Equation 3.3

where:

L = the apparent length of the coastline or other "fractal" boundary

s = the size of the fundamental unit of measure or the grain of the measurement

k = a scaling constant

D = the fractal dimension

Observations that fit Equation 3.3 are said to be "self-similar" as a finer scale of study results in similar patterns appearing at the smaller scale to those at the broader scale. This convenient "scaling rule" has proven to be a very useful in describing many kinds of complex boundaries and behaviours (Mandelbrot 1983; Milne 1992). One test of the principle of self-similarity is that the equations can be used to produce computer-generated shapes that have a decidedly "natural" and organic look to them (Mandelbrot 1977).

3.3.3. Representative Units

Various methods have been used by earth scientists in an attempt to determine whether certain preferred spatial and temporal scales exist at which simple conceptualisations of critical processes are possible. Of the numerous methods reported in the literature, two of the most relevant to the KNPRRP are examined in this document.

Distributed Parameter Models

In many hydrological models, an attempt to quantify the hydrological variability that occurs at a range of scales is made by subdividing the catchment into a number of units or sub-areas. Models which use these methodologies are known as distributed function hydrological models. Commonly, these subdivisions are referred to as sub-catchments (Schulze, 1995), Hydrological Response Units (Flügel, 1995), hillslope units and regularly spaced square grid elements (Bathurst, 1986). The basic assumption behind these methods is that the parameters and processes within each unit are uniform and that the local scale interactions represented are applicable to the whole unit. Output from each of these units is aggregated to form the output for the catchment under consideration. In all cases, modelling is simplified because areas of the catchment within these units, are assumed to behave similarly in terms of their hydrological response. Implicit in the improvement of distributed hydrological models is their ability to represent the dominant physical properties at a number of space and time scales. In reality, the extreme heterogeneity in catchments and the large number of parameters required to quantify it, limit the effectiveness of the so-called "distributed approach". This form of aggregation effectively side-steps the hierarchy of scale by ignoring the natural heterogeneity within the unit. However, it recognises the heterogeneity at the broader scale of characteristics that distinguish the units from each other.

Beven (1987) believed that a theoretical crisis in hydrology was imminent because little or no success had been gained in relating the complexity at small scales, to the relative simplicity evident at broader scales. He believed that hydrology in the future would require a macroscale theory that dealt explicitly with the problems posed by spatial integration of heterogeneous non-linear interacting processes. Dooge (1986) suggested that hydrologists should search for scale independent, unifying hydrologic principles to accommodate complex issues regarding spatial variability, aggregation and scaling. Beven (1989) argued that the equations on which physically-based models are based, are those of the small scale physics of homogeneous systems, and that the scale in real applications of physically-based models is much larger. There is a need therefore to aggregate the small scale physics to the model scale. However, Beven (1989) continued that there is no theoretical framework for carrying out this lumping of point scale processes to spatially heterogeneous model units. It is merely assumed that the small scale physical equations can be applied at the model scale with the same parameters. Beven (1989) believed that, in doing so, a "conceptual leap" is made. Following these conclusions, Grayson *et al.* (1992) stated that physically-based distributed models are assumed to be based on physical processes that can be represented in a deterministic way, and that this assumption is possible in laboratories, but is violated in the field. Beven (1989) and Grayson *et al.* (1992) both concluded that physically-based distributed models lose their physical basis, and that they are merely finer scale lumped models and are subjected to the same disadvantages as the lumped conceptual models.

The Representative Reach Concept

A representative reach is a reach of river assumed to be representative of all similar reaches in a river system (Heritage *et al.*, 1997). It has been recognised that within a river zone (Figure 2.5), there are a number reaches that are similar to each other in having the full range of biotopes and geomorphological features found in the zone associated with that particular reach type (King and Tharme, 1993b). The selection of representative reaches within a catchment has, in the past, followed an imprecise and vague methodology aimed at selecting river reaches which cover the full range of aquatic habitat available in the river. More recently, with the assumption that the river geomorphology may form a template for riparian habitats, the selection of representative reaches has been governed by geomorphological criteria. Thus, the identification and selection of representative reaches is an attempt to rationalise a river system by identifying reaches that are representative of repeatable geomorphological types of the whole (Heritage *et al.*, 1997).

As discussed in Section 3.2.1, the larger the sample size, the greater the degree of confidence with which the biotic responses identified by ecologists can be quantified. The larger the data set, the greater the variation accounted for by the observations and the less the variability associated with any predictions derived from that data set. This has a parallel when applying a predicted assemblage response to a single point in space (Levin 1992). For example, applying any biotic response models produced to a single particular reach of river and expecting the model to simulate accurately, for example, the fish or riparian vegetation composition of that reach, is likely to produce very poor results. Typically, this single reach will display a high degree of variability in terms of the biotic entity being simulated. Furthermore, at this scale, processes not accounted for in the model, for example biological interactions, may cause much of this variability. However, if the reach being simulated is thought of as representative of all such reaches within the spatial extent in which the biotic phenomena were observed (i.e. it represents the average of all such reaches) the variability is reduced, and the model may be used with more confidence. As noted in Section 3.2.2, many researchers have found that local interactions, be they ecological, hydrological or hydraulic, are more pronounced at local than broader scales (Wiens, 1989; Frissel *et al.*, 1986; Blöschl and Sivapalan, 1995). In effect, applying the concept of a representative reach over a broad extent, has the effect of moderating the local interactions. Any simulation models produced then fit into the zone of predictability as identified by Wiens (1989) in Figure 3.12.

Thus, it is necessary that any simulation models produced should operate closer to the extent, rather than the grain, of the observations used to develop them. If predictions aimed at the experimental unit (grain) are needed, only the response data collected at that experimental unit should be used in its development (in the case of an empirical type of model), or a great deal more data should be collected in order to understand the biotic processes forming the observed responses and a mechanistic type model developed.

3.3.4. Scale and GIS

One of the most significant advances, in hydrological modelling, and in other earth sciences, of the past decade, has been the availability of tools that assist the manipulation of vast amounts of spatial data in the form of Geographic Information Systems (GIS). The use of GIS databases allows the representation of the earth in a manner known as georeferencing. A georeferenced database uses some co-ordinate system that can be related to the earth's surface (Ball, 1994).

GIS helps decision making in fields relating to ICM because many of these decisions have some spatial element. A GIS can access data spatially and provide a means for its visual inspection, comparison and analysis. GIS also offers the possibility of zooming into any sub-area down to the limits of the resolution of the database. Maidment *et al.* (1996) foresaw a major role of GIS in hydrological modelling in its capability to assist in explicit treatment of spatial variability. Thus, GIS is a powerful tool to represent spatial variability and to do spatial analysis. It is important to note, however, that a GIS is not a source of information, but only a way to manipulate information (Fedra, 1995). Furthermore, GIS may be useful for disclosing patterns, but it can actually impede progress by making non-useful (increased) levels of complexity possible (Reid and Ziemer, 1997).

GIS systems have advanced a great deal since the 1970's where they were primarily visualisation tools, whose output was used to aid decision-makers by displaying baseline and possible spatial patterns resulting from a management choice. In the 1980's these cartographic tools advanced by being linked to an attribute database management system (DBMS). Thus, it became much easier to examine the spatial context of the data and analyse combinations of the dataset. The advent of object-orientation in the 1990's has meant that the most advanced GISs are tightly-coupled spatial-feature systems in which data respond to spatial manipulation and spatial patterns immediately reflect manipulations in the database (Reynolds *et al.*, 1996).

The primary use of GIS is for the organisation of spatial data. Spatial data and information are readily available via digitising and scanning techniques and remote sensing. This information comes in a wide variety of forms, from complex topologically structured data, through huge satellite images, to simple tables of events.

The stored spatial data are explicitly (in the case of vector) or implicitly (in the case of raster) spatially indexed. Therefore, they can also be presented attractively and informatively, thus contributing to a better understanding of the problem at hand.

GIS has the ability to manage and perform complex processing on the spatial component of the data as well as the statistical aspects. In this way the actual geographic boundaries of regions defined in an area may be manipulated. This allows for the integration and synthesis of environmental information using natural units, such as, catchments, natural forest areas, soil units, etc. which may be combined with anthropogenic administrative and data collection units. GIS may then provide a tool for combining these separate themes of information, collected at different scales, to define and map systems at a common scale. But scientists and managers who want to use this technology intelligently in their work, must actually integrate information themes, comprehend processes, and formulate management strategies themselves (USDA, 1996). Integration, comprehension, and management cannot be accomplished mechanically. GIS merely provides a link between the users' or decision-maker's viewpoint and the natural boundaries of the problem.

In spite of the growing interest and demand, current GIS technology is limited in its applicability for environmental decision-making for a number of reasons (WMC, 1996). Spatial databases are frequently very large, and exceed the capacity of existing desktop computer systems. If detailed gridded data are available, the sheer data volume, and the need to perform repeatedly complex geometrical computation on spatial objects are the cause of the practical upper limit on the useable size of spatial databases in current GIS. Even with only moderately large databases, users commonly note "lack of user friendliness", "slowness" and "unreliability" (WMC, 1996).

Thus, the important uses of GIS in consideration of scale issues are to provide a graphical spatial context for many different spatial data sets, the ability to overlap and focus on different spatial scales. The belief that because of GIS scale has become a spurious issue (Ramsey *et al.*, 1995) and that GIS provides a panacea for scale problems in natural science disciplines, is false.

Chapter Four

MODELS AS TOOLS TO ASSIST INTEGRATED CATCHMENT MANAGEMENT

Models which provide a quantifiable response to a given development scenario are sought within many disciplines in order to aid objectivity in planning exercises. A further, and fundamentally important, reason for model development lies in their use as tools to assist in developing and nurturing communication between scientists of different disciplines and communication with affected stakeholders.

A model is effectively a simplified representation of some part of the real world. A model predicts effects from causes. Any description of the causes and effects in a system by means of symbolic logic can be considered to be a model of that system.

The development of an Integrated Catchment Information System (ICIS) (introduced in Section 2.4 and discussed in detail in the following chapter), which includes an integrated system of simulation models or Integrated Modelling System (IMS), faces major difficulties in the linking of catchment abiotic and biotic processes. As discussed in Chapter 2, this was a major component of Phase II of the KNPRRP and is a significant portion of the research reported in this document.

A problem identified in forging predictive links between the abiotic and biotic responses to flow changes, is that research in the abiotic and biotic fields suffered, until recently, from too little contact (King and Tharme, 1993a). It has been said that "multidisciplinary communication is one of the missing links in science" (Pattern, 1994). Modelling, especially that involving the use of simple models, can be a powerful tool in aiding communication amongst scientists (and others) (Starfield, 1996). Associated with this, is an emerging view that an integrated suite of such models may act as a living repository for the knowledge which the collective scientific community has about the catchment in question (Maaren and Dent, 1995).

4.1 TYPES OF MODELS AND MODELLING TERMINOLOGY

A model can either be a mathematical or statistical description of specific aspects of a process, or it can be in the form of qualitative descriptions of a cause and its effect. Computer-based modelling can be described as a method of expressing the parts and relationships of a concept or idea on a computer by symbolic logic. Examples include the rules governing a simulation to investigate the economics of the marketplace, a spreadsheet to calculate population growth, or the diagrams, formulae and software rules that may enable a user to study water movements in the hydrological cycle. Modelling software varies widely in form and function, from topic-specific software where the user manipulates variables within pre-defined limits, to dynamic modelling systems and spreadsheets where the user has to specify the rules based on mathematical formulae, to knowledge-based systems where the rules are made of logical text statements. Knowledge-based systems are those in which the expert knowledge of a person or group of persons is captured. These are also often referred to as "expert systems".

It should be noted that there are many different usages of "labels" such as "expert systems" and that their usage in this document may not always fit the reader's perception thereof.

4.1.1 Types of Models

Typically, models are divided into deterministic and stochastic sub-categories as shown in Figure 4.1. Essentially, the differentiation between classes of deterministic models is one based on the level of complexity used to represent the real world process to be simulated. This ranges from the complex mathematics of partial differential equations (PDE) to the simple IF-THEN rules included in what are known as qualitative rule-based models (QRBMs). Simulations of catchment hydrology are commonly performed with physical conceptual models. The empirical, conceptual and mechanistic models form what is referred to in this text as "traditional" or "quantitative" models. Thus, in the remainder of this document, models which are constructed using complex mathematical functions, are referred to as quantitative models and can be seen to form the "traditional" modelling approach. QRBMs, which are described in more detail below, can be seen to form a more novel modelling approach.

Models can also be classified as discrete or continuous. Discrete models are those that do not specifically account for time. Continuous or dynamic models are those that accommodate changes with time and often reflect an average response to average inputs and conditions.

Models may also be referred to as distributed or lumped parameter models as described in Section 3.3.3. In lumped models, the various parameters are homogeneous throughout the system being modelled. Distributed systems attempt to account for heterogeneity in the system under consideration by allowing the model parameters to assume different parameters spatially inside a particular modelling unit.

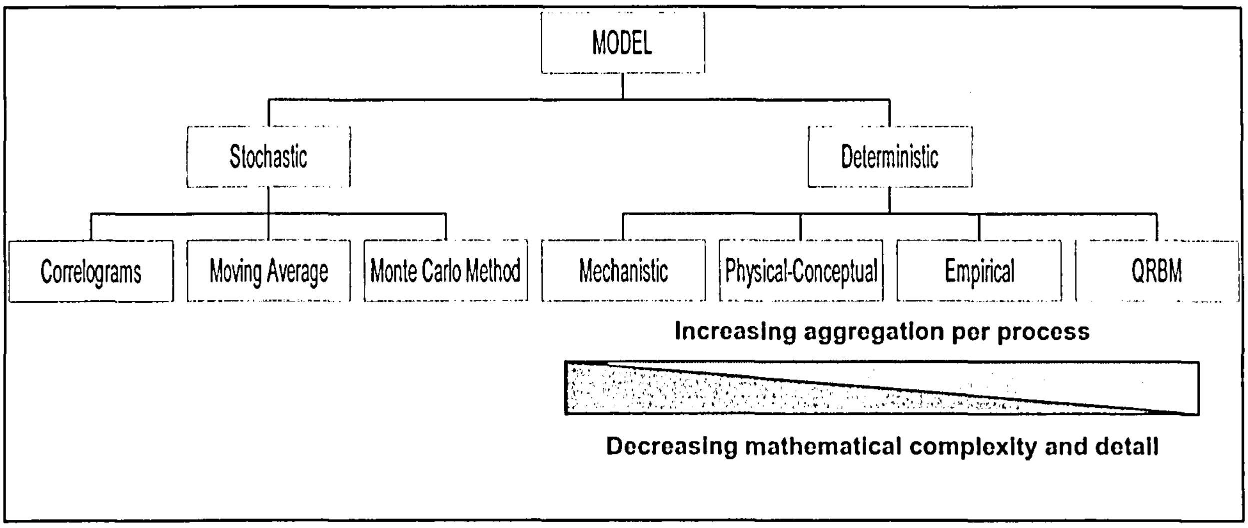


Figure 4.1 A categorisation of models, showing various modelling techniques and their relative complexity.

4.1.2 Modelling Terminology

Simulation is a term commonly applied to modelling exercises. A working definition of simulation is (Starfield *et al.*, 1990):

> *Simulation is the process of designing a model of part of the real world, then conducting experiments with the model to describe, explain, and predict the behaviour of that real world system.*

Thus simulation modelling is an experimental and applied methodology which seeks to;

- describe the behaviour of the system,
- construct theories or hypotheses that account for the observed behaviour, and
- use these theories to predict future behaviour, that is, the effects that will be produced by changes in the system or in its method of operation.

Critical to simulation modelling are the concepts of verification and validation. Model verification and validation are means of confirming that the model is internally consistent (verification), and accurately represents the portion of the real world the modeller is concerned with (validation) (Oreskes *et al.*, 1994). Validation exercises are performed by checking the correspondence between reality and the output of the simulation. Further observation of reality might be required to validate a model.

Models may include various components, such as pre- pr post-processing functions. Another modelling term commonly used is the "model engine", i.e. the component of the model which includes the algorithms that physically manipulate the input to produce output.

In the context of this document, it is important to distinguish between *qualitative* models and the better known *quantitative* models.

4.1.3 Qualitative Models versus Quantitative Models

There are instances where the intricate and complex nature of the process may defy manageable mathematical description. In these cases, qualitative models may be formulated. The simplest form of a qualitative model is the "rule-based" model. In recognition of this qualitative way of handling relationships between variables, this approach has become known as Qualitative Rule Based Modelling and the models developed are known as Qualitative Rule Based Models (QRBM). QRBMs may be used just as any other model to calculate or derive a value for an output variable given a set of input variables. However, this is done using logical inference and makes use of "IF-THEN-ELSE" constructs (i.e. rules) to describe process behaviour rather than continuous rate-based or mass balance-related algorithms. This is explained further using ideas formulated by Nicolson and James (1995).

In "traditional" models, relationships between constituents are generally mathematical, whereas, in a rule-based system, they are based on heuristic logic (Davis *et al.*, 1989). For example, if the flood levels of a river need to be simulated, then flow depth is an important process component to portray. This could be described as a real variable which has a name (e.g. depth), and which takes on some real value (e.g. the depth of flow measured in metres at the midpoint of the river). To assign a value to this variable in the model, a flow resistance equation (such as the well-known Manning equation), which relates the flow depth to the discharge for given channel roughness, slope and cross-section, could be used. Hydrological and hydraulic models make use of several equations such as these (e.g. continuity of water mass, flow resistance, sediment transport, soil moisture balance), either in the form of partial differential equations (PDE) or simple capacity-limited or mass-balance concepts, or empirical regression equations. The resolution of these equations generally requires numerical methods, and is computationally intensive. Many hydraulic sediment-movement models such as HEC-6 (Hydrologic Engineering Centre, 1977) are PDE-type models. Catchment hydrology models such as ACRU (Schulze, 1995), VTI (Hughes and Sami, 1994) and HSPF (Bicknell *et al.*, 1996) usually combine PDEs with a variety of mass balance and empirical equations to produce an output streamflow value.

It has been recognised that knowledge-based simulation systems do have some significant advantages over quantitative numeric type simulation systems. Simulation methods that use detailed equations to describe processes usually lead to the derivation of a single answer at an arbitrarily high level of precision. In many cases, it may be adequate to supply an answer which falls in a range of values or in a "class", or an optimal versus several sub-optimal solutions.

It may be unnecessary for a model for ecosystem response prediction, to predict depth of streamflow to the accuracy of, say, a centimetre, and it could be sufficient to merely know that the flow depth is either within the channel, or is overtopping the banks. These are qualitative descriptions which describe some quality of the flow depth. Use could be made of a descriptive variable which could have one of two states, namely in-channel or overtopped. To predict changes from one state to another, simple IF-THEN type rules are applied in the form IF (some condition is met), THEN (the value of the state variable changes from one state to another). In the example, the rule may be IF (discharge > 50 $m^3.s^{-1}$) THEN (depth = overtopped). The rules forming the QRBM are often elicited from human experts in the field of interest, but may also be elicited by other means such as direct observation, experimentation, or hypothetical application of more detailed models.

4.2 MODELS AS INTEGRATIVE COMMUNICATION TOOLS

The integrative power of model development has been noted by several authors (Holling, 1978; Starfield *et al.*, 1993; Grayson and Doolan, 1995; Pattern, 1994). Modelling has the ability to bring both knowledge and intuition to the fore, and make them explicit by means of rules or equations. Models, be they quantitative or qualitative, structure knowledge, and the process of model building imposes orderliness on understanding and enforces consistency in analysing different aspects of a problem (Pattern, 1994). Amongst other benefits, models are known to identify shortfalls in understanding and data availability and thus help direct further research and monitoring.

In a workshop environment, it has been found that model development has been a highly successful method of bringing about a "group dynamic" (Holling, 1978; Grayson and Doolan, 1995; Pattern, 1994). The use of models and model building described in this document, both to explicitly facilitate communication, and as potential management tools, represents a fundamental break with the manner in which decision support for water resources-related planning by modelling has been undertaken in the past. Typically, in catchment planning and management and associated modelling exercises, one or two large multi-purpose models have been applied (Donigian *et al.*, 1991; Midgley *et al.*, 1994; Fedra, 1995). These models have typically been manager- and user-unfriendly, difficult to engage, not transparent, required extensive training to use and needed powerful computing facilities and complex databases to operate. The applications of such multi-purpose models have been specifically of a water resources engineering nature. However, with the recognition that effective natural resource management requires effective communication among interdisciplinary participants, comes recognition that this type of multi-purpose model may be a hindrance to such communication.

It has been noted that communicating the structure of such models to others can become an "insurmountable obstacle" to collaboration with, and acceptance of the model (Maxwell and Constanza, 1996). In Phase II of the KNPRRP, a lecture on the structure of a large, complex hydrological modelling system (HSPF) which was proposed as core component of an ICIS, led to confusion amongst ecologists and complicated the whole process of integration of predictive systems. It was only with a proposal for the development of simple discipline based QRBMs that the process of integration of knowledge and models and collaboration of scientists was able to continue. Consequently, the work reported here has focussed on the development of a suite of small, single-purpose models developed "in-house" to address specific problems, and which may form modules of an integrated system, rather than the use of any large multi-purpose models. Starfield (1996) believed that this movement represents a shift to what he has termed a "pragmatic modelling paradigm".

It has long been recognised that complex modelling endeavours benefit from being broken down into distinct components or modules and these benefits are well documented (Silvert, 1993a,b; Leavesley *et al.*, 1994). In the case of models used to simulate ecosystem processes, the separation of the model into distinct, but interdependent components, allows the formation of teams of specialists from different disciplines working on separate components of the model. This enables them to focus on the section of the model where they can contribute their expertise and where they feel a "comfort zone", whilst retaining the interdisciplinary nature of ecosystem modelling.

The model development work presented in this document is based on the following recognition: That, in order to adequately tap into the level of scientific understanding of the different disciplines involved in the development of computer models to simulate biotic responses to abiotic processes, the models need to be easy to use, and should be engageable by participants with limited modelling experience, and should have an interface accessible to water resources managers. The functioning and technical details of these models are described in the following chapters of this document.

4.3 MODEL INTEGRATION

The idea of an ICIS has been introduced and discussed in Chapter 2. It is recognised that in order for an ICIS to adequately represent catchment components and processes, it must include an integrated system of simulation models which represent these. The term "model integration" is often misunderstood. In this document, "model integration" is used as a generic term for linking models i.e. exchange or transfer of input and output between models, by both simple and complex means.

Models can be integrated either in series or in parallel. Series type integration is most common and involves taking the output from one model and using it as input for the next once the first model has completed its run.

Parallel linking of models or model components involves using, in the same time step, the output from one component as input to the next and thus has the potential to accommodate feedback between the models. This is also referred to as "deep" or "definitional" integration and may yield a new model which combines two (or more) components (Geoffrion, 1996). A further method of linking models in parallel is by means of message passing where separate programs, sometimes on different computers, exchange data in "real time" over distributed networks.

4.3.1 Feedback in Biophysical Systems and in Models

Feedback is a term common to both scientists dealing with natural systems and to simulation modellers. Although "feedback" represents a form of interaction amongst either components of the natural system or of the model, the natural scientists' perspective of feedback and that of the programmer/software engineer do differ in some important ways.

In the natural sciences, many interactions of biological, chemical and physical feedback mechanisms are recognised. For example, climate changes can induce changes in ecosystem structure and function that can alter carbon uptake, which in turn can alter the future climate. Thus, feedback in this context is a closed loop effect and may be represented in models as such.

However, nature is very complex, and not all effects are direct and obvious. There are many effects on species or other parts of ecosystems that do not directly result from a particular stress or other event, but have a strong result in an indirect way. Figure 4.2 illustrates this problem. For example, in a catchment situation, it is possible that change in the catchment, such as the construction of a dam, may impact on streamflow in the lower reaches. Stabilisation of streamflow by the upstream dam may allow the invasion of woody vegetation into stream bank areas where regular seasonal flooding would have prevented or limited natural vegetation development. This increased woody vegetation on the riverbanks may trap greater amounts of sediment than in the past, and thus provide a greater area for the woody vegetation to invade – an indirect feedback.

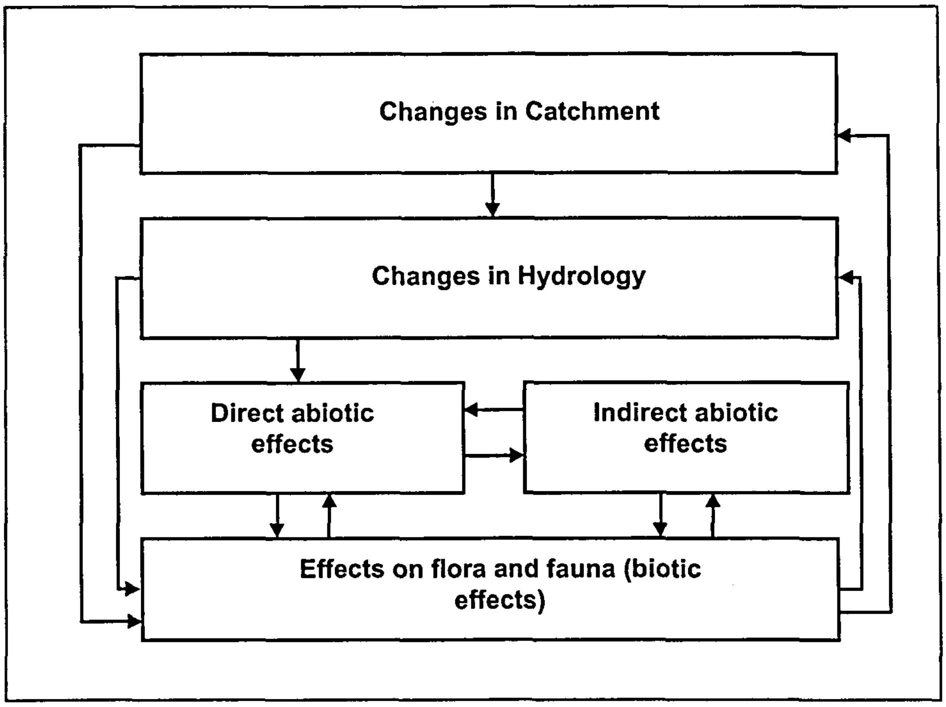


Figure 4.2 Feedback between abiotic and biotic components.

In a simulation exercise, if the output of part of the model is fed back to the input, this is known as feedback in a modelling sense. A simple example of this is a model representing an air-conditioning system. The output (the room temperature) affects the input (the thermostat) which controls the air-conditioner, which affects the output. This is a particularly complex problem in simulation with computer based systems due to the discrete nature of representations of processes in computer systems (see Section 4.6.1). The implication is that output of the model must loop back to also form its input. Thus, feedback cannot be encompassed by simulation systems that operate in series. The model components need to operate in parallel if feedback between them is to be accommodated.

4.3.2 Linking Models in Series

Series type integration is most common and involves taking the output from one model and using it as input for the next. This implies all calculations of one model need to be finished before another model can start its work. Series type integration of components is also referred to as "procedural", "functional" or "loose" integration. This type of integration does not result in the formation of a new model, rather it leaves the models as they were and usually involves directing the output from one model to a storage system which enables it to be used as input for the next model - once the first model has completed its run (Geoffrion, 1996). Converting the output of the first model from its unique format to the unique input format of the other model involves the use of some sort of data transformation program (Figure 4.3). This is a fairly common approach, since it requires little if any model software modifications.

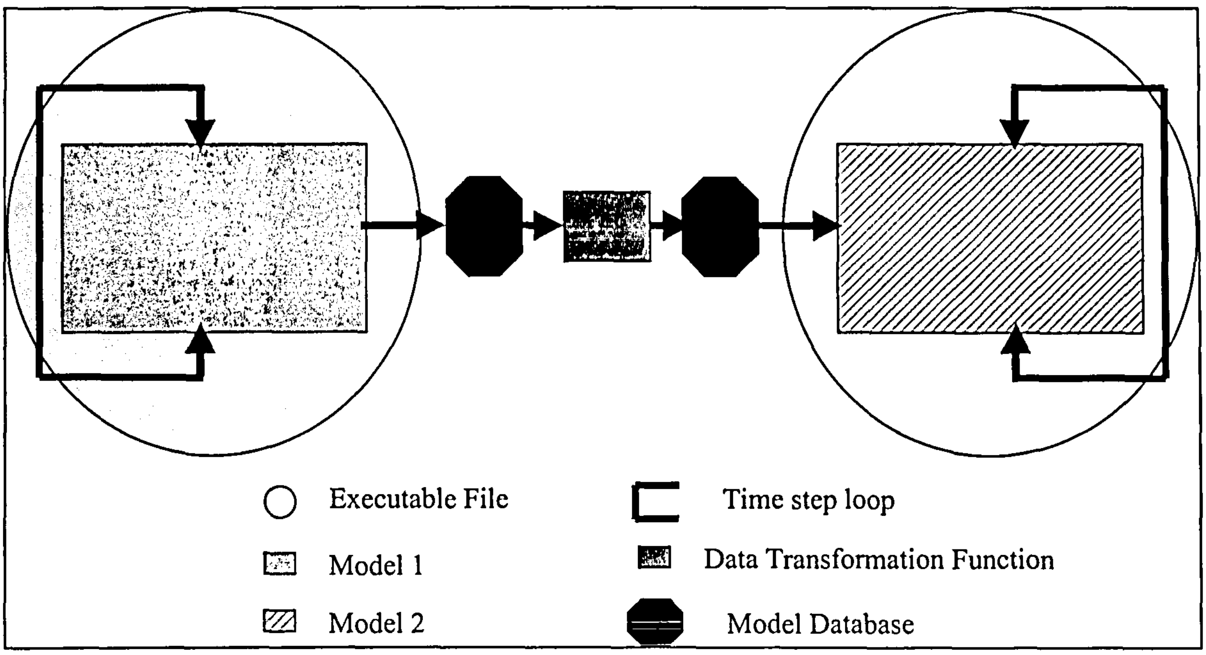


Figure 4.3 Linking models in series. The two models complete their runs independently of each other. Model output from one is converted to model input for the other.

Communication between the models may be facilitated by a time manager and a set of files that is accessible by all the models. Having both (or more) models using the same database format will greatly facilitate this process (Figure 4.4). Usually only the file formats and sometimes the corresponding input and output routines of the model, are adapted. However, a problem with this method is that the code from one of the models involved may need to be altered to match the data format or the resolution of another. More often than not, this is a task that only the model developers have the expertise to do, not the secondary user for whom this linking is probably most convenient. This is the preferred method of integration in several water resources planning projects, for example the integration of the MODFLOW groundwater model and the DUFLOW open channel model as part of a DSS to assist in the management of the water resources of the Netherlands (Haagsma and Johans, 1996).

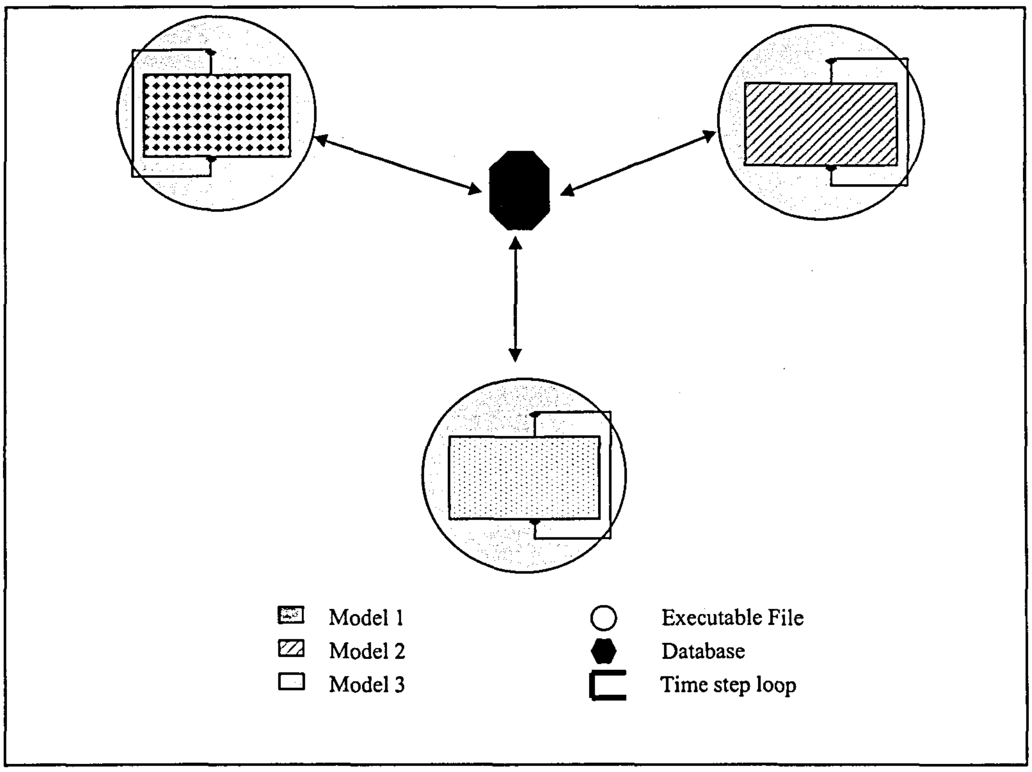


Figure 4.4 Linking models in series with a common database. The models still complete their runs independently of each other, however integration is simplified by modifying the models to read and write to the same database.

Series links are often referred to as "peer-to-peer" configuration and are characterised by a "poor" or "loose" link and "low usability". Costs of implementation, however, are usually low (Abel *et al.*, 1994). This type of link does not allow feedback between the two systems. However, communication through the input/output files makes this type of loosely coupled models very flexible.

4.3.3 Linking Models in Parallel

Parallel linking of models or model components involves using the output from one component as input to the next, in the same time step, and thus has the potential to accommodate feedback between the models. This is also referred to as "deep" or "definitional" integration.

Deep integration provides a common interface and transparent file or information sharing and transfer between the respective components and may yield a new model which combines two (or more) components (Geoffrion, 1996). The available literature reports three methods of linking models in parallel:

i) The first involves the restructuring of the models, so that they read the same database, but more significantly, so that they can be compiled into one executable program. The Modular Modelling System (MMS) (Leavesley *et al.*, 1994), an integrated modelling system developed for use in water resources management, is an example of such a system. The core components are those of the Precipitation-Runoff Modelling System (PRMS) as well as newly written modules to provide the ability to simulate water quality and simple biological functions. Modules additional to those supplied by the developers can be developed and coded to match the structure of the other MMS routines according to strict guidelines provided by the model developers. Although many subroutines are made available to the user, the executable code compiled need only include the modules selected by the user and the required control libraries. An example of this method of component linking is shown in Figure 4.5.

   This method is most commonly referred to as an "embedded system configuration". One component, the master, has the ability to invoke actions by the agent components. Such embedded systems provide a higher degree of efficiency in linking of capabilities and higher usability than simple series based linking.

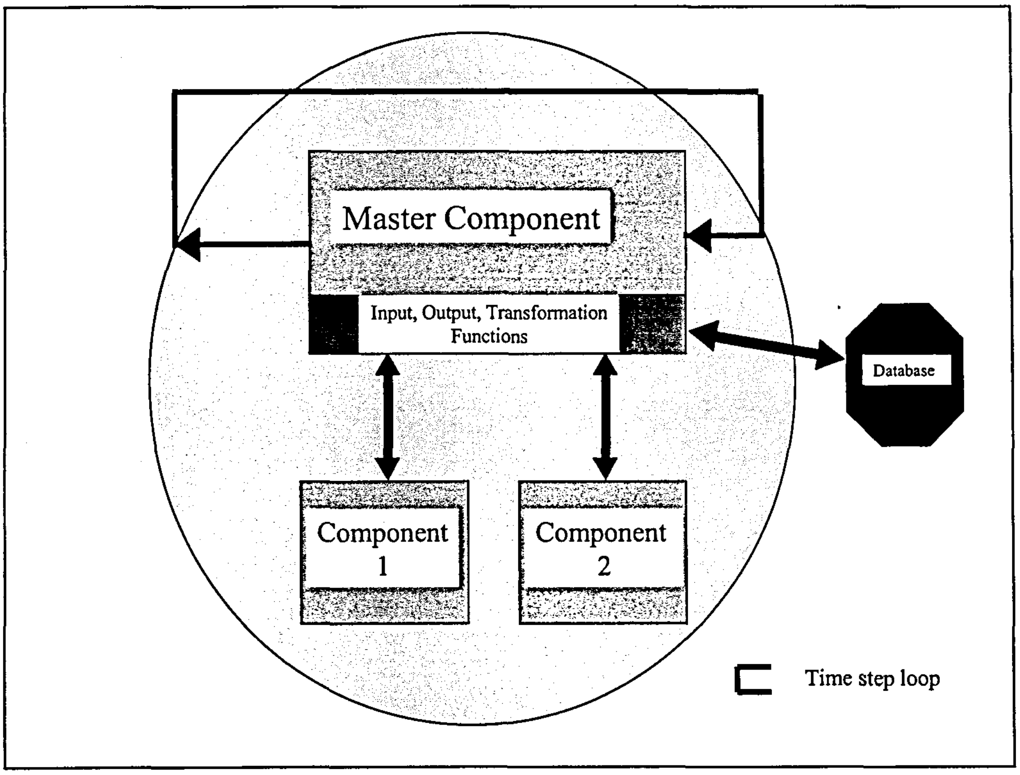


Figure 4.5 Linking models in parallel.

ii) A second method of linking models in parallel is one which is currently receiving much attention worldwide. Federated database research involves the coupling of multiple databases maintained by autonomous, heterogeneous database management systems. Thus, a programme, separate from the models to be linked, may operate these models and control their input and output functions in such a way that a parallel link is achieved as illustrated in Figure 4.6. Federated database systems have been used successfully to integrate different models on the same computer system. The best example of this in the hydrological field comes from the CSIRO in Australia, which has developed the HYDRA system in which a catchment hydrology model and a hydro-dynamic estuary model are linked using this methodology (Davis *et al.*, 1994). The Australian modellers have also developed a similar system known as the Integrated Quality Quantity Model (IQQM) which is used to simulate water quality and quantity interaction in the Murray-Darling basin using federated database technology (Abel *et al.*, 1994).

Control of the linking processes rests with a message passing interface whilst the different components retain their own database access functions and remain as separate stand alone executables. In other words, data input, output and transformation processes are retained by the individual components.

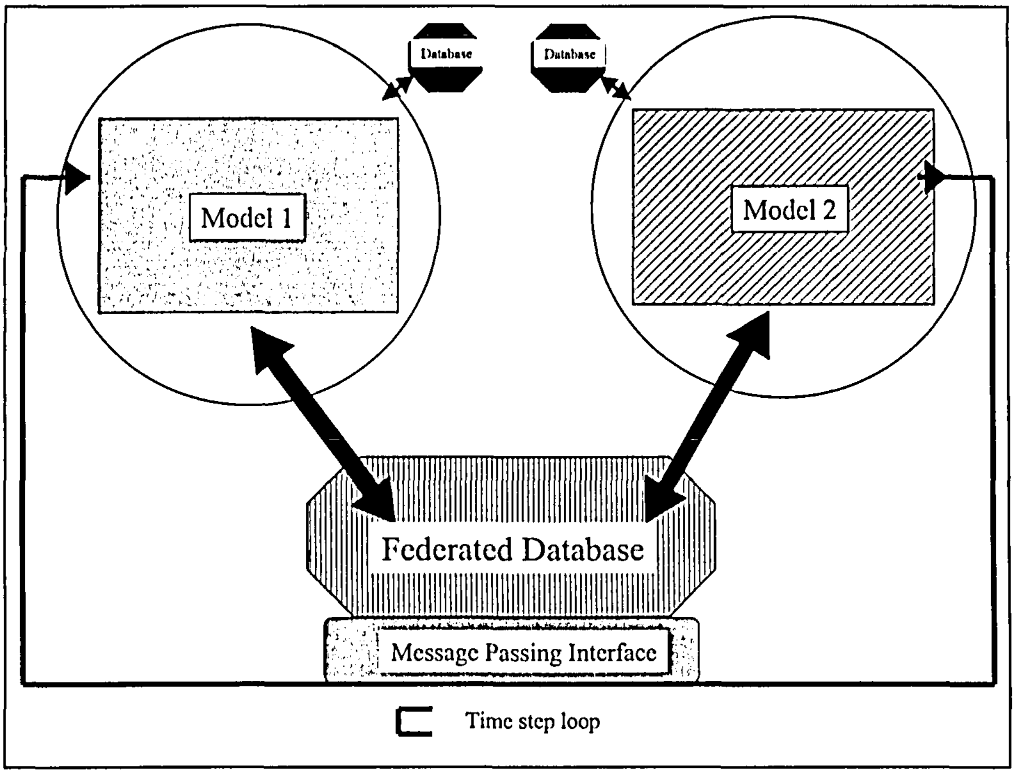


Figure 4.6 Models linked using federated database technology.

This is currently an active field of research and is the preferred method of linking components in many large catchment management systems, including the Florida Everglades Project, some components of the Chesapeake Bay Program and in some large multi-disciplinary (usually grid based) modelling systems such as the Across Trophic Level Simulation System (ATLSS) (Costanza and Maxwell, 1995).

iii) Closely related to the use of federated databases is the use of distributed database management systems, the third method of linking models in parallel. A distributed database management system (DDBMS) is a single logical database that is physically distributed on several computers, communicating through a computer network, usually a Local Area Network (LAN). It provides multiple access to the database and mechanisms to prevent conflict in update, retrieval and backup of data. DDBMS can be very useful for very large multi-component modelling systems with large databases where most users are concerned with only a small subset of the database, while still permitting access to the user with broader needs.

4.3.4 Models with Hybrid Linkages

Many simulation models make use of both parallel and series type integration of the components making up the system. In a South African context, this is the case in both the ACRU (Schulze, 1995) and DISA (Görgens, *et al.*, 1992) models when simulating the irrigation requirements in a catchment downstream of a dam. In the DISA model, irrigation abstractions down the river are performed in series while releases from the dam are modelled in parallel in order to allow feedback to ensure adequate water releases for salinity maintenance downstream.

4.4 ACCOMMODATING MULTIPLE SPATIAL SCALES AND ASYNCHRONOUS TIMING IN MODELS

It has been suggested in Section 4.3 of this document that a modelling system that is both able to integrate a variety of models, and provide useful management information must be able to operate at asynchronous time steps, and at multiple spatial scales. This raises some issues related to dealing with these processes in computer based models.

Both the spatial and temporal domains may be dealt with as a continuum of scales. This is best applied if fine resolution base data are available. With increasingly sophisticated methods of data collection, this may be a reality in the future. However, in the South African situation, spatial data are usually available at a variety of disjunct scales and this is the case in the KNPRRP. Structuring computer modelling systems along a hierarchical structure will facilitate and maximise the efficient use of these data and allow the models to operate at different spatial and temporal scales.

4.4.1 Asynchronous Time Scales

When considering hierarchical systems, moving up the hierarchy results in an increase in the measure of time (e.g. a move from minutes or hours to years or decades) and vice versa (e.g. going from minutes to seconds). This is more a relative effect than an absolute one. It is possible to measure all phenomena observed in seconds, but then the passage of a year would be a very large number (31.536 million seconds). Measuring the growth of a tree in seconds could require 3153.6 million seconds (100 years) before the tree reaches maturity. From a simulation modelling perspective, a one-second resolution would require many calculations, which often translates to many hours of computer time, whereas the rate of change of the process may be quite slow. Thus, it is more useful to utilise a measurement of time that is consistent with the process in which we are interested (Ball, 1994; Ball *et al.*, 1996).

Continuous versus discrete modelling refers to how time is represented in a simulation system. As discussed previously, time is continuous, i.e. time is marked by an uninterrupted extension in sequence. Or to put it another way, it has no distinction of content except by reference to something else, such as a number (e.g. seconds, minutes, and hours) (Ball *et al.*, 1996). Discrete time is then a sequence of distinct intervals in which intervening information of a specific type is disregarded or assumed to be unimportant. These intervals are not necessarily equi-distant and discrete time can therefore be seen as an intermittent process.

The use of a computer based simulation system requires that some decisions about how time is represented must be made. The digital computer represents numbers directly as digits using the binary nomenclature (i.e. ones and zeros). Time therefore, must be implicitly represented as an interval or step. Computer based simulation models are therefore discrete and usually have constant time-steps. However, if time is referenced relative to something such as an event that is significant in the life-history of the process being simulated or observed, it is possible to measure time advance by other means.

A common approach is to treat time in reference to specific "significant" events (Ball *et al.*, 1996; Maxwell and Costanza, 1996). In most models, there is a period of time, however finite, in which the solution to the process algorithms is static. No change is occurring; therefore the computer system may be doing meaningless calculations. Looking only at the time in which something "significant" occurs means that the intervening period can be ignored. This approach is known as "discrete event simulation" (Zeigler, 1976). Using this approach, the model only performs calculations when an "event" triggers an operation. In the case of the KNPRRP, a process of interest such as a freshet which may stimulate fish breeding may last a day, whilst a winter low flow condition, which may not have any significant impact on the fish population may last several months. Thus, although utilising an input timestep of a day to ensure that processes such as freshets are not "missed", the model may only initiate a fish breeding process if a certain flow threshold is reached. The process is not simulated at every time step, as the majority of the time, the calculation would return the same value. As is explained in more detail in Chapter 9, this is an important aspect of the BLINK models as it offers a method of scaling fine scale temporal information to coarser scales within the models.

4.4.2 Multiple Spatial Scales

If a continuum of spatial data, starting at a fine scale, is available, accommodating multiple spatial scales in a computer based modelling system may follow a similar approach to that described above for the temporal component. The fine scale data may be included in a grid in a GIS system and used to provide information applicable to the selected spatial scale by some means of aggregation. However, spatial data of this resolution are rarely available in southern Africa, necessitating an alternative approach to management of spatial data.

Typically, spatial data are collected at different scales by the different disciplines involved in an ICM decision support exercise. Hydrologists may collect data applicable to the land segment of the whole catchment under consideration. Geomorphologists may collect data gathered from surveys of the river channel and ecologists from surveys of particular habitat units (Figure 2.5). In the KNPRRP, it was accepted that methods for matching these apparently disparate spatial scales in modelling are needed. It should be noted that serial integration, as described in Section 4.3.2, may provide a practical method of scaling smaller spatial scale models to accept input from larger systems. For example, a hydrological model may operate at the extent of a river basin. However, the smallest spatial scale at which it can produce accurate output represents its grain. In the case of the KNPRRP, this may be the "representative reach". Thus, the model integrates large-scale processes and produces output at a smaller scale, which may be used as input to another model. This concept is expanded upon with reference to the KNPRRP in Section 8.1.

Other methods to achieve this are explained in Chapter 8 in the description of a "scale matching" exercise in the KNPRRP that formed the foundation of an integrated predictive modelling system linking biotic and abiotic aquatic processes to physical catchment developments for the Sabie River.

Chapter Five

AN INTEGRATED CATCHMENT INFORMATION SYSTEM

It has been recognised by many practitioners that full analysis of the many catchment problems faced by those attempting ICM requires an extensive set of capabilities. Computer based information systems in which the tools representing these capabilities are integrated to provide decision support to managers and stakeholders, play an increasingly important role in ICM initiatives, both internationally and locally. These systems are developed with the recognition that in any given software system for real-world applications, several sources of information or databases, more than one problem representation or model, and a multi-faceted and problem-oriented user interface need to be combined in a common framework to provide realistic and useful information.

With the new management approach embodied in the concept of Integrated Catchment Management and the focus on an "environmental water reserve" brought about by the new South African Water Law, management decisions must now involve larger areas of interest, multiple spatial and temporal scales, cross many different organisational hierarchies, and involve diverse groups of stakeholders. Water resources will be managed with an ever-increasing number of objectives in mind. To do this, managers and stakeholders must rely on up-to-date information, modelling and communication. Both the National Water Act and recently drafted guidelines for achieving ICM (DWAF and WRC, 1998) recognised that the provision of information, and systems which provide decision support pertaining to the catchment, is a key aspect when striving for the goal of ICM.

It has been suggested that the number of definitions of the term Decision Support Systems (DSSs) nearly match the number DSSs in use (Young *et al.,* 1995). In this project, DSSs are considered as software systems that facilitate management through integration of three types of information:

i) Information on the state of the environmental system (in the case of ICM, the catchment),

ii) modelling (simulation) of the system, and

iii) evaluation of different scenarios/plans.

The many objectives of ICM are influenced by choices made at a number of levels of decision-making. Decision support must be provided as it relates to specific system goals at different levels of the catchment hierarchy (e.g. site, individual enterprise, catchment, region). Decision making in a hierarchical context is an iterative process with multiple levels of decision making involved in order to flow from broad scale management goals for very large regions, down to the finer details required for specific operational schemes for individual tracts of land or river reaches. Each inter-related level requires more precision of detail as the spatial and temporal scales becomes smaller. A centralised information system provides the possibility of highlighting many of the links between different decision-making levels and different sub-systems, thereby enabling users to gain a more holistic appreciation of a complex situation.

Thus, such information systems offer multiple representations of the available management options by offering combinations of facilities that allow *interactive* assessment of the various aspects of the problem through different models, data visualisation, multi-criteria evaluations and reports. Rather than attempting to *a priori* resolve and formalise the problem in its entirety, only easy-to-formalise components are represented and augmented with software tools that allow users to flexibly navigate the decision space or problem representation. In the case of ICIS, this usually results in systems that are constructed around three main components (Figure 5.1):

i) **State information:** representation of the environmental resource's state at any point in time. For water resources this includes information such as historical flows, reservoir storage and channel features, water and energy demands, etc.

ii) **Process information:** first principles governing the resource's behaviour over time. Simulation models representing a resource's dynamics (e.g. hydrology models) are part of this component.

iii) **Evaluation tools:** models for transforming raw data into information relevant for decision making; e.g., multi-criteria evaluation models, display tools, report generators, etc.

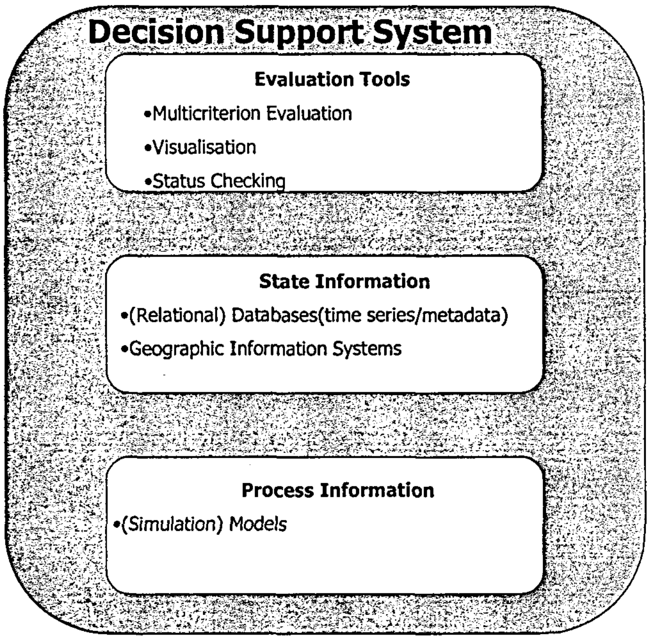


Figure 5.1 Conceptual model of an Environmental Decision Support System (after Reitsma and Carron, 1997).

Maps generated with a GIS are commonly used to provide a "front-end" to such systems. In GIS, the basic concepts are location, spatial distribution and relationships between basic elements. These basic elements are all spatial objects. In environmental modelling systems, by contrast, the basic outputs are state (expressed in terms of numbers, mass, or energy) of interaction and dynamics and stored in a database. The basic elements are process representations of biological species, chemicals, and environmental media such as air, water or sediment (Fedra, 1995). There appears to be much room for overlap between GIS and environmental modelling systems. Thus the integration of GIS and environmental models to provide useful decision support systems has been the focus of attention in many research fields.

5.1 REVIEW OF AVAILABLE DECISION SUPPORT AND MODELLING SYSTEMS

A number of existing DSSs were assessed during the course of this project in order to assess their applicability to the KNPRRP. A broad interpretation of DSSs was taken in order to show the diversity of the systems available. Common to all of the systems below is a focus on simulation modelling or the ability to include simulation models in the system. A brief overview of some of these systems is presented here. With the exception of HYDRA, all of these systems were tested "hands on".

It should be noted that the dynamic nature of the development of software systems implies that any review of these systems may not reflect their current status. The systems reviewed below were available in 1995, and the review reflects their status at that time. Of more importance than the specific features of each system are the generic lessons that may be learned from them. These are discussed in Section 5.1.1 below.

Catchment Management Support System (CMSS)

The Catchment Management Support System (CMSS) (CSIRO, 1994) has been developed by various organisations involved in catchment management in Australia. It is a computer program, operating on a PC or workstation in a graphical environment, used to assess likely changes in nutrient loads entering streams following changes in catchment land use. Its design philosophy is based on the implementation of simple relationships between selected components, and as such is similar to that of CRAM and G2 (see below), although it does not place a great emphasis on a GIS link. Input data are land use, nutrient generation rates and management practice data. Output is a simple function of these inputs presented in the form of high quality colour graphs and maps.

CRAM - Catchment Centred Resource Assessment and Management System

The Catchment Centred Resource Assessment and Management system (CRAM) (Meyer and Scholes, 1994) was developed by the CSIR as an integrated catchment management system, using the Crocodile River as a prototype. It is a hydrologically based system which is easy to use and allows for simulation of environmental, social, economic and hydrological impacts of changes in a catchment.

Its major strength is its GUI and the subsequent ease of use of the system. Different catchment development scenarios are easily selected and run, while output is clearly displayed. An adequate GIS link is in place and it utilises an efficient database management system.

Its major weaknesses are the simplistic algorithms used in simulation of hydrology in particular, but also in other aspects which are simulated. The hydrology component is apparently to be replaced with the well known Pitman Monthly Model (Pitman, 1973), however, this still restricts simulations to a monthly time step. CRAM may be used as a useful "gaming" or scenario generation tool, however model output cannot necessarily be accepted as accurate.

The CRAM system GUI and GIS links are amongst the most advanced of the DSSs reviewed for the KNPRRP, however the simulation components are not of the required standard.

G2-AEAM

The G2 model is developed by utilisation of the Adaptive Environmental Assessment and Management (AEAM) process (Holling, 1976; Walters, 1986). The AEAM process involves the development of simulation model in a multi-disciplinary workshop environment. Algorithms used in the model are developed by sub-groups of the workshop. These algorithms are developed for pre-defined spatial and temporal (monthly) scales. For example, a hydrology sub-group will typically develop an algorithm which expresses monthly runoff as a simple function of rainfall. Further algorithms representing hydrological responses to changes in landuse are adopted by consensus. The algorithms developed by each different sub-group are returned to the workshop, and entered into the pre-existing G2 BASIC shell. The model is then run, and simple graphics operating in real time show output from the model.

The strength of this approach, is that, through the workshop environment, consensus is achieved amongst the various expert groupings regarding the algorithms etc used in the model. The model is put together easily, and results are available for discussion in a simple and useable form very rapidly. Discussion of results amongst the workshop participants once the model has been completed and run is reported to be very fruitful (Grayson et al., 1994). Its obvious weakness is the limitation of the algorithms produced and the similar "generalisation" achieved by operating at a regional scale on a monthly time-step.

HSPF-ANNIE

This is not really a DSS, but may be viewed as a useful modelling system that could be considered as a "backbone" for the KNPRRP.

The model, HSPF, utilises a WDM binary file as a time series database. ANNIE is a program which manages and displays data stored in the WDM. Thus, the HSPF user must be familiar with ANNIE in order to provide data for the model and to view results. ANNIE has a text based user interface which is not of the same standard as others reviewed. Using ANNIE for data manipulation, and obtaining listings and detail of the data stored in the WDM can be frustrating. The strength of the WDM is its ability to store time series of varying intervals and the inclusion of flags representative of, for example, data quality for wide variety of time-series data types which have been encountered by the USGS, the system developers. ANNIE has facilities to import and export files in ASCII format, thus enabling the user to transfer/transform data into and out of a WDM file.

The HSPF model itself is a highly structured and well documented FORTRAN program. It is written in ANSI standard FORTRAN 77, and is thus easily transferable between various platforms. Efficient use of available memory allows its use on a wide range of personal computers. Its rigid structure is a great advantage to the programmer who is intent on gaining an understanding of the programming structure of the model, with a view to adding or modifying algorithms or modules in the model. However due to the size and complexity of the code this requires a large investment of time. The program is not modular, in that the modules utilised are not easily interchangeable, and new modules or algorithms are not easily added to the existing code. In fact, adding of modules to the program is an extremely complicated task, necessitating an in depth knowledge of the HSPF code and development philosophy. Addition of a new "section" to an operating module is, because of the rigid program structure, an even more complicated task. Very few people have gained sufficient knowledge of this model to be able to perform these tasks and the only changes to the code have been made by the developers themselves (Johansson, pers. comm., 1995). In addition, it has not been developed to perform the task of being a DSS in a multidisciplinary research programme, where the idea is to link predictive models other than those already existing in the programme. The model has been used with success in large basin scale projects involving the control of water quantity and quality. It includes simple biotic simulation routines, but these have not been commonly used (Dillaha, 1990).

HYMAS

HYMAS (Hughes, 1994) is a DOS based shell used to operate several hydrological related models, including the VTI and PITMAN models. The menu-driven user interface is friendly and easy to use. It is, at this stage, only keyboard driven. HYMAS provides facilities for the user to manipulate time series and edit input information for a variety of models. It uses a binary database unique to the shell, which does have the ability to store data in a variety of time steps. HYMAS has several post-processing options allowing a variety of useful output options to be utilised. A GIS link was considered but the developers considered this to be outside of their field of expertise and noted that this could be done at several levels of complexity, but should be done by experts in the GIS field (Hughes, pers. comm., 1995).

HYMAS is not a shell that can be realistically considered for the KNP rivers in its present form as it is restricted to the DOS platform and has no GIS link. It is, however, an example of a well written, easy to use "shell", with sensible options available to the user. Several of its features could be included in the KNPRRP modelling system shell.

MIKE-11

MIKE-11 has been developed by the Danish Hydraulic Institute as an engineering software package. It incorporates modules for the simulation of flows, water quality and sediment transport in rivers, estuaries, irrigation systems, channels and other water bodies. The package also includes a simple SCS based rainfall-runoff module. No land based water quality simulations are possible and all input water quality data to the channel must be obtained elsewhere.

The system operates in a relatively user-friendly shell, operable under both DOS and Windows. Physical catchment and channel parameters are input via this shell. Time series management is not available, although the system allows the import and export of data in a number of commonly used ASCII formats. Graphical representation of simulated results is possible within the system. MIKE-11 provides options for passive linking of modules in the system.

MIKE-11 has been used in a variety of catchments worldwide. Modelling exercises are generally concentrated on hydrodynamic channel and estuarine processes. In South Africa, the model, particularly the hydrodynamic module, has been used by the CSIR on a number of local catchments and estuaries. A major disadvantage of MIKE-11 for the KNPRRP is its high cost.

The Modular Modelling System

The Modular Modelling System (MMS) (Leavesley et al., 1994) has been developed by the USGS as a common framework in which to focus multi-disciplinary research. It has been developed in the hope that researchers in a variety of disciplines may develop and test models to investigate questions in their own fields of study, whilst working co-operatively on multi-disciplinary problems. This eliminates the need for each researcher to develop the complete system model. MMS is operated via a X-windows based GUI on a UNIX based workstation. Pre and post-processing tools are available, allowing graphical representation of data, and tools for manipulation of data. The core of the system is a model component which provides tools for linking process modules representing various catchment processes. A GIS link has also been developed.

The thrust in the development of this system has been the hydrological modules. These have been linked in "real-time" in a variety of applications (Runkel and Restrepo, 1993). Other modules may be added, provided they conform to a set of programming norms as described by the program developers. Modules to be added may be written in FORTRAN or C.

Hands on testing of the system revealed difficulty in compiling the programme to run on the CCWR UNIX system, little user-support and more complex than anticipated set-up and operation procedures. Although the mechanism for adding operating modules to the system seemed sound, the time-investment required in order to become proficient in the system seemed inappropriate given its other shortcomings.

RAISON

RAISON (Regional Analysis by Intelligent Systems ON microcomputers) for Windows is a software package developed by Environment Canada in the mid 1980s for ecosystem management on a catchment basis. It is a versatile environmental information system with built in expert system capabilities specially designed for decision support applications. It offers a generic framework that integrates data, text, maps, objects and knowledge input. The system also provides a library of user-friendly tools, including a database management system, mapping systems, graphics, statistics, and a rulebased expert system. With these inputs and tools, the user may produce output for interpretation, integration, advice, classification, analysis and recommendations.

RAISON is now available as a Windows version which has evolved from its DOS based predecessor of the mid-1980s. It also has the ability to import from, or export to, many commercially available databases, spreadsheets and GISs. It offers a map-based GUI which is customised for each application.

The system has had extensive use in Canada and other countries and has been adopted in Australia as the DSS for environmental flows (Young, pers. comm., 1994). It is the most complete of the DSSs reviewed and initial impressions are that it could be suitable for use in the KNPRRP. However, the software is relatively expensive, and local support is unavailable.

SWAMP-HYDRA

The HYDRA system (Davies et al., 1994) is based on the premise that, for a variety of reasons, existing or "legacy" models will continue to be used. HYDRA is being developed as a shell which allows these pre-existing modules to be connected. The proto-type system, SWAMP, has been developed around the HSPF model. The development of HYDRA involves the incorporation of other legacy models, such as estuarine and catchment management models.

The HYDRA system builds upon advances in the integration of GIS with other models. These advances have mainly occurred in the field of federated databases, as discussed in Chapter 4. The system consists of a GUI developed with the idea that the water resources manager is the primary user. Options are, thus, representative and geared towards likely management questions. A system manager is the central component of HYDRA. It controls all model-model and model-user communications. The system manager possesses its own local database implemented in memory which stores data required by the various active model components. The final component of HYDRA is a library of legacy models which may be integrated by the HYDRA system, each with its own distinct "driver".

Although the approach adopted by the system developers seems sensible, the level of computer science and information technology required, as well as the hardware requirements are beyond the scope of the KNPRRP.

WDM Guide

The WDMGuide system was developed as a prototype information system for the KNPRRP by the TITT sub-programme (Van Rensburg and Dent, 1997). The software runs on a PC under Windows or on a UNIX workstation and is based on ArcView ver. 2 and its associated Avenue programming language. It utilises the multi-tasking facilities of the UNIX and Windows operating system to provide flexibility to the user. It has been named WDMGuide as a result of focus on the development of user-friendly, mouse and menu driven interaction with time series stored centrally in a WDM file on a workstation accessible via the internet, as well as image and Arc/Info data sets which reside locally on a PC.

Its features include:

- Graphical query of selected variables at any point in the selected stream network.
- The ability to query and plot a number variables simultaneously.
- Query and display for available images per subcatchment.
- Animation of monthly time-series of a selected variable.
- Accessibility to data via remote networking.

The WDMGuide system is interesting in that it offers a system which is based largely on easily available commercial software to which simple functionality may added by use of public domain software tools. In terms of its cost and support via the CCWR, it offers an attractive solution for the KNPRRP.

5.1.1 SUMMARY

There are two broad philosophies used in the development of these catchment management systems. CRAM, CMSS and G2 all make predictions pertaining to changes in the catchment based on simple, and even simplistic, algorithms. Their emphasis is on the provision of a system which can rapidly show potential impacts of change in clear, colourful ways. The accuracy of the result produced is secondary to the goal of achieving communication between catchment managers and planners and researchers in different disciplines. The G2-AEAM approach has been successfully used in Australia (Doolan et al., 1993; Grayson et al., 1994). The second approach is to provide a modelling system which provides simulation of catchment processes that are more physically realistic. These systems, such as HSPF, HYMAS, MMS and HYDRA operate on finer spatial and temporal scales than systems such as CRAM and G2. They are thus, more data intensive and need some modelling expertise to operate.

This component of the KNPRRP Decision Support Sub-Programme is attempting to combine these philosophies by providing clear graphical representation of results from available models, be they physically meaningful and data intensive or not.

It is significant to note that the first group of models have generally been used by those involved largely in the ecological disciplines, but with a trend towards interdisciplinary science, whilst the second group have been developed by scientists and engineers in the hydrological sciences. The BLINK models included in the IMS attempt to bridge this gap.

The RAISON, CRAM and WDMGuide systems are all systems capable of fulfilling the functionality requirements of a DSS for the KNPRRP. However, based on the cost of both the software and support for the RAISON system, and given the local GIS expertise available via the WDMGuide and its strength in remote networking, a decision was made to accept the prototype DSS developed by Van Rensburg and Dent (1997) and add functionality to it. The movement of this system from prototype to operational resulted in a system that became known the Sabie Integrated Catchment Information System (ICIS). The ICIS provides a framework of tools to assess impacts of change in a catchment in a spatial context. Furthermore, the ICIS aims to provide a management tool that can be used to compare different catchment development scenarios, i.e. the "what-if" situation. Thus, the systems combine GIS technology, with simulation tools and evaluation tools.

It is axiomatic to the objectives of the ICIS, i.e. to provide decision support for management decisions, that any tools developed as part of the system, should be easy to use and understand, simple to operate and produce easily interpreted output. However, such a system should be generic in its design so that it may be transferred with minimum effort to other catchments where water management decisions are required. Currently, the ICIS framework has been applied to five other catchments in southern Africa (Jewitt *et al.,* 1997a).

The ICIS was developed using the Sabie River Catchment as a prototype field area. The vast majority of the software routines included in the system have been developed by staff at the South African Computing Centre for Water Research (CCWR) and build on ideas and algorithms originally proposed by Jewitt and Görgens (1995) and Van Rensburg and Dent (1997).

5.2 FEATURES OF THE ICIS

A conceptual model of the ICIS is shown in Figure 5.2. The various components in the system interact by exchanging data and information, the control of which is the task of the system manager.

The development of the ICIS has followed a multi-level approach to the presentation of information. For example, in the physical component subsection, access is available to hydrological, geomorphological, and climatological information. Each of these offers various levels of information. In the hydrology section, there is an overview level, suitable for the user who would like to gain a brief insight into the hydrology of the catchment. From this level, further detailed analyses, or tools to provide detailed analyses are available for those who would like to obtain more detailed information - up to the level of detail required. The same is true of any information presented in the ICIS, i.e. detailed information for experts in the particular field, less detailed and easier to understand information offering greater perspective for non-experts.

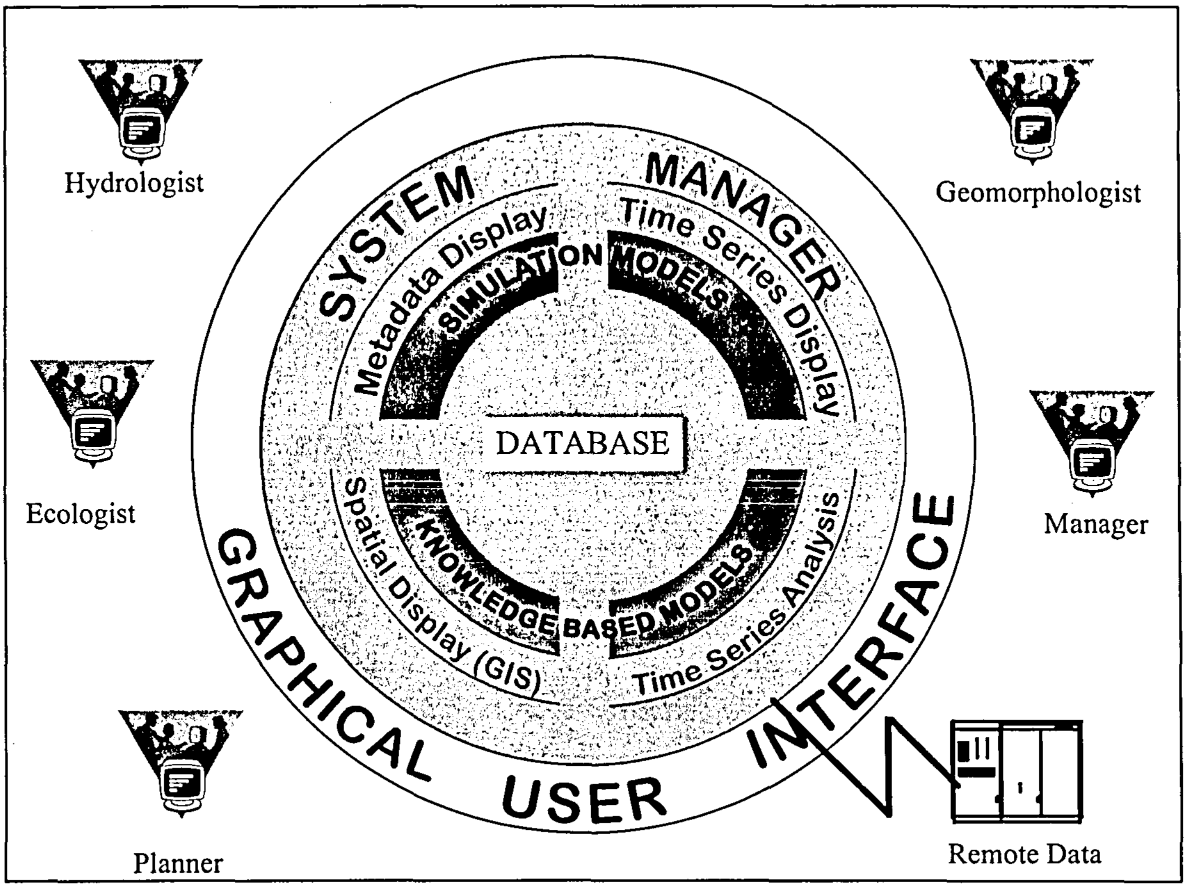


Figure 5.2 A Conceptualised Integrated Catchment Information System for the KNPRRP (Jewitt and Görgens, 1995).

The sub-systems which collectively make up the ICIS currently include (Jewitt *et al.*, 1997a):

- A *Graphical User Interface (GUI)* provided by the ARCVIEW GIS system. The decision to use ARCVIEW as the primary GUI was prompted by the need to present the user with a *familiar picture*, i.e. a map of the catchment.
- A *system manager* to interpret commands from the GUI and communicate with other components of the system implemented in the AVENUE scripting language of ARCVIEW.
- *GIS functions* for display and interrogation of spatial data.
- *Tools for display* of metadata and time series data (Visual interpretation of data sets and processes is a major field of development in many areas of science, with the aim of bringing greater understanding to complex problems).
- Various *predictive tools*, including numeric simulation models and knowledge based predictive tools.
- A comprehensive *computerised database* for storage of spatial data, metadata and time series data of interest to stakeholders who require information on the rivers in the KNP.
- A wide range of *line graphics* as well as the full display graphics capabilities of ARCVIEW 3.0.
- Routines to perform *"animated" displays* of colour coded projection of variable values on selected river segments within the catchment; (the Sabie catchment, on which the system was prototyped has been divided into 56 sub-catchments for analysis and display).
- A versatile *package to display daily simulated and observed results* in a range of relevant water resources formats.
- The ability to *access a range of pictorial images* through a simple point and click of the mouse, this latter functionality is exceptionally useful when communicating with a range of users and viewers of the system who are at different levels of understanding on components of the ICM process.
- The *display and analysis of a range of geomorphological features* of rivers which are central to their ecological functioning.

- *Tools to link to remote databases* and information sources, such as the CCWR database situated in Pietermaritzburg and the WWW.

The system offers access via the GUI to information pertaining to the socio-economic, physical and ecological sub-systems of a catchment. In addition, access to simulation models available for scenario assessment is available. This information is made accessible by simplifying the GUI into four sections to provide direct access to hydrological, ecological, geomorphological and socio-economic information. A fifth section provides access to specific predictive tools for scenario assessment and includes the BLINK models. These include;

- a hydrological simulation model used to predict the streamflow and sediment response to changing catchment conditions,
- a fish model which simulates and displays graphically the effects of streamflow on selected fish population dynamics in shallow waters in rivers of the Kruger National Park,
- geomorphology and riparian vegetation models which simulate and display graphically the effects of streamflow on geomorphology and riparian vegetation dynamics in the rivers inside the Kruger National Park, and
- connections to hypertext software systems which enable the user to interrogate the rules used in the fish, geomorphology and riparian vegetation models mentioned above.

This section effectively includes the Integrated Modelling System developed as part of the BLINKs project of the KNPRRP. Integration of this suite of models with the ICIS is described in Section 9.1.

5.3 TECHNICAL ASPECTS

The ICIS is effectively part of a decision support system that makes use of ARCVIEW and a range of other software on a PC and larger host computers at remote sites. The ability to connect the system to other computers on the wide area networks is vital in the southern Africa subcontinent where the role-players are scattered geographically and yet are required to communicate continuously. Communication between participants is essential for the generation of scenarios that form the basis of informed interaction by all stakeholder representatives.

The hardware requirements to run the system are at least a 486 processor, 16 Mbytes of RAM and 60 Mbytes of disc storage (for the data alone) and a connection to the Internet. The system makes use of the multi-tasking capabilities of Windows95 as its platform and for the most part runs in a shell developed within the ARCVIEW 3.0 GIS product. The external process calling function of ARCVIEW is utilised to seamlessly call programmes written in FORTRAN, Turbo Pascal, Delphi as well as public domain WWW browsers for hypertext. These programmes run on the user's local machine, some of them under DOS. In addition, a vital component of the system is the connectivity to the wide area networks.

5.3.1 The Graphical User Interface and System Manager

The importance of the GUI should not be underestimated. It has been noted by several researchers that the use of high resolution graphics has been a great aid to enhancing communication between researchers from different disciplines (e.g. Thiessen and Loucks, 1992; Palmer *et al.*, 1993; Punnet and Stiles, 1993). With the use of an effective GUI, the differing views of managers and researchers may be represented. The managers' view is represented by the GUI and the researchers' view by the data, algorithms and rules in the models embedded in the system (Davis *et al.,* 1994). The system manager effectively translates between these views, accessing the various databases, both locally and remotely, and providing the data to the other components of the system where it is required, either for display, or as input to other components of the system.

The KNPRRP ICIS uses the ARCVIEW GIS system to provide both the GUI and the system manager. The decision to use ARCVIEW as the primary GUI was prompted by the need to present the user with a *familiar picture*, i.e. a map of the catchment, and by the increasing use of GIS systems as the front end to data display and management systems both locally and internationally (e.g. Cobban *et al.*, 1995; Da Costa *et al.*, 1995; Reynolds *et al*, 1996). Figure 5.3 is a "screendump" showing the ICIS GUI and a familiar picture represented by a map of the Sabie Catchment. With reference to Figure 5.2, it can be seen that the GUI provides a uniform view of the catchment and forms a starting point from where the different participants can access data pertaining to any component in which they may be interested.

The system manager is effectively the switchboard of the system, communicating both with the user via the GUI and the applications embedded in the system.

The efficient storage and retrieval of time series is a challenge and has received much attention in both the scientific and business worlds. The use of simulation models in a catchment subdivided into numerous sub-catchments, requires that large volumes of time-series information be stored and utilised. Innovative techniques for the storage of time series in relational databases have been investigated, for use in the ICIS (Greyling, 1996; Horn, 1997), though these are still in the development phase and none have, as yet, been implemented in the ICIS. However, these methods have been used in other projects (Beuster *et al*, 1997).

The bulk of the time-series generated by hydrology models used in the project (Chapter 7) are stored on the mainframe system in a database designed specifically for the storage of time-series, *viz.* a Watershed Data Management (WDM) file. This is a binary system aimed at the efficient access to and storage of time-series. However, interaction with the WDM via modern client-server methods is not possible, and the system was inappropriate for a graphical PC environment at the time of investigation (Ninham Shand, 1995).

5.3.3 Data Display Tools

Various tools are needed for the display of model output. Many of these have been produced under the auspices of the KNPRRP and are unique to the type of output being displayed. Other information relating to terms and concepts used, background information and instructions to the user are displayed using a hypertext browser. Visual interpretation of data sets and processes is a major field of development in many areas of science, with the aim of bringing greater understanding to complex problems (Cox, 1990).

The field of data visualisation is increasingly applied to the management of environmental resources (Orland and Daniel, 1995; IMLAB, 1996). Visualisation tools have been used to assist in the compilation of large and complex natural resource data sets (e.g., Loh and Rykiel, 1992), by natural resource scientists seeking to better understand their science (e.g., Larson *et al*, 1988; Onstad, 1988; Cox, 1990). The visualisation tools developed for this project to display output of the models developed, continue this line of thinking. In particular, innovative methods of displaying output from the QRBMs have been developed with the assistance of computer scientists at the CCWR. This includes the display of time-series of QRBM output and interactive graphical representation. Figure 5.4 shows some of the graphical output resulting from these developments. More detail on the output is provided in the descriptions of the models themselves in Chapter 8.

software has been shared with a wide range of users which include some stakeholders who compete for water resources.

The ICIS is currently installed at 13 research, government, stakeholder and statutory institutions who are connected with the Kruger National Park Rivers Research Programme and plans are advanced to install it at several historically disadvantaged Universities, as well as at institutions in Mozambique and Swaziland, where it will be populated with data for their local requirements (Jewitt *et al.*, 1997a). Improvements and features which emerge from this process of sharing and interactions will be included in new releases of the software which are available free of charge. Maintenance of the ICIS and further developments are performed in conjunction with the CCWR.

The recent global release of the public domain ArcExplorer software offers a further way forward for these ICIS systems. ArcExplorer is free software developed with the aim of providing easy access to GIS data on local networks or via the Internet. In situations where no additional capabilities, apart from simple viewing of spatial data pertaining to the catchment at hand are required, ArcExplorer is a useful tool. Future ICIS developments are likely to follow a path where ArcExplorer based ICISs are provided as a feeder to the more powerful ARCVIEW version of ICIS.

At the time of writing, a major weakness of the ICIS was its PC system database. No formal database exists; rather time-series are stored in flat ASCII format, while metadata relevant to the KNPRRP is stored in a relational database searchable by SQL operated through the ICIS GUI. Future development of the ICIS system must consider the need develop a single unified database on the PC system, and consider the possibility of client-server interactions with the mainframe.

Chapter Six

THE SABIE RIVER CATCHMENT

The Sabie River catchment has been used as the prototype study area for model development, as well as ICIS development. In this chapter, the biophysical characteristics of the Sabie River are explained.

6.1 PHYSICAL CHARACTERISTICS OF THE SABIE RIVER CATCHMENT

The Sabie River lies within the Nkomati Basin, which is an international basin draining regions of the Republic of South Africa, the Kingdom of Swaziland and Republic of Mozambique. The Sabie River and its main tributary the Sand River, drains a catchment area of over 6000 km^2 at the international border between South Africa and Mozambique on the eastern boundary of the Kruger National Park (Figure 6.1) and over 7000 km^2 at its confluence with the Nkomati. It rises on the eastern slopes of the Mauch Berg in the Mpumalanga Drakensberg at an altitude of about 2200 m and flows eastward through Mpumalanga and the Northern Province over the Lowveld and Lebombo geomorphological zones for some 210 km to its confluence with the Nkomati River in Mozambique (Figure 6.1). The river flows throughout the year and is fed by two major tributaries in the Lowveld zone, *viz.*, the perennial Marite River and the seasonal Sand River. The catchment is located north of Nelspruit in Mpumalanga in an area which stretches latitudinally from $24^0 30'$ to $25^0 15'$ S and longitudinally from $30^0 40'$ to $32^0 10'$ E (Figures 2.1 and 6.1).

The river has slowly incised into the geological surface in the past ten thousand years to create a wide macro-channel (Van Niekerk *et al.,* 1995) within which all contemporary flows and sedimentary deposits are contained. The incision has also exposed extensive areas of bedrock within the river which, together with alluvial areas, create a diverse geomorphology. A dolomitic area runs from north to south through the upper reaches of the Sand and Sabie catchments. Runoff processes associated with Karst hydrology can be expected to dominate the production of streamflow in areas falling within this area.

Vegetation and landuse are varied. Much of the upper reaches of the catchment are afforested with exotic tree species. Large scale irrigation, chiefly of citrus crops, is found in the mid-regions of the catchment. The catchment also contains six game or nature reserves and several small towns, while a large number of rural settlements are found in the catchment (Figure 6.1)

A detailed description relevant to the theme of this document appears below.

6.1.1 Climate and Hydrology

Flow in the Sabie River is perennial, however, it is subject to discharge extremes similar to other semi-arid systems in the area. It is strongly affected by seasonal summer rainfall, resulting in periods of high flow and sporadic flooding during the summer months, and low flows during winter. The estimated mean annual runoff (MAR) is $633x10^6$ m^3 per annum and the virgin MAR is estimated to be $762x10^6$ m^3 per annum (Chunnet and Fourie, 1990). Precipitation is concentrated in the highland areas to the west of the catchment (1800-2000 mm p.a.), declining to 450-650 mm p.a. over the Lowveld and Lebombo geomorphological zones. In contrast, evaporation is lower in the west (1400 mm) rising to 1700 mm in the east. Seasonal trends are clear in both the precipitation and the flow regime. Consequently, an estimated 80% of runoff is generated in the upper 20% of the catchment. Sediment production is highest to the west of the KNP, particularly in the Sand River subcatchment, where dense rural populations with subsistence lifestyles have removed vegetation and enhanced land degradation. This is one of the reasons why the Sand River contributes significant amounts of sediment to the Sabie River.

Climatic cyclicity has also been identified for the Lowveld region. A quasi 18 year rainfall cycle appears to exist and has been linked to the influence of El Nino on the region (Tyson 1987; Mason 1995). This is reflected in the flow pattern of the Sabie River. A "double" El Nino event is believed to have led to an extended dry period in the region in 1983/4 (Mason 1995) and much reduced flow magnitude and variability in the Sabie River.

Twenty-five DWAF Quaternary Catchments (QCs) have been delineated for the Sabie-Sand system. The Sabie River Catchment is typical of many in South Africa in that the available catchment hydrometeorological information is generally of poor to medium quality and flow gauging structures are sparsely distributed. Flow records show many days of missing data, and frequent overtopping of weirs during high flow events. Twenty-one South African Weather Bureau (SAWB) rainfall stations are found in, and in close proximity of, the catchment. Temperature, evaporation and wind data are scarce, and the only source of these data in the Sabie Catchment is the SAWB station situated at Skukuza in the KNP.

The existing dams have an estimated gross storage capacity of $29x10^6$ m^3 of which $14x10^6$ m^3 are stored by the Da Gama Dam. Farm dams account for an estimated further $20x10^6$ m^3 storage (Pike *et al.*, 1997). The Corumana Dam in Mozambique has a gross storage capacity of $1200x10^6$ m^3. In addition, construction of the Injaka Dam, with an estimated storage capacity of $101x10^6$ m^3, on the Marite River will begin shortly. A further dam, the Zoeknoeg Dam was constructed on a tributary of the Sand River, but failed soon after construction and no longer has any storage capacity.

Major water users are commercial afforestation, irrigation and abstractions for stock watering and domestic use. In addition, there are two water transfer schemes in which 600 000 m^3 per annum and 500 000 m^3 are pumped out of the Sabie catchment area to supply water to Pretoriuskop and KaNgwane respectively (Tharme, 1997; Pike *et al.*, 1997). Table 6.1 shows the 1993 water requirements in the Sabie Catchment.

Environmental water requirements for the Sabie River have recently been quantified by an Instream Flow Requirements (IFR) workshop. These requirements are likely to be finalised and published during the course of 1998 (Tharme, 1997). Prior to the IFR workshop, it was estimated that the annual requirement of the aquatic ecosystems in the KNP section of the Sabie River would be approximately $200x10^6$ m^3 per annum (Breen *et al.*,1994).

Table 6.1 Estimated Water Requirements of the Sable River Catchment in 1993 (Tharme, 1997).

Portion of catchment		**Mean Water Requirements ($x10^6$ m^3 per annum)**				
Subcatchment	Province	Domestic, Municipal and Industrial	Livestock and Game	Irrigation	Afforestation	Total
Sable River	Northern Province	4.7	0.5	17.4	3.2	25.8
	Mpumulanga	6.1	0.4	51.7	95.5	153.7
	Total	10.8	0.9	69.1	98.7	179.5
Sand River	Northern Province	8.1	0.8	11.7	11.3	31.9
	Mpumulanga	0.0	0.1	0.0	0.0	0.1
	Total	8.1	0.9	11.7	11.3	32.0
TOTAL CATCHMENT	Northern Province	12.8	1.3	29.1	14.5	57.7
	Mpumulanga	6.1	0.5	51.7	95.5	153.8
	Total	18.9	1.8	80.8	110.0	211.5

6.1.2 Geomorphology of the Sabie River

The Sabie River is a mixed bedrock/alluvial system (Van Niekerk *et al.*, 1995). Five different primary channel types have been identified, namely single thread, braided, pool/rapid and mixed and bedrock anastomosing, with varying degrees of bedrock influence (Van Niekerk *et al.*, 1995) ranging from fully alluvial braided through to bedrock dominated anastomosing. Although alluvial and bedrock channels are generally considered to be fundamentally different in character (Ashley *et al.*, 1988; Wohl, 1992), alluvial channels and those formed completely in bedrock may be regarded as occurring at opposite ends of a continuum of channels of varying sediment supply in relation to transport capacity (Ashley *et al.*, 1988). The characteristics of the five channel types are summarised below (Van Niekerk *et al.*, 1995):

1) Bedrock anastomosing

Bedrock anastomosing channels consist of multi-channel bedrock distributary reaches. Typically, the incised macro-channel is widened to extend across an area three to four times the average width and this effect extends for several kilometres downstream. Geomorphological diversity is high, with many features occurring at a low density.

2) Pool-Rapid

The pool-rapid channel type is also geomorphologically diverse and displays many bedrock features. Typically the rapids are free of sediment. The pool areas are more variable, ranging from sediment free bedrock areas to bedrock lined pools, incorporating a variety of bar types.

3) Single thread

The alluvial single thread channel type has developed in sections of the Sabie River where alluvium has accumulated to cover any bedrock influence in the macro-channel. Few geomorphological features are recorded in the active channels, which are composed largely of deep alluvial pools, with rare mid-channel and lateral bars.

4) Braided

The degree of braiding in the Sabie River, as defined by the number of braid distributaries, is low. Geomorphological diversity is lower than for those channel types directly influenced by bedrock.

5) Mixed anastomosing

Mixed anastomosing channel types exhibit a high geomorphic diversity, displaying multiple bedrock, mixed and alluvial distributary channels, that divide and rejoin over a distance much greater than the distributary width.

6.1.3 The Common Fish Species of the Sabie River

A full description of fish of the Sabie-Sand system is provided by Weeks *et al.* (1996). A total of 45 indigenous species of freshwater fish are resident in the Sabie-Sand system, 39 of which have been recorded in the Lowveld reaches. The presence or absence of a number of these fish species is largely dependent on prevailing flow and temperature conditions. Only one species, found in the system, *Opsaridium peringu,* is considered rare (Weeks *et al.*, 1996). The fish fauna of the Sabie River represents one of the most diverse populations in southern Africa and as such also forms an important ecological resource for a diversity of piscivorous animals.

Using electro-fishing techniques considered standard by aquatic ecologists, and data spanning three and a half years, the most abundant or ecologically important species were identified. Twelve species typically make up over 78% of the catch. Each selected species makes up at least 6% of the total catches for any given field trip within the Lowveld. These species have been defined as the "Lowveld baseline assemblage" for the system (Weeks *et al.* 1996).

It is the changing patterns of seasonal abundance established for these species both for normal and extreme (i.e. drought) seasonal conditions, that form the basis of potential prediction of the fish response to varying hydrological conditions. To facilitate interpretation and allow for coarser resolution of any predictive models that may be developed (see Section 8.1.2), the shallow-water species are, where possible, grouped according to shared life-styles, based on life-history attributes (Weeks *et al.*, 1996). These groups are listed below, together with characteristics that may be important in the development of a suite of predictive models (Weeks *et al.*, 1998):

1) Cichlids

Cichlids are secondary freshwater fishes, considered advanced in evolutionary terms. They typically dominate shallow waters in the Lowveld prior to the seasonal rains or during drought periods. They share a breeding style that involves pair formation and complex parental care of both the eggs and young. Some of these flourish in drought conditions, and are able to survive extreme drought conditions by breeding at a stunted size. Others are found in extremely shallow habitats and are generally less affected by flow extremes.

2) Small Cyprinids (Minnows)

These small species are common, often being observed in shoals in sluggish to moderate flow velocities. One of these, *Barbus viviparus,* is often the most numerous fish sampled in the Lowveld. Fish in this group are the first to breed following drought conditions, often with the first freshet.

3) Yellowfish

Adults of this group are common in deeper Lowveld river runs. The juveniles, like the mudfish, favour the shallow habitat of rapids for cover.

4) Mudfish

Mudfish often grow to a large size. They are good swimmers and are frequently adapted to strong flowing habitats. Mass migrations often precede seasonal breeding with large numbers of eggs released. Adults are found in cover in strongly flowing deeper habitats, as well as deep pools, while juveniles prefer the shallow habitats afforded by riffles.

5) Rock Catlets

This group is made up of small localised species adapted to life in fast currents. Breeding takes place in summer, with only a few large eggs produced. They are unable to survive in oxygen-poor waters and therefore in drought or no-flow conditions.

6) Robbers

Robbers are primary freshwater fishes found in mainly tropical waters of both Africa and the Americas. They are seasonal spawners, simply scattering their eggs in suitable substrata.

These descriptions are also available in hypertext format in the ICIS.

6.1.4 Riparian Vegetation of the Sabie Catchment

A description of the riparian vegetation along the Sabie River inside the KNP has been produced by Van Coller and Rogers (1995). Riparian vegetation patterns were analysed and patterns have been related to physical habitat templates. Van Coller and Rogers (1996) have used discontinuities in the distribution patterns of suites of species to define vegetation types. There are six vegetation types that comprise all the species within the riparian zone (riparian as well as terrestrial species), and each vegetation type is associated with certain response functions to hydrological and geomorphological environmental factors. These are (Van Coller and Rogers, 1995):

1) The *Breonadia salicina* vegetation type

This vegetation type is characterised by an evergreen tree canopy and is associated with geomorphic features that are predominantly bedrock-influenced. Species in this group are associated with year round hydrological influence in close proximity to the active channel. This vegetation type predominates in the granitic and rhyolite geological substrata, and can be found along most of the length of the Sabie.

2) The *Phragmites mauritianus* vegetation type

This is a reed vegetation type and is mainly associated with alluvial geomorphic features that are regularly influenced by hydrology. The *Phragmites mauritianus* vegetation type occurs more predominantly where the geology is basaltic in nature, and tends not to occur higher up in the Sabie catchment. This vegetation type is also important because of its stabilising effect on alluvium and it therefore plays a role in sediment dynamics.

3) The *Phyllanthus reticulatus* vegetation type

This vegetation type is similar in distribution, extent and hydrological influence preferences to the *Phragmites mauritianus* vegetation type although it is more drought resistant. It is dominated by deciduous shrubs that are important food resources to fauna utilising the riparian zone (both leaves and fruits).

4) The *Combretum erythrophyllum* vegetation type

This vegetation type is characterised by a deciduous tree canopy and is associated with geomorphic features that are predominantly alluvial in nature. The species in this group tend to occur where the hydrological influence is seasonal and to a lesser degree ephemeral, but not in close proximity to the active channel. This suite, like the other tree groups, is more abundant where the geology is granitic in nature, and can occur along most of the length of the Sabie.

5) The *Diospyros mespiliformis* vegetation type

This vegetation type is associated mainly with the macro channel bank, but to a lesser degree with ephemeral alluvial features. Species in this group occur in association with non-alluvial soils or fine consolidated sediments.

6) The *Spirostachys africana* vegetation type

This vegetation type is associated only with the macro channel bank. Species in this group occur in association with non-alluvial soils from weathered parent material. These species are drought resistant. They form a boundary zone between the riparian zone with the terrestrial zone, and comprises some terrestrial species which colonise the riparian zone (Mackenzie *et al.,* 1998).

Some exotic invasives have become a concern along the Sabie river riparian zone, and in particular *Lantana camara* and to a lesser degree *Melia azedarach*. Higher up in the catchment outside of the KNP many *Pinus* and *Eucalypt* species have been planted in commercial forests. These species have been observed to invade the riparian zone.

6.2 CATCHMENT MANAGEMENT ISSUES IN THE SABIE CATCHMENT

Catchment management has been identified as an important need in all of the rivers of the KNP, however, it is generally felt that it is in the Sabie-Sand system that this is most critical. The Sabie catchment is unique in that it has no serious water quality problems, and it is, prior to the construction of the Injaka Dam, the only perennial river, of the six flowing through the KNP, that is unregulated by any dam. The Sabie has for the past ten years not suffered from major flow or quality problems, unlike other KNP rivers and as such, has stood out as a flagship for successful river conservation (NPB, 1996). However, the increasing strain on a limited water resource (see Table 6.1) has put the river under extreme pressure.

The lowest recorded flow in the Sabie River for the period 1953 to 1984 was 650 litres per second. This occurred during the drought years of the 1960s and low flows of this order had been rare occurrences. In 1995, the flow at Lower Sabie reached a low of only 15 litres per second. The increase in afforestation (84000 ha of exotic forests in the upper catchment of the Sabie river) and irrigation in the areas upstream from the park have reduced the flow over the years. The increase in informal abstraction of water downstream from the town of Hazyview (Figure 6.1) over the past three years appears to now have a significant impact on the flow in the river. The deteriorating water quality from increased sediment yield resulting from unsuitable land-use management in the catchment, and enhanced loadings of point and non-point pollutants resulting from increased levels of industry and agricultural practices has exacerbated this situation.

It has been noted that pollution from short-lived gold mining virtually exterminated the natural fauna in the middle reaches of the Sabie River early in the century. The remarkable recovery of the river fauna has been attributed to the presence of refuge tributaries in the system (Weeks, *et al.*, 1996). This highlights the need to consider the river system as a whole when considering management options.

Clearly, an ICM approach is required to ensure an adequate flow of water in the Sabie River in the light of the many competing users of water in the Sabie. The management issues regarding equity in allocation of these resources are complex. The KNPRRP continues against a background of great political change within South Africa, a large poverty-ridden rural population within the river systems upstream of the KNP, and the identified need of the Reconstruction and Development Programme of the SA government to provide 25 litres of water per person per day to within 200m of their doorstep. Supply of water to these impoverished rural communities is a priority (DWAF, 1997). Furthermore, South Africa has an international obligation to allow flow in the Sabie River to reach Mozambique, and the Curumana Dam just downstream of the KNP and the international border. The aquatic ecosystems of the Sabie River also have water needs and recently, attempts have been made to quantify this need through an IFR workshop (Tharme, 1997). The three water requirements mentioned above will form the "reserve" as identified by the new SA Water Bill (DWAF, 1998) and discussed in Section 2.1. These requirements, once quantified, will have first call in the allocation of water.

It has been recognised in the KNPRRP that over 90% of the water flowing through the park rises in the catchments to the west of the reserve and that it is imperative to develop modelling systems to aid in understanding the hydrological system dynamics outside of, as well as inside the KNP. The KNPRRP has also recognised that the management of the environmental reserve is going to require ongoing and dynamic systems to assist the process of day-to-day management of the river systems in the catchment and the conflicts that will inevitably arise over environmental allocations of water. Thus, the development of a hydrologically based Integrated Modelling System within an ICIS, with which model components representing the aquatic ecosystems of the Sabie River may be integrated, has come to be the focus of the research that is reported in this document.

Chapter Seven

PREDICTIVE MODELS IN THE SABIE RIVER CATCHMENT

As explained in Chapter 2, Phase II of the KNPRRP was aimed at, *inter alia,* developing decision support tools for catchment management with an emphasis on those that link abiotic components and aquatic biotic response to upstream catchment developments. The aim of this research has been the development of a hydrologically driven computer based modelling system which will enable the *integration* of the predictive methods used by different water related disciplines. Using the Sabie River catchment as a case study, the systems builds on the insights discussed in Chapters 3, 4 and 5.

It was decided that the modelling system should be generic in its design so that it may be transferred with minimum effort to other catchments where water management decisions are required. It should also be compatible with the ICIS described in Chapter 5.

7.1 REQUIREMENTS OF A MODELLING SYSTEM FOR THE KNPRRP.

Given the dependence of aquatic habitat on flow and sediment conditions, the simulation of catchment hydrology and sediment production on a daily basis was considered critical to the success of the project. Thus, the required modelling system had to include robust physically meaningful hydrological modules to provide information for other predictive models incorporated in the system.

With the prior knowledge that spatial information regarding hourly rainfall would be inadequate, it was accepted that hydrological models which operate at a daily time step were most appropriate for this project. Two examples are given to indicate this point. Flood events are important in transport of pollutants (including sediments). In order to simulate these events even reasonably, at least, a daily model is required. Secondly, ecologically important low flows may be significant over periods of several days, rather than months. If needed, daily simulation values can be aggregated up to any longer time step.

A set of generic requirements that needed to be fulfilled by the hydrological modelling system selected for use, based on the needs identified in Chapters 3 and 4, is shown in Table 7.1.

Table 7.1. Requirements for models for the simulation of hydrology in the Sabie River Catchment.

Simulation Criteria	Rationale
Operating System Platform	Given the geographic distribution of KNPRRP participants, the selected models had to operate on both PC and UNIX platforms to facilitate effective computer networking.
Source Code	The code had to be well documented in an accepted programming language to facilitate the addition or modification of algorithms.
Support and Availability	The models had to be readily available and support for them easily accessible.
Management of Time Series	Sound management of time series was required as model linkages would depend upon integration of time-series.
Specific Support Software (parameter optimisation, result analysis, etc)	Input and output of model parameters as well as analysis of model results are greatly enhanced by the availability of good support software.
Spatial Resolution (degree of lumping vs distribution of processes)	Assessment of impacts of land-use change on the response of the Sabie River required that the model is sensitive to small-scale changes.
Temporal resolution of processes	Sensitivity of ecosystem responses and water quality processes to variation required a finer, rather than coarser temporal scale: at least daily
Aggregation of processes and degree of calibration.	The simulation of processes had to be physically based to accommodate moderate changes in land use and to enable confidence in their results in the absence of calibration data.
Operates in series or parallel	If changes in one catchment influence another (upstream) catchment in a time-dependent way (e.g. irrigation releases from a dam to accommodate downstream demand), parallel processing would be optimal.
Important water quality parameters simulated	The models needed to simulate at least water temperature and sediment production as well routing of these through the river channel system. The simulation of nutrients was considered of secondary importance.
Inclusion of groundwater dynamics	Sections of the Sabie catchment are influenced by limestone areas. Furthermore, riparian vegetation was judged to be sensitive to groundwater availability.
Inclusion of river channel processes	Instream biota respond directly to in-channel processes.
Inclusion of new algorithms and code	The models had to permit easy modification or addition of new algorithms to enhance the simulation exercise.
Suitability for scenario assessment	It was imperative that the model allowed easy adjustment of parameters to simulate changes in catchment landuse or planning options.
Degree of calibration	The lower the degree of calibration, the better the model would be suited to scenario assessment

7.2 REVIEW OF AVAILABLE CATCHMENT HYDROLOGY MODELS

The following catchment hydrology models, readily available in South Africa and which operate on a daily or finer time step, were considered for use in the KNPRRP: ACRU, HSPF and VTI. Their development philosophies are described briefly, the simulation options available in these models are listed, and their structure, cost and institutional acceptance are discussed. Finally the peripheral software tools and their institutional support is analysed. Similar to the review of DSSs in Section 5.1, it must be noted that the description of the models below were valid in 1995, but the rapid pace of software development implies that any updates to the models since then cannot be considered.

Similar to many computer program packages, these hydrological models comprise hundreds of files, hundreds of routines, and tens of thousands of lines of source code. Thus HSPF, for example, is not a simple, single model, as its name implies, but actually many separate FORTRAN source-code sub-programs packaged together with a vast array of data files. This is also true of ACRU and to a lesser extent VTI, which is written in C and is a less comprehensive model than the other two.

7.2.1 Variable Time Interval (VTI) Model

The VTI model (Hughes and Sami, 1994) is described as a semi-distributed variable time interval model. The model is an extended version of the single event flood model (OSE2) (Hughes, 1984; Hughes, 1989) which has been adapted into a continuous time-series model.

The model has been developed as a compromise between complex, highly physical and data intensive modelling approaches and the simpler empirical approaches. The model utilises several parameters, some of which have physical meaning, some of which are estimated from physical indices and some of which are completely empirical. The complexity of the model algorithms has been limited to prevent the model's information requirements becoming too limiting. A unique feature of the model is its ability to simulate at a variable time interval according to user selected rainfall thresholds.

The authors point out that three main points have governed the development of the model:

1. The suitability of the algorithms for representing hydrological processes at the scale of sub-catchments in a practical semi-distributed modelling system.

2. The availability of information on physical catchment properties and how this can be used to estimate parameters, without introducing too high a degree of empiricism.

3. The model and parameter estimation procedures should be applicable to a wide range of climate types, excluding those where frozen ground or snowmelt affect hydrological processes.

VTI uses a semi-distributed, or sub-area (rather than a grid square or slope element) approach to cater for spatial variation. Thus, model components are based on simulating the integrated response over a sub-area, rather than at a representative point. Many of the functions are therefore of a distribution type, where the internal sub-area variation in hydrological processes are represented by probability distributions. There are two basic runoff generation methods, one which is dependent upon rainfall intensity and the infiltration characteristics of the catchment soils, and the other which is dependent on the dynamic moisture status of the catchment or sub-areas. A third runoff generation function allows for the simulation of groundwater baseflow

A strength of the VTI model are its sub-surface moisture simulation routines, particularly its innovative handling of groundwater dynamics. However, sediment production from the catchment is not simulated by the model, nor is any other water quality constituent. River channel transport processes are not included in the models, it only offers basic hydrological routing capabilities.

The model is operated from a user-friendly HYMAS shell. Physiographic variable input and time-series preparation are all completed by the user working largely within the HYMAS shell. Several support facilities for results analysis are included in the HYMAS shell. These include easy-to-use comparative statistics and graphical portrayal of observed and simulated results as well several other post-processing options useful for analysis of low flows etc. A drawback of the model for this project, is that its use is restricted to a PC platform.

7.2.2 HSPF

HSPF is a comprehensive package for simulation of catchment hydrology and water quality. The model was developed by Hydrocomp (USA) under contract to the US-EPA as a completely new model incorporating features of the Stanford Watershed Model, the Nonpoint Source (NPS) model (Donigian and Crawford, 1976), ARM (Donigian and Crawford, 1976) and other models.

Usually, nonpoint source models concentrate on the generation and transport of pollutants across the land surface to watercourses, or through the soil profile to groundwater. On the other hand, water quality models are usually developed with a focus on the transport and fate of pollutants in streams, rivers and reservoirs. HSPF is one of the few models which combines both the loading and receiving water aspects into one overall model, although its major use has been that of a pollutant fate model.

Spatial variation of rainfall and physiographic catchment parameters is provided for by dividing the catchment into areas of similar hydrological response. Rain is partitioned as rainfall onto impervious areas, which runs off directly, and an infiltrated portion. Infiltration is divided into surface runoff and interflow and flow into the lower soil zone which contributes to groundwater storage.

Water quality simulations are provided using algorithms from the Agricultural Runoff Management Model (ARM) and the Nonpoint Source (NPS) models developed by the US EPA. Water quality channel transport algorithms were obtained from the Chemical Migration and Risk Assessment Methodology (CMRA) and incorporated into HSPF to provide simulations of the fate and transport of chemicals in one-dimensional channels. The model simulates transport of sand, silt and clay and organic chemicals and transformation products of those chemicals. Transfer and reaction products modelled are hydrolysis, oxidation, biodegradation, volatilisation and sorption. Resuspension and settling of silts and clays are based on the computed shear stress at the sediment-water interface. Resuspension and settling of sand is a function of the stream's estimated total sand transport capacity. Exchanges of chemicals between benthic deposits and the overlying water column are also simulated.

The model is built on a systematic framework in which a variety of process modules permit the continuous simulation of a comprehensive range of hydrologic and water quality processes. The framework evolved from a top down approach emphasising structured design and the model is planned around a time series management system as discussed in Chapter 5.

HSPF is a "parameter optimisation" or calibration model in that it is necessary to run the model repetitively to find the optimum value of a model parameter, i.e., one that provides a computed response that best-fits an equivalent function that is deemed to be correct. The model's required calibration and its lumped parameter approach makes it difficult to evaluate changing catchment conditions, because the model is calibrated to existing conditions and users would be uncertain how to modify parameters for other scenarios. Furthermore, the fact that HSPF has not been extensively used in South African means that little local knowledge about, and few recommendations regarding parameter values, are available.

The model's major potential strength, and one particularly important in terms of the KNPRRP, is its ability to simulate water quality components both on the land surfaces and in the river channel. Although many of these simulations are relatively coarse and utilise largely empirical algorithms, the water quality simulations provide a feature which ACRU and VTI do not have.

At the time of study, input and output time series were managed using ANNIE, a menu driven program designed to manipulate data in the time series database, the binary WDM file. ANNIE is not particularly user friendly by comparison with HYMAS. ANNIE operates on DOS and UNIX platforms, amongst others, although manipulation of the WDM is required if the same file is needed on both DOS and UNIX platforms, due to differences in the way in which these operating systems consider binary data. Model input parameters are controlled by the user control input (UCI), an ASCII file, which needs to be produced by the user according to a rigid input format. No "front-end" was available for the UCI at the time of study and, particularly in the case of large catchments with many of HSPF's options being utilised, the size and lack of transparency of this file can be particularly intimidating to the user.

A model as comprehensive as HSPF has extensive data needs. Continuous rainfall records are required, as are records of evapotranspiration, temperature, solar radiation and others at a time-step similar to that of the simulation. Observed streamflow records are required for calibration of simulated flows. Measured water quality data are required for calibration in terms of simulated water quality output. The user must supply a large number of parameters for the various processes, although default values are provided for many of these.

User support in South Africa is provided by the CCWR, and some assistance is available from Hydrocomp in the USA. During recent years a limited "expert system" has been available for calibration of the rainfall-runoff functions in the model, but it only operates in British units.

7.2.3 ACRU

The ACRU agrohydrological modelling system has been developed in the Department of Agricultural Engineering[1] at the University of Natal. The ACRU model is described by the

[1] Now the School of Bioresources Engineering and Environmental Hydrology

developers as a multi-purpose and multi-level integrated physical conceptual model that can simulate streamflow, total evaporation, and land cover/management and abstraction impacts on water resources at a daily time step. It differs from HSPF in that the model is not considered to be a parameter optimisation model in that model simulations are perceived to be based on physically meaningful parameters.

Model documentation was first published in 1984 (Schulze, 1984) and updated in 1989 (Schulze, George, Lynch and Angus, 1989). The latest available version of the model, at the time of writing was ACRU325 and updated documentation has been published (Schulze, 1995). Model input parameters are contained in a menu file. Input to the menu is controlled by a "menubuilder" program where the user enters parameter or catchment related values or uses defaults provided.

Spatial variation of rainfall, soils and landuse is facilitated by operating the model in "distributed" mode. In this respect, the ACRU, HSPF and VTI models follow a similar philosophy. The catchment to be modelled is sub-divided into cells or subcatchments, each of which represents a relatively homogenous area. In reality, this ideal is compromised by the need to simulate output at specific sites such as dams or flow gauging weirs.

ACRU differs from VTI in that the model's soil water budgeting routine is performed in a lumped fashion with all units expressed in mm. The point of simulation is assumed to be representative of the subcatchment. Outflow is then directed to downstream model subcatchments.

The ACRU model revolves around multi-layer soil water budgeting. Similar to VTI, runoff is generated as stormflow dependent upon rainfall intensity or from dynamic soil water budgeting. Components of the soil water budget are integrated with modules in the ACRU system to many other catchment components including irrigation requirements and sediment yield.

A unique feature of the model is its ability to incorporate multiple levels of input. For example, if daily temperature is required for estimation of PE and is not available, the model is able to utilise monthly temperature data for this purpose. Furthermore, model documentation contains an extensive database of recommended model parameters for South African conditions. However, as in the case of HSPF, data requirements can be extensive for large projects. These include both physiographic and hydrometeorological variables.

At the time of writing, the model did not provide for simulation of channel processes apart from a Muskinghum based runoff routing function. Simulation of reservoirs is provided for by a stand alone module within the system. Farm dams are accounted for by routing only a specified proportion of generated runoff through the dam module. Simple methods of estimating nutrients and bacteria from the catchment have recently been included (Kienzle et al., 1997). Sediments are generated using an adaptation of the MUSLE/RUSLE methods with the K factor or soil erosivity factor being dependent upon simulated soil moisture.

Strengths of ACRU are its design to utilise multiple levels of South African data, its various support facilities to aid the user in input preparation and its ability to simulate agricultural practices such as irrigation and farm dams. The Menubuilder suite of programs are of benefit to the user in determining input parameters. These include tools to determine soils, landuse parameters and the like. However, the menubuilder suite of programmes is not particularly user-friendly and the programs utilise keys and editing options not commonly used and can be frustrating to use. Similar to the HSPF UCI, the menu file can be very large and may create difficulties for the inexperienced user.

User support is provided by the model developers who continually update and improve the model in response to user requests.

7.2.4 Comment and The Way Forward

Simulation of water quality outputs from the surface area of the catchment, in particular sediment, is a major function of this project. The ACRU model has the ability to generate daily sediment output and is therefore preferred to the VTI model. One of the HSPF model developers, Prof. R. Johannson (pers. comm., 1995) suggested that runoff components, such as quickflow, baseflow, etc. simulated by ACRU, could be used to "drive" water quality simulations in HSPF. A demonstration in this regard has been completed by Van Rensburg and Dent (1997).

Given the apparent unavailability of an appropriate integrated modelling system from international sources, and following the potential benefits of an ACRU-HSPF link evident in the implementation of the HSPF model by Van Rensburg and Dent (1997), and especially in the light of the support of the HSPF model offered by the CCWR, an ACRU-HSPF linkage for the KNPRRP was accepted by the Project Management and Development Committee. The remainder of this section will focus on the implementation of this link between the ACRU and HSPF models. The focus of this integration is the interface between catchment and river channel, with ACRU simulating the land surface processes, and HSPF the in-channel hydraulic and water quality processes.

This methodology has the advantages of utilising the "tried and tested" ACRU model to perform hydrological simulations from the catchment whilst using HSPF to obtain the hydraulic and water quality functionality that ACRU lacks.

7.3 IMPLEMENTATION OF AN ACRU-HSPF LINK FOR THE SABIE RIVER

The ACRU model was used to simulate the catchment hydrology for the period 1937 to 1995 inclusive. Due to a lack of meteorological data, the channel hydraulics were only simulated for the period 1967 to 1995 with HSPF.

7.3.1 Simulation of Land Surface Hydrology with ACRU

Hydrological simulations of surface runoff and sediment yield were performed by the School of Bioresources Engineering and Environmental Hydrology at the University of Natal and are fully reported by Pike *et al.*, 1997, reproduced here as Appendix I.

Sub-Catchment Delimitation

For the purposes of this study, the Sabie catchment was divided into 56 sub-catchments. The 25 Department of Water Affairs and Forestry (DWAF) Quaternary Catchments (QCs) making up the area were selected as the basic spatial units of the Sand and Sabie systems when subdividing them into more homogeneous hydrological regions. Due to the range of soils, land uses, reservoir locations and climatic variation, the QCs were subdivided into 17 and 39 subcatchments for the Sand and Sabie catchments respectively. The breakdown of the catchment into 56 subcatchments (ranging in area from 8.51 to 311.72 km^2 is explained in detail in Appendix I.

Simulation of Sediment Production

The Modified Universal Soil Loss Equation (MUSLE) is used within the ACRU modelling system to estimate individual subcatchment sediment yields on an event-by-event basis. This equation requires the following information as input for each of the subcatchments (Smithers and Schulze, 1995);

- event-by-event stormflow volume and peak discharge,
- weighting parameters for stormflow and peak discharge,

- a maximum and minimum soil erodibility factor,
- a slope length and steepness factor,
- monthly vegetation/ surface cover factors,
- a management practice factor, and
- the fraction of the event based sediment yield from the subcatchment that reaches the outlet on the day of the event.

Estimation of sediment yield with ACRU also requires that the peak discharge be simulated. This also requires the following information as input:

- average slope (%) of each subcatchment and
- the 2-year return period value of the 30-minute duration rainfall intensity (I_{30}, mm.h^{-1}).

The average subcatchment slopes were calculated from a 200x200 m altitude grid of the Sabie Catchment using *ARC/INFO* GIS routines (Pike *et al.*, 1997).

Simulation of Streamflow and Model Verification

An important 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. Where no observed data are available, it has to be ensured that sensible values are generated. According to Pike *et al.* (1997), the poor quality of streamflow data in the Sabie catchment has limited the effectiveness of such a verification exercise.

Table 7.2 shows the quality of the data collected at the nine gauging weirs in the Sand and Sabie catchments. The shaded rows identify seven weirs where Pike *et al.* (1997) suspected that overtopping of the structures occurs during flood events without the relevant flags for suspect data appearing in the data record.

A plot of simulated versus observed values of daily streamflows for the full period of observed record for weir X3H006 (at the outlet of subcatchment 30) is shown in Figure 7.1. Pike *et al.* (1997), show that these figures highlight the problems of conducting verification studies in catchments where uncertainties exist pertaining to both the volume of irrigated water abstracted and the extent of existing irrigation.

Table 7.2 Quality of observed daily streamflow records for the nine flow gauging weirs in the Sand and Sabie catchments (Pike *et al.,* 1997).

Catchment	Sub-catchment	Weir Ident. Code	Monitoring Period	Number of Months Monitored	Number of Months of Reliable Data	% of Months with Reliable data
SAND	12	X3H008	1/11/1967 - 31/12/1995	338	213	63.0
SABIE	18	X3H001	1/11/1948 - 31/7/1995	561	532	94.8
	19	X3H002	1/5/1964 - 31/12/1995	380	208	54.7
	21	X3H003	1/11/1948 - 30/9/1995	563	556	98.8
	27	X3H011	1/1/1979 - 31/11/1995	203	184	90.6
	30	X3H006				
	31	X3H007	1/1/1964 - 31/8/1991	332	297	89.5
	35	X3H004	1/11/1948 - 31/12/1995	566	551	97.3
	52	X3H015	1/1/1988 - 28/2/1993	62	62	100.0

Months with high flows are often simulated well. However, Figure 7.1 also highlights several potential anomalies in either the rainfall or the streamflow record where extraordinarily high streamflow is recorded but very little response is simulated by the model (e.g. the summers of 1979, 1982, 1986, 1987, 1993 and 1994) or *vice versa* (e.g. the summers of 1974, 1992 and 1995). Potential problems in the timing of either the rainfall or streamflow data (e.g. the summers of 1973 and 1990) are also identified by the verification study. The *ACRU* model also tends to underestimate autumn and winter low flows.

Median annual sediment yields per subcatchment are shown in Figure 7.2. The simulated sediment yield is closely related to land cover and slope, with the steeper subcatchments producing more sediment than those characterised by shallower gradients. The well-conserved areas in the Kruger National Park produce lower sediment loads than the cultivated areas and the former independent homelands.

The lack of observed sediment information has prevented a similar verification for the simulation of sediment production from the catchment. Confidence in the simulated results is enhanced by comparison with results of studies of long-term sediment production in the Sabie Catchment, such as those of the sediment yield map by Rooseboom, *et al.* (1992). Pike *et al.* (1997) report that the figures estimated by the ACRU model are consistent with those of Rooseboom *et al.* (1992) for the region.

Despite the problems experienced by Pike *et al.* (1997), the relatively poor streamflow simulations, and unverified sediment simulations, the ACRU model output was judged to be sufficiently accurate for use in this project. Furthermore, the simulation of the Sabie system hydrology was going to be refined as part of a separate ongoing WRC project (Pike, pers. comm.). As discussed in the following sections of this chapter, the hydrological trends simulated are more important than detailed simulations of daily streamflow and sediment loads for the purposes of developing an Integrated Modelling System for the rivers of the Kruger National Park. The output from the ACRU models are time series of streamflow and daily sediment load at selected points in the catchment. These time series are used as input to HSPF, as well as a suite of QRBMs, a description of which follows.

It should also be noted that output from the VTI model is also available for the Sabie as a result of its implementation for the determination of Instream Flow Requirements for the river. Output from this modelling exercise are also included in the modelling system and are accessible via the ICIS.

7.3.2 Simulation of Channel Processes with HSPF

From the discussion in previous chapters, it is clear that the water quality characteristics of primary importance to ecosystem based management in the Sabie River are sediment and temperature. Therefore, in order to assess the applicability of the HSPF model for simulation of channel processes in the Sabie River, the model was tested in terms of it ability to simulate sediment transport and water temperature. In the HSPF model, these two components are linked, as water temperature affects the viscosity of water in the channel, and thus the settling rate of sediment particles. Furthermore, water temperature is considered to be one of the most fundamental indices used to determine the nature of an aquatic environment.

In HSPF, computations for a reach of river are performed with the module known as RCHRES. This module simulates the processes which occur in a single reach of river. There are ten subdivisions of the RCHRES module. In the Sabie River, simulation of hydraulic behaviour, water temperature and sediment transport was considered to be important. Thus, the subroutines known as HYDR (simulation of hydraulic behaviour), SEDTRN (simulation of the behaviour of inorganic sediment) and HTRCH (simulation of heat exchange and water temperature) are utilised.

The hydrodynamic component (HYDR) uses "storage routing" or "kinematic wave" methods. Consequently, momentum is ignored and backwater or super-critical flow effects cannot be predicted. Flow is assumed to be unidirectional. Inputs to the reach, either from the land segment being simulated (in this case by ACRU), or from an upstream reach, are assumed to enter the reach through a single point or gate. Water may leave the reach through five possible outflow gates e.g. for abstraction purposes. Precipitation, evaporation and other fluxes are considered in the module, but are not governed by these gates. Flow depth in and surface area of the channel is determined empirically from stage/discharge and surface area/discharge relationships (known as F-Tables) established for each reach.

ACRU-HSPF Link - Technical Aspects

The link between ACRU and HSPF is made in series following the method described in Section 4.3.2. In this case, daily streamflow and sediment values computed at each subcatchment outlet are produced by the ACRU model in its native binary time series storage format. A stand-alone conversion utility is then used to transfer these data into a WDM file. In the Sabie River simulation, this WDM is the main Sabie WDM file consisting of all hydrometeorological variables available for the Sabie system on the UNIX platform. Figure 7.3 illustrates this procedure. The implementation of this link follows a similar methodology to that in the Chesapeake Bay Programme.). The linkage between ACRU and HSPF performed here is somewhat more sophisticated than that link, as the WDM is used as common database, whereas in the Chesapeake Bay Programme, hydrological output from HSPF is linked to an estuary model in series via the transfer of flat ASCII files (Schenk, pers. comm.).

An HSPF User Control Input (UCI) file was then created for the HSPF components of the simulation. A reach of river was established for each of the 56 ACRU subcatchments to represent the channel component of each subcatchment. The network block is the HSPF component which determines the flow network in the system to be simulated. In this section of the UCI, ACRU daily flow and sediment values are routed through specific reaches in the HSPF model. The configuration of ACRU subcatchments and associated HSPF reaches used is illustrated in Figures 7.4 to Figure 7.6 below.

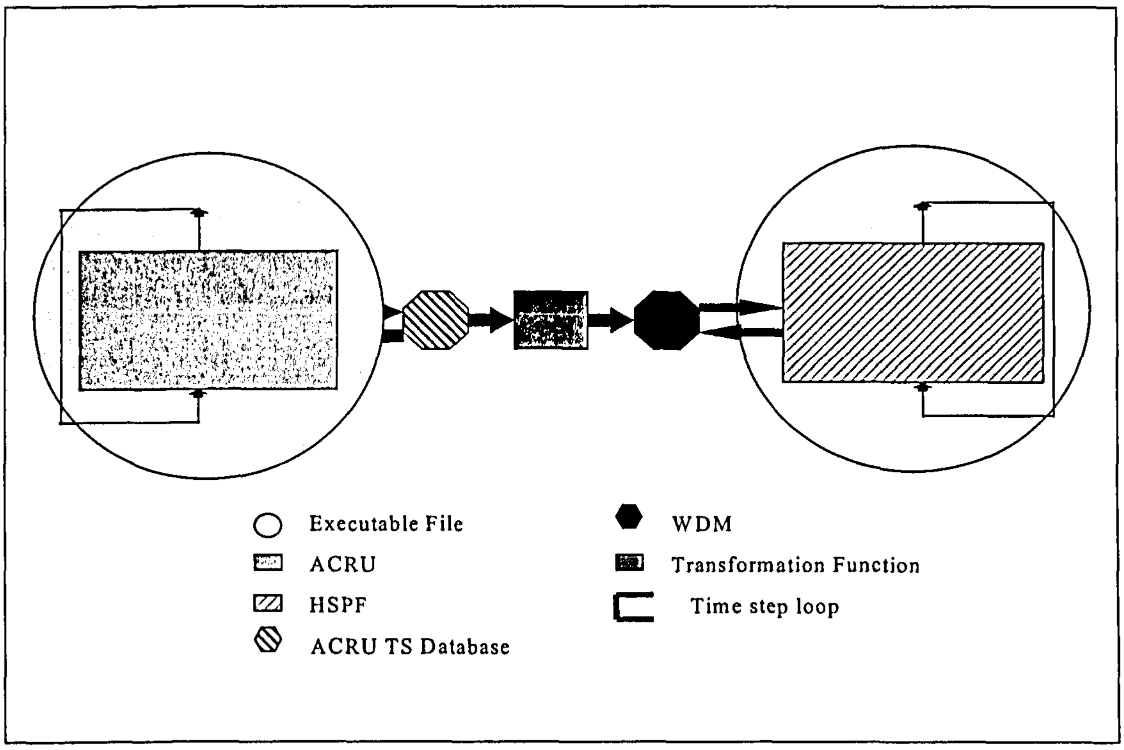


Figure 7.3 Series link between the ACRU and HSPF models as used in this project.

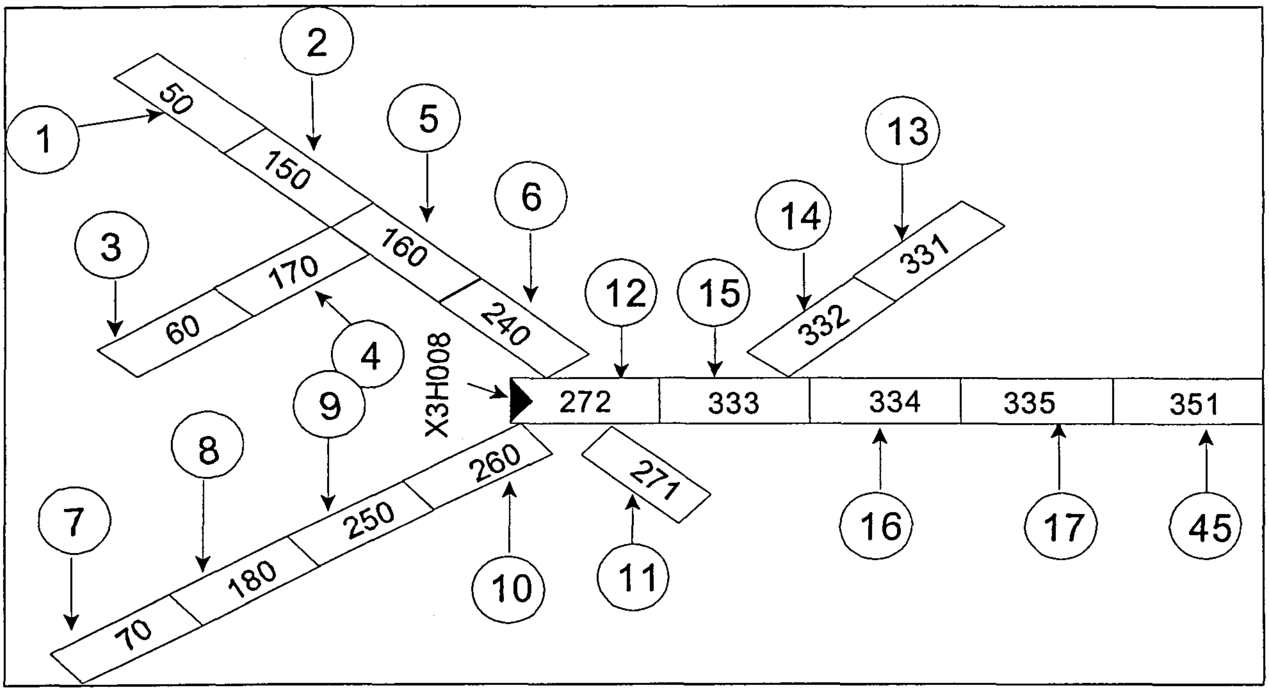


Figure 7.4 ACRU Subcatchment (circles) and HSPF reach (rectangles) configuration for the Sand River (triangle=flow gauge).

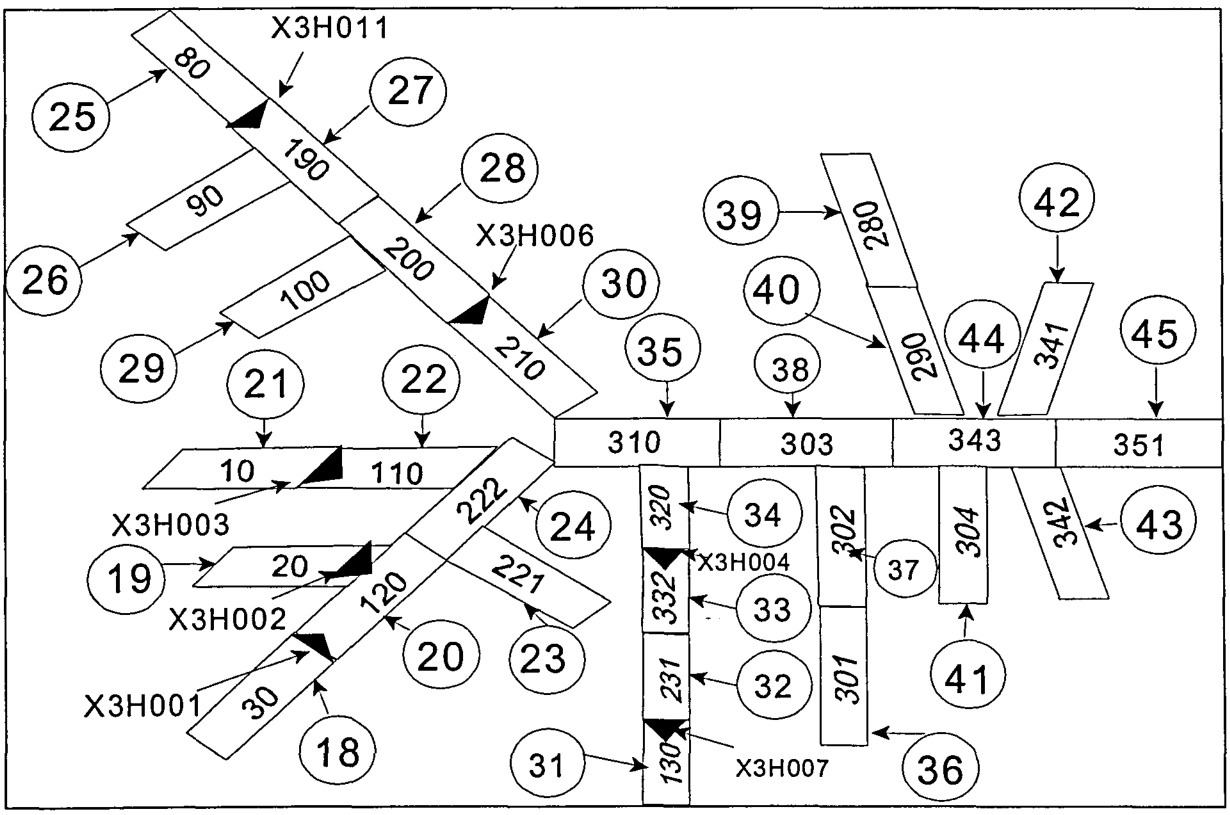


Figure 7.5 ACRU Subcatchment (circles) and HSPF reach (rectangles) configuration for the upper Sabie River(triangle=flow gauge).

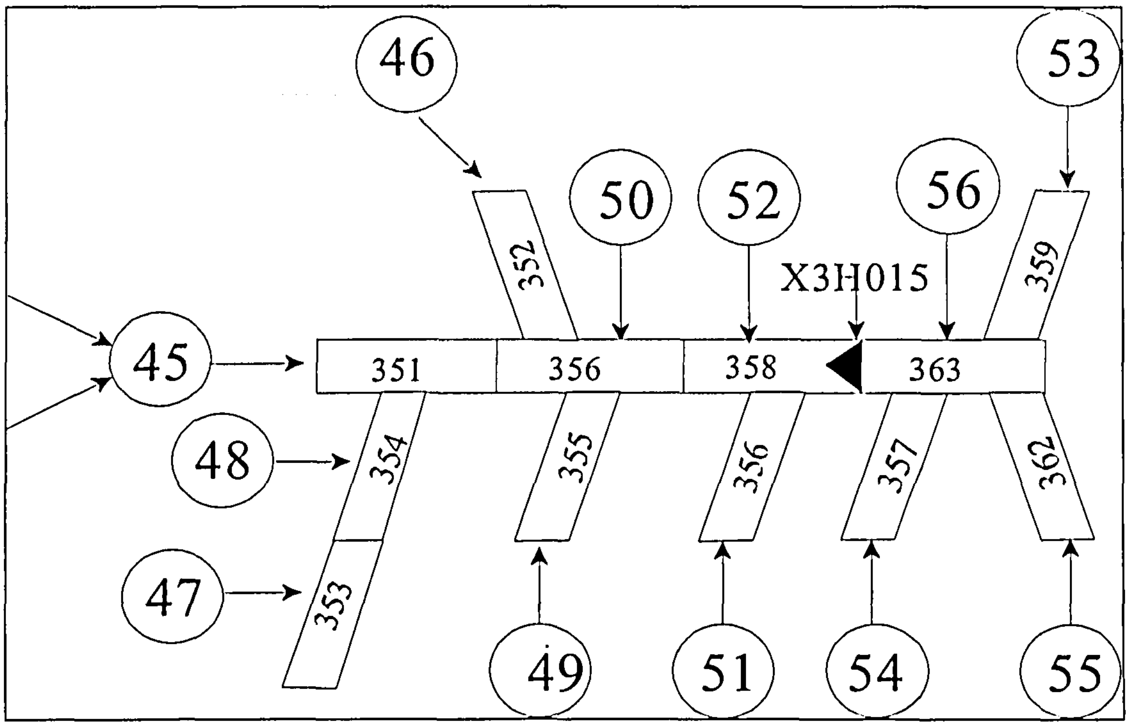


Figure 7.6 ACRU Subcatchment (circles) and HSPF reach (rectangles) configuration for the Lower Sabie River (triangle=flow gauge).

Simulation of Hydraulic Behaviour with Subroutine HYDR

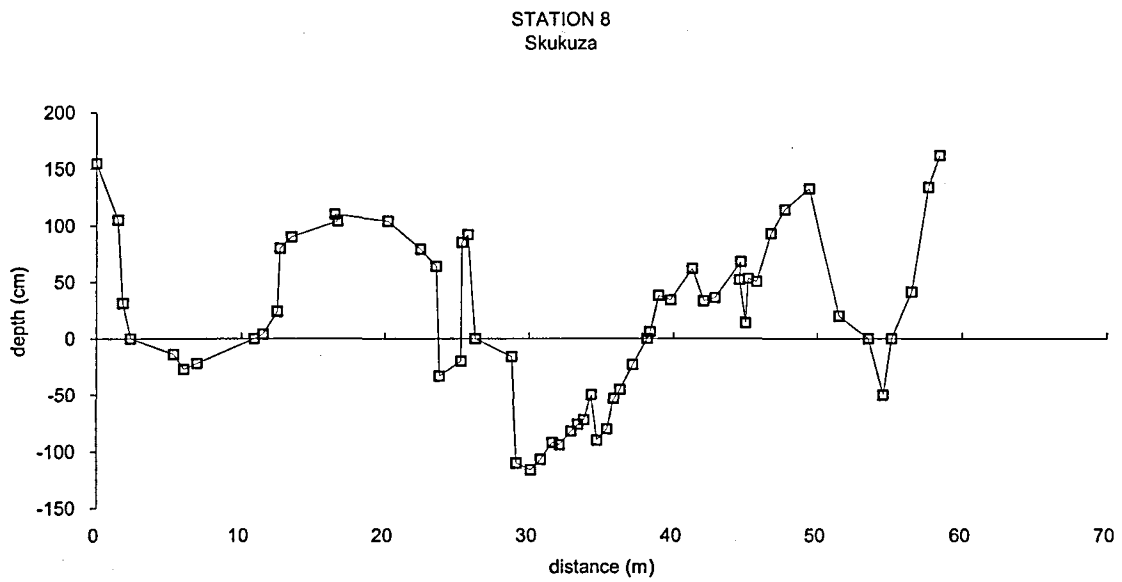
The principal task of this subroutine is to estimate the total outflow at the exit of the reach and, hence, the volume in the reach at the end of the time interval considered.

HSPF makes no assumptions regarding the shape of a RCHRES. However, HSPF does assume that:

- There is a fixed relation between depth (at the deepest point in the RCHRES), surface area, and volume.
- For any outflow demand with an f(VOL) component, the functional relation is constant in time.

These assumptions rule out cases where the flow reverses direction or where one RCHRES influences another upstream of it in a time-dependent way (the so-called backwater effect). No account is taken of momentum. The routing technique falls in the class known as "storage routing" or "kinematic wave" methods.

The user specifies the properties of a reach in a table called RCHTAB or F-Table (Figure 7.7). This table has columns for the depth, surface area, volume, and volume dependent functions. Each row contains values appropriate to a specified water surface elevation. The system obtains intermediate values by interpolation. Thus, the number of rows in the F-Table depends on the size of the cross section and the desired resolution. Figure 7.7 below illustrates the representation of a cross-section typical of the Sabie River near Skukuza by a relatively detailed F-Table.



DEPTH (m)	AREA (HA)	VOLUME (Mm3)	DISCH (CMS)	FLO-THRU *** (MIN) ***
.000	.000	.0000	.000	0.0
.250	1.500	.002	.097	321.08
.500	3.000	.007	.618	202.22
.750	4.500	.017	1.823	154.30
.833	7.125	.022	2.064	175.40
.917	9.750	.029	2.685	178.49
1.000	12.375	.038	3.651	173.35
1.083	15.000	.049	4.984	165.11
1.167	17.625	.063	6.721	156.14
1.250	20.250	.079	8.903	147.42
1.417	25.500	.117	14.763	131.95
1.583	30.750	.164	22.880	119.28
1.750	36.000	.219	33.557	108.96
2.083	42.000	.349	69.836	83.38
2.417	48.000	.499	117.500	70.83
2.750	54.000	.669	176.633	63.16
3.083	60.000	.859	247.433	57.89
3.417	66.000	1.069	330.162	53.98
3.750	72.000	1.299	425.126	50.94
4.083	78.000	11.549	532.655	48.48

END FTABLE335

Figure 7.7 F-Table for Reach 351, representing the reach of the Sabie River at Skukuza.

Besides calculating outflow rates and the volume in a RCHRES, HSPF can compute the values of some auxiliary state variables. These include depth at the deepest point of the cross-section, surface area of water in the RCHRES, average depth in the RCHRES as well top width and hydraulic radius. Surface area of the water is an important parameter in the simulation of water temperature. The average cross section (volume/length) and the average velocity (discharge/AVSECT) in the reach may also be calculated. Bed shear velocity and bed shear stress may also be estimated. These are required if the SEDTRN section is invoked.

Simulation of Water Temperature with Subroutine HTRCH

Five time series of meteorological data are required to simulate the temperature balance within a reach. These are:

1. solar radiation in langleys/interval
2. cloud cover in tenths
3. air temperature in degrees C
4. dewpoint temperature in degrees C
5. wind speed in meters/interval.

There are no significant internal sources or sinks of temperature within a RCHRES. Changes in heat content are due only to transport processes across the RCHRES boundaries. Module section HTRCH considers three major processes: heat transfer by advection, heat transfer across the air-water interface, and optionally, heat transfer across the water-sediment (bed) interface. The processes of diffusion and dispersion are not considered in HSPF.

Heat is transported across the air-water interface by a number of mechanisms, and each must be evaluated individually. The net transport across the air-water interface is the sum of the individual effects. Mechanisms that can increase the heat content of the water are absorption of solar radiation, absorption of longwave radiation, and conduction-convection. Mechanisms that decrease the heat content are emission of longwave radiation, conduction-convection, and evaporation.

In the case of the Sabie River simulation, the SAWB meteorological station at Skukuza was the only one in and surrounding the Sabie River catchment which could supply good quality sunshine hours, cloud cover and wind speed information for any reasonable length of time. Other stations in the catchment were able to supply air temperature and dewpoint temperature values. Table 7.3 provides a summary of the availability of data for use in the Sabie simulation.

Table 7.3 The availability of data in and around the Sabie Catchment required for water temperature simulations with HSPF.

Station Name	SAWB Station ID	Data Type	Start	End	Data Quality[1]	Units
Friedenheim	0555866	Dew point temperature	May-73	Dec-92	**	C
Friedenheim	0555866	Sunshine hours	May-73	Dec-92	**	hrs
Friedenheim	0555866	Windrun	May-73	Dec-92	***	km/day
Graskop	0594626	Dew point temperature	Oct-89	Jul-90	*	C
Graskop	0594626	Sunshine hours	Oct-89	Aug-90	*	hrs
Graskop	0594626	Windrun	Oct-89	Aug-90	**	km/day
Graskop School	0594596	Cloud	Aug-85	Aug-90	*	various
Graskop School	0594596	Dew point temperature	Aug-85	Nov-88	*	C
Graskop School	0594596	Sunshine hours	Nov-85	Sep-89	*	hrs
Graskop School	0594596	Windrun	Nov-85	Sep-89	*	km/day
Lydenberg	0554816	Sunshine hours	Oct-89	Aug-90	**	hrs
Lydenberg	0554816	Windrun	Jun-85	Oct-92	***	km/day
Lydenberg - Vis	0554816	Cloud	Jan-60	Sep-92	**	various
Lydenberg - Vis	0554816	Sunshine hours	Aug-62	May-85	**	hrs
Lydenberg - Vis	0554816	Windrun	Aug-62	May-85	**	km/day
Nelspruit	0555837	Cloud	Jan-61	Jan-93	**	various
Nelspruit	0555837	Dew point temperature	Jan-60	Apr-73	*	C
Nelspruit	0555837	Windrun	Jul-60	Apr-73	*	km/day
Nelspruit Agric	0555837	Sunshine hours	Apr-60	Apr-73	**	hrs
Nooitgedacht Agric	0442811	Cloud	Jan-60	Sep-96	**	various
Nooitgedacht Agric	0442811	Sunshine hours	Jan-60	Feb-61	****	hrs
Nooitgedacht Agric	0442811	Windrun	Aug-88	Sep-96	***	km/day
Skukuza	0596179	Cloud	Jan-60	Sep-96	***	various
Skukuza	0596179	Dew point temperature	Jan-60	Sep-96	***	C
Skukuza	0596179	Sunshine hours	Jan-60	Dec-91	**	hrs
Skukuza	0596179	Windrun	Jan-60	Sep-96	***	km/day
Tzaneen	0679260	Cloud	Feb-79	Jan-91	***	various
Tzaneen	0679260	Sunshine hours	Jan-79	Dec-96	**	hrs
Tzaneen	0679260	Windrun	Jan-79	Jan-91	***	km/day
Tzaneen - Grenshoek	0679106	Cloud	May-86	Sep-96	***	various
Tzaneen - Grenshoek	0679106	Sunshine hours	May-86	Aug-96	***	hrs
Tzaneen - Grenshoek	0679106	Windrun	May-86	Sep-96	****	km/day

[1]Missing Data Quality * Very Poor ** Poor *** Fair **** Good

Daily sunshine hours were converted to solar radiation using the Glover and McCulloch (1958) approximation of the Angstrom (1924) formula. The output was then converted from MJ $m^{-2}day^{-1}$ to the langleys per interval required by HSPF. Furthermore, in order to use solar radiation values in the HTRCH section, these must be disaggregated into hourly or 2-hourly values. This cannot be a simple linear disaggregation in order that the rising and setting of the sun may be accounted for. Similarly, pre-processing was necessary for maximum and minimum temperature. Shading effects by for example, riparian vegetation, are accounted for by a factor representing the ratio of radiation incident to the water surface.

The temperature of the water entering the reach from a subcatchment is also required. As ACRU has no water temperature simulation routine, incoming water temperature is assumed to be 0.75*average air temperature for the day (Johansson, pers. comm.). The model developers caution that the heat exchange calculations do not give realistic results if the average depth of water in the reach falls below 5cm.

Only occasional water temperature readings are available from the DWAFs national water quality monitoring database and therefore, the temperature simulation cannot be verified. However, typical results of the water temperature simulation are judged to be poor as illustrated by Figure 7.8 below for the typical period of January to March 1971.

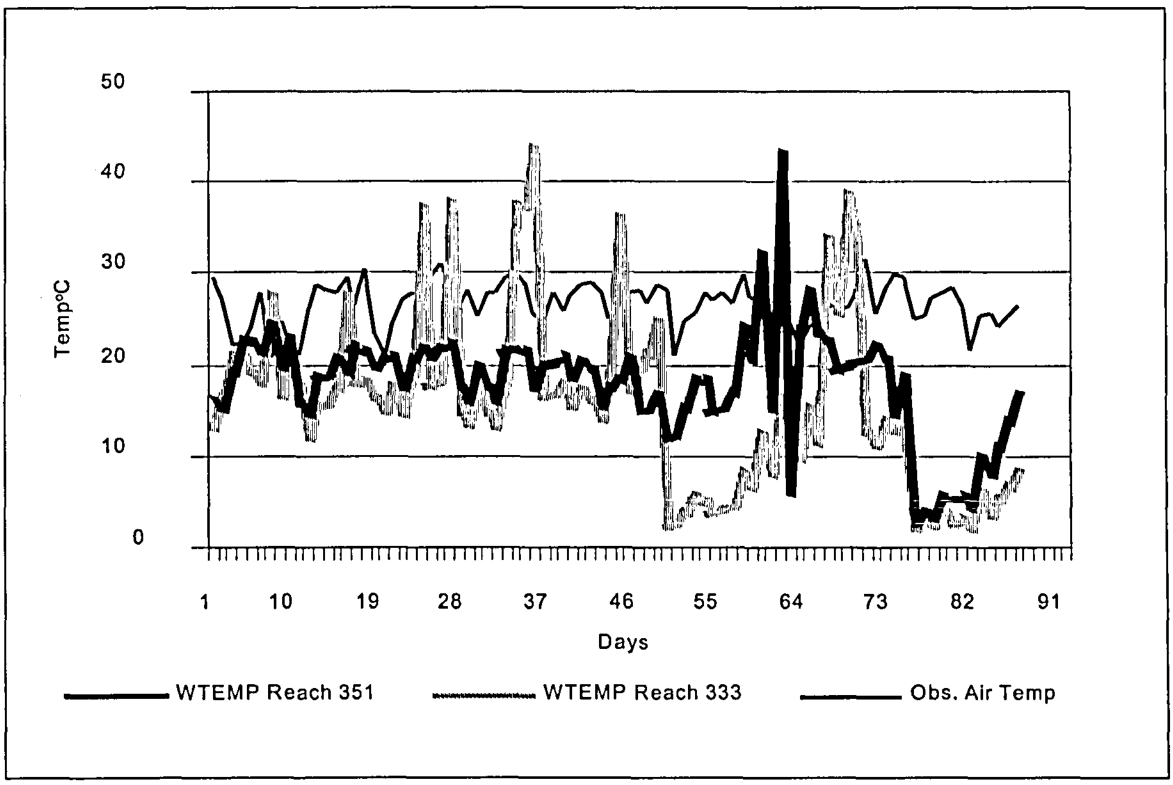


Figure 7.8 Simulated water temperature for two reaches of the Sabie River and observed air temperature, January to March 1973.

Although very little water temperature data is available to verify these results, the large and rapid fluctuations in water temperature are clearly unrealistic. These are caused by at least two factors:

i) The simulated average depth of water in the reach is often below 2.5cm, and thus, as noted by the developers, the water temperature algorithm can be expected to often be unstable as illustrated by Figure 7.9. Furthermore, it seems from this study that the water temperature simulation becomes unstable for average water depths of approximately less than 8cm rather than 2.5cm.

ii) Inadequate input data, both climatalogical and physical for the model needs.

It is possible to modify the F-Tables representing the depth-volume relationships in a reach to ensure that depth of water in the reach is always deeper than the required 2.5cm, i.e. to create a "v-notch" in the river bed. This does create more stability in the water temperature simulation, however if sediment transport is being simulated, this notch is continually scoured of all sediment creating warnings by the model that no sediment is left in the reach. This is clearly not a realistic alternative. Furthermore, the water temperature simulation is strongly dependent upon net heat exchange at the water surface. The nature of the Sabie and Sand rivers and most other southern African rivers is such that surface area increases rapidly with increased flow in the river (see the F-Table in Figure 7.7 above). Thus, the water surface area is large relative to the volume of water in the reach, leading to massive longwave heat loss during higher flows. Furthermore, incoming (shortwave) solar radiation is low at these times due to cloud cover. Although observed data are not available for verification, it is clear that the model under-estimates water temperature in periods of high flow. As illustrated in Figure 7.9 this results in rapid water temperature fluctuations with flow variation.

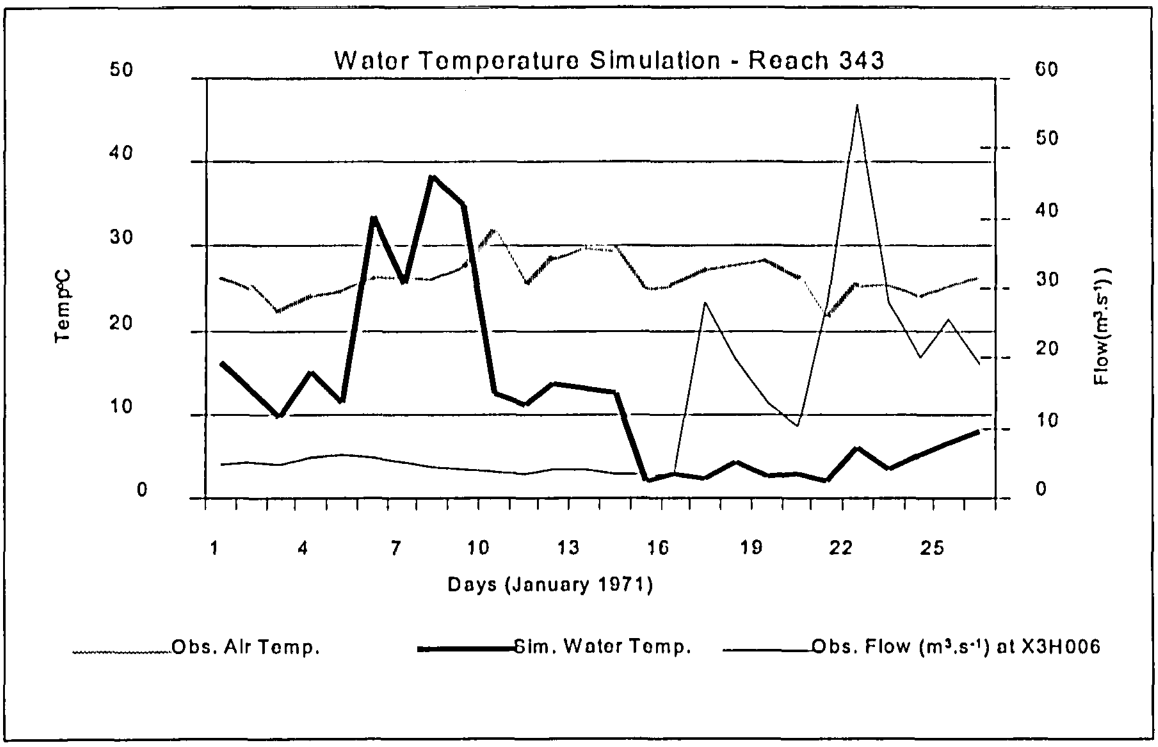


Figure 7.9 The water temperature simulation is inaccurate for periods of low and high flow.

Simulation of Sediment Transport with Subroutine SEDTRN

The purpose of this subroutine is to simulate the transport, deposition, and scour of inorganic sediment in free-flowing reaches and mixed reservoirs.

Both the migration characteristics and the adsorptive capacities of sediment vary significantly with particle size. Consequently, HSPF divides the inorganic sediment load into three components (sand, silt, and clay), each with its own properties. Parametric information required for cohesive sediments (silt and clay) include:

1. particle diameter - D
2. particle settling velocity in still water - W
3. particle density - RHO
4. critical shear stress for deposition - TAUCD
5. critical shear stress for scour - TAUCS
6. erodibility coefficient - M

Parameter values required for noncohesive, or sand, particles depend on the method used to compute sandload. In this exercise, the so-called Toffaleti method is used to calculate the capacity of the flow in the reach to transport sand. This requires that values must be defined for median bed sediment diameter (DB5O) and particle settling velocity (W).

The daily sediment yield provided by ACRU was divided into sand, silt, clay proportions based on the assumption that 50% of the sediment produced could be classified as sand, 30% as silt and another 20% as clay (Johannson, pers. comm.). HSPF default values were used for the other parameters.

HSPF assumes that scour or deposition of inorganic sediment does not affect the hydraulic properties of the channel. Furthermore, it is assumed that sand, silt, and clay deposit in different areas of the RCHRES bed; consequently, the deposition or scour of each material is not linked to the other fractions (i.e., "armouring" is not modelled). Longitudinal movement of bed sediments is not modelled. Furthermore, the model developers recognise that the Toffaleti formulations equate depth of flow to hydraulic radius and that this approximation is best for wide (large) rivers. They state "To the best of our knowledge the accuracy of this approximation for narrow streams has not been documented" (Bicknell *et al.*, 1993).

No time series of sediment data is available for calibration of the HSPF simulations. As expected, there is a strong relationship between streamflow and estimated sediment transport through the reach as illustrated for reach 430 in Figure 7.10 below.

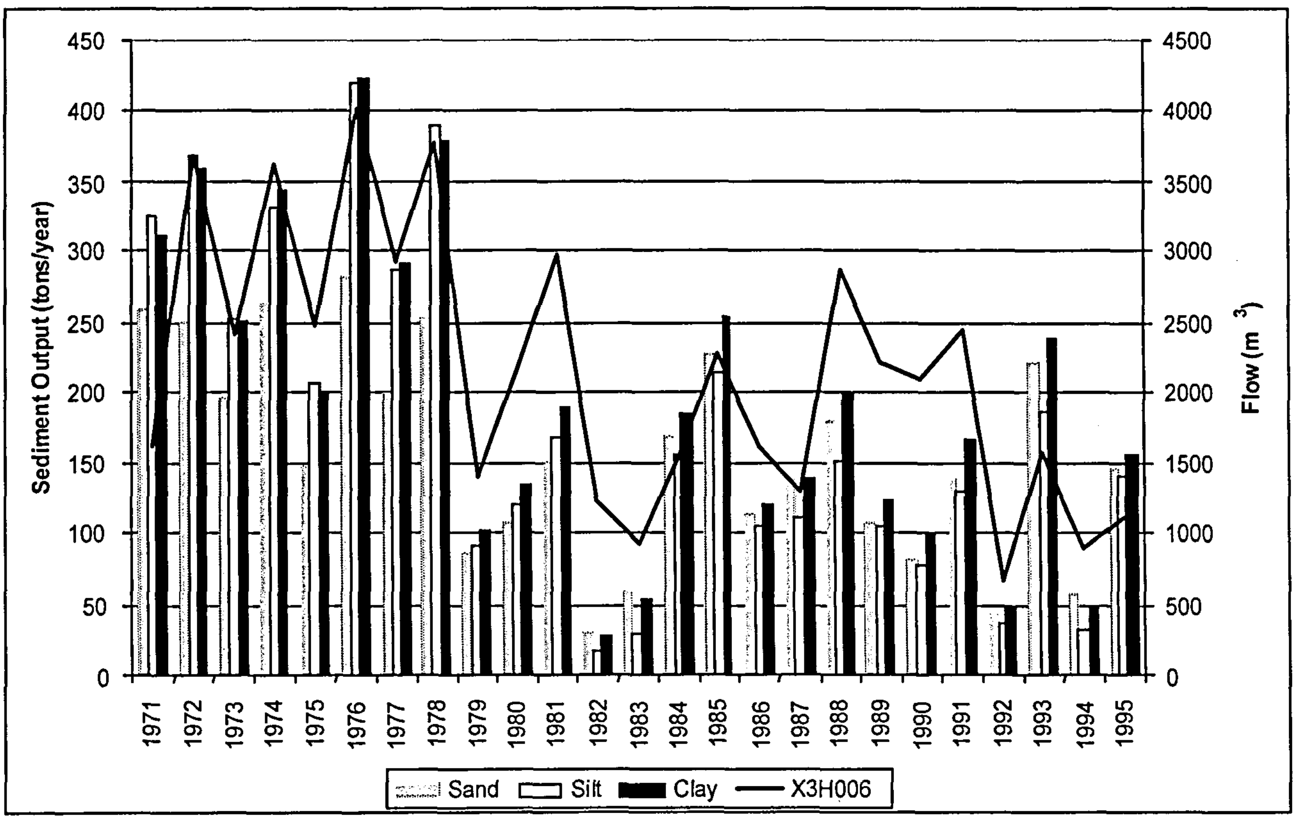


Figure 7.10 Annual sediment output from Reach 343.

The ACRU-HSPF link does seem to fulfil the requirement of routing peripheral ACRU generated sediment input downstream as illustrated by Figure 7.11. The figure shows the increasing annual sediment load passing through three sequential reaches in a downstream direction. In particular. A large increase in annual sediment load can be noted between Reaches 210 and 310 as Reach 310 is a confluence of three tributaries of the Sand River (Figure 7.5).

7.3.3 Issues and Concerns

Despite the many apparent merits of linking two models so that the best features of either serve the objective at hand, it remains somewhat of a "forced marriage". The exercise described above, is an example of a common modelling problem: i.e. an attempt has been made to make readily-available models fit the situation rather than applying or developing a model suitable for the problem at hand. In this exercise, we have attempted to apply the HSPF model to a situation for which it may be unsuitable. Consequently, the simulation represents a river that is "Sabie-like" in many respects, but cannot be considered a true representation of the Sabie River.

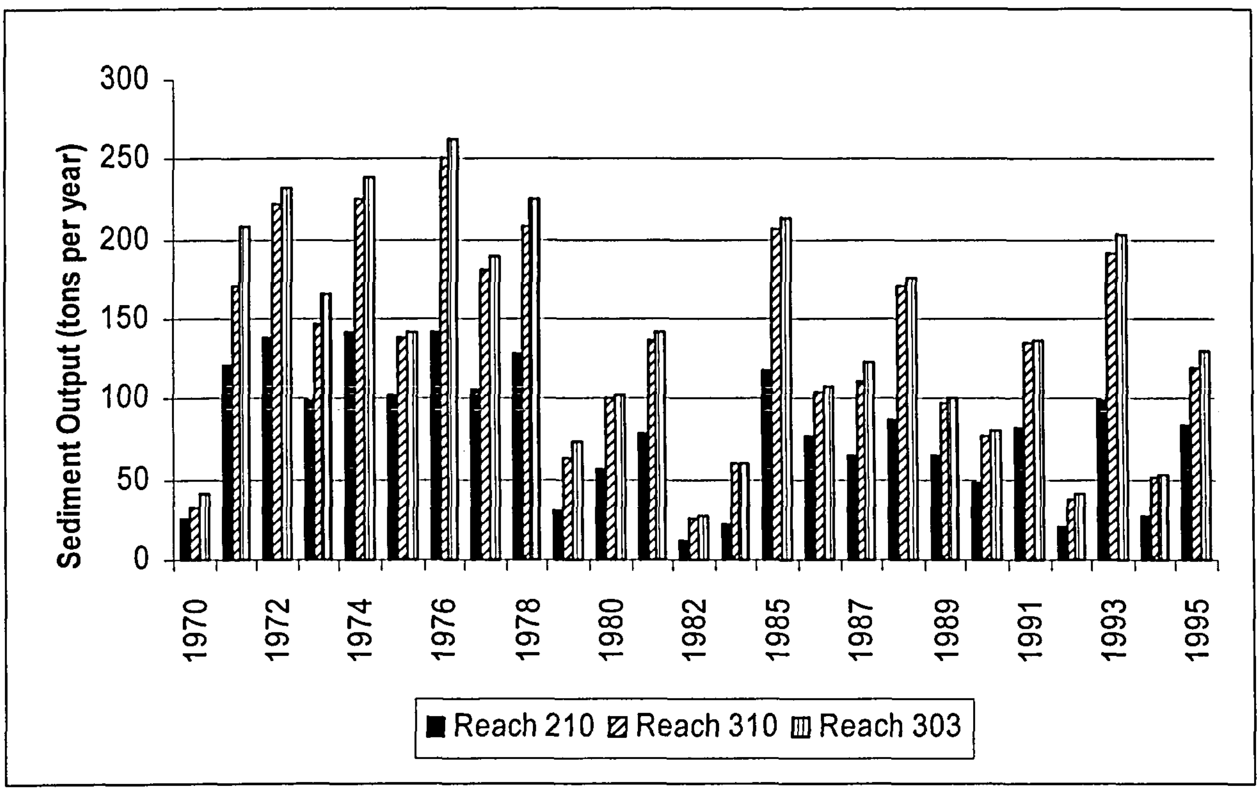


Figure 7.11 Annual sediment output from three sequential reaches in a downstream direction.

Furthermore, simulation of channel hydraulics, sediment transport and water temperature has been greatly complicated by having to activate many components of the model not applicable to the task at hand. In addition, the necessity to operate at sub-daily time steps for temperature simulation is incompatible with both the availability of input data and the output requirements.

We have the following concerns about this implementation, which, though it illustrates the technical feasibility of an ACRU-HSPF linkage, yields issues which we could not resolve within the context of this study:

- In the temperature simulation, it does appear contradictory to make the coarse assumption that the temperature of water flowing off the catchment can be approximated as 0.75*daily air temperature and then attempt to model temperature changes in the reach at an hourly scale using a complex data intensive process. A more pragmatic solution may be to assume that water temperature in the reach may be estimated as some coarser function of air temperature.

- Similarly, a coarse assumption regarding sediment particle sizes is made when passing ACRU generated sediment to the HSPF RCHRES module. A complicated and data intensive sediment transport routine is then invoked, at far more complexity than is justified given the coarse estimates regarding the initial input data.

- Despite its detail, as a 1-D model, HSPF cannot provide many of the outputs deemed important by geomorphologists or aquatic ecologists. For example, information on individual active channels in anastomosing reaches cannot be simulated. Furthermore, the use of a single F-Table based on poor cross-section data undermines any meaningful simulation of hydraulic parameters within each reach. HSPF is unable to provide any information on how the channel form may change. Sorting and armouring is not simulated and this may lead to large errors in sediment movement estimates in armoured reaches of the river. For this reason, in the BLINK project, other modelling approaches were used to provide answers to these problems at scales relevant to river morphologists (Heritage et al., 1998). These models used daily streamflow and sediment yield from the ACRU model as input, to form a further series type link to the ACRU model and are fully reported by Jewitt *et al.*, (1998) and summarised below.

Conclusions

i) The data required to operate the RCHRES module of HSPF correctly are not available in the Sabie River catchment. These data include hydrometeorological variables such as solar radiation, windrun, dew-point temperature and number of sunshine hours as well as the physical cross-section characteristics of the river channel. Although default values are available for many parameters, these appear to be applicable to large northern hemisphere rivers and may not be appropriate for the southern African situation where rivers are intermittent or flows become very low in the dry season.

ii) The RCHRES module of HSPF may not be suited to the simulation of small (narrow) shallow rivers with highly variable streamflow, typical of those in South Africa and may be more suitable to large deep rivers with relatively low variation in streamflow.

iii) Calibration of the model for the Sabie River is not possible due to the scarcity of data, with exception of daily streamflow.

iv) In terms of sediment and temperature, the RCHRES module appears to have inappropriate data requirements relative to the usefulness of its output for the KNPRRP. In other words, large amounts of data are required to produce average condition type simulations, where simpler or less detailed output may be required, or simpler less data intensive methods may be used to generate the same level of output. This is because, as noted by Johnston and Novak (1997), the model was designed as a pollutant fate model and has no integral ecosystem representation. Because of this "there is no inherent way of using the model to link a source (a point or nonpoint origin of a pollutant) to an ecological receptor (some ecological or biological entity that is affected)".

Recommendations

The availability of the land-use sensitive ACRU catchment model with seminal water quality functions means that the use of HSPF in its entirety is not necessary and may only add unnecessary complexity to the exercise. However, the ACRU model, like other available hydrology models needs some hydrodynamic channel flows component in order that the river channel processes are simulated. This facility in HSPF offers an attractive solution. However, the linkage with HSPF as a whole is probably not necessary. Furthermore, it is not possible to enable only the channel hydraulics component in HSPF. It has been recognised by modellers that it is very difficult to adapt models (either in part or in its entirety) in order to integrate them with other models (Johnston and Novak, 1997). With respect to HSPF, it has been stated that modification of the code is a complicated task best left to the model developers (Johanson, pers. comm., 1994). Given its volume of code, it is suggested that the same is true of ACRU.

Thus it is recommended that future linkages of hydrology and hydraulic components of models follow the "embedded" option described in Section 4.3.3 and that a single appropriate hydrodynamic component be included in the ACRU model by its developers. This has the advantage of minimising the complexity of the modelling system, allowing feedback between the linked components and increasing functionality of the system. The inclusion of improved soil-moisture budgeting components in HSPF is also an option to consider, however, this is likely to be a highly complicated task. Alternatively, where suitable input and calibration data are available, the HSPF model could be used in its entirety, but in the context of this study, there seems to be little advantage in pursuing an ACRU-HSPF serial link any further.

A further approach may be consideration of the Objectives Hierachy produced by Rogers and Bestbier (1998) and after consideration of the Thresholds of Probable Concern derived for functions such as water temperature, a more appropriate model or models to serve those needs may be selected. This idea is explored further in Chapter 8.

7.4 THE BLINK MODELS

Parallel to the ACRU-HSPF modelling exercise described above, a set of Qualitative Rule Based Models has recently been completed in order to link catchment abiotic and biotic processes in the Sabie River. These models and their development are described in detail by Jewitt et al. (1998). The ACRU hydrology model is used for the simulation of daily sediment and streamflow. A brief description of the remaining models follows.

7.4.1 The Geomorphology Model

The use of a geomorphological approach to relate habitat suitability to river channel morphology, and thus integrate abiotic and biotic catchment components in the KNPRRP BLINK programme required that some form of geomorphic predictive system must exist in order to provide input to the fish and riparian vegetation models. A full description of the model and its development is described by Heritage *et al.* (1998).

The approach followed in this project has been to develop a QRBM in which rules, based on the expert knowledge of geomorphologists familiar with the Sabie River, are used to predict the dynamics of a selected representative reach of the river, a concept first proposed by Nicolson and James (1995). Expert knowledge gained through extensive field experience, detailed examination of temporal aerial photographic sequences and space for time substitution techniques, have allowed rules to be developed concerning morphological change in the Sabie River in the Kruger National Park in response to changing flow and sediment regimes. The geomorphology model is designed to accept flow and sediment input for a selected representative reach on the Sabie River and predict the changes in the composition of that reach in terms of percentage composition of geomorphic units, i.e. the changing sediment balance within each channel type causes a change in the geomorphological composition at the scale of geomorphic unit (Heritage *et al.* 1998).

Hydrological Input

Daily streamflow values are simulated using the ACRU model for any point on the Sabie River. The annual flow regime has been divided into four categories which are used to drive the model (Heritage *et al.,* 1998):

1. Category one is baseflows. These are geomorphologically insignificant due to their inability to transport sediment.

2. Freshets (category 2) may alter some instream morphologic units.

3. The annual flood (category 3) is competent to redistribute significant volumes of unconsolidated sediment and may also result in the erosion of some consolidated deposits.

4. The major flood category will overtop the active and seasonal distributary channel network and has the ability to alter the morphology of areas between these channels, macro-channel features such as bedrock core bars, islands and macro-channel lateral bars will be subject to change.

A pre-processing function in the model is used to analyse the daily hydrological sequence in order to provide an index showing into which one of these categories the annual flow regime fits.

Sediment Input

The ACRU sediment production model has been used in this project to simulate sediment loads on a daily timestep for each of the 57 sub-catchments of the Sabie catchment located inside and outside of the Kruger National Park.

Sediment input for the year is categorised as:

1. Low
2. Reduced
3. Moderate
4. High

based on an assessment of the current year's sediment load relative to that of the previous forty years. Thus a simple sediment index is created for use as input to the model.

Model Resolution

A set of rules governing the changes in composition in terms of geomorphic units has been developed for each of the five channel types described by Van Niekerk *et al.* (1995) and described in Section 7.1.2. The rules provide an estimate of the changing composition of the selected representative reach according to the input provided by the annual streamflow and sediment load indices described above. Output is:

1. An estimate of the composition of the channel type expressed as a percentage of each geomorphic unit present.

2. A description of the channel type (e.g. bedrock-pool) as these may change over time according to changing catchment conditions represented by the model input.

Temporal Scale

The rules representing the geomorphological processes operate at a time step of a year. The year considered runs from November to October as fish data representing the preceding dry season are collected in October. The model accepts input from the ACRU model at a daily timestep and calculates annual flow and sediment indices.

Spatial Scale

In effect, the model has no finite spatial scale. Simulations are applicable to all channel types in the Lowveld regions of the Sabie catchment represented by the representative reach selected. The model produces output at the spatial scale of the channel type as represented by any individual representative reach. Internally, changes in the channel type are predicted at the scale of the geomorphic unit.

7.4.2 The Fish Model

The fish model developed is also a QRBM which uses simple IF-THEN "rules" to relate the response of the fish groups (identified previously) to, in the short term (seasonally), varying flow conditions and in the medium and long term, to changes in channel composition. The model is described in detail by Weeks *et al.* (1998).

The major abiotic influences accounted for by the modelling system are described below.

Temperature

The fish groups whose responses are simulated in the model are those found in the Lowveld section of the Sabie River. The distinction between Lowveld and other areas of the Sabie Catchment is one based on temperature. Thus, the overriding influence of temperature is addressed, although this is done implicitly as it is accepted that the model may not be valid in the non-Lowveld reaches of the river.

Hydrology

A further important abiotic influence affecting fish response is the catchment hydrology. The changing patterns of abundance established for these species in detailed field studies (Weeks *et al.*, 1996), for both hydrologically normal and extreme seasonal conditions, form the basis of the fish response to catchment hydrology. Floods and the small summer flow events known as freshets are important to the ecological functioning of the river for a variety of reasons. Freshets occur between summer baseflows as a result of minor rainfall events in the catchment. On the Sabie river, flow peaks during freshets are typically in the order of 20 $m^3.s^{-1}$ and last for two to three days before summer baseflow conditions (6-15 $m^3.s^{-1}$) are restored. The first freshet of the season is needed to restore water quality and make habitat available, thus stimulating breeding in the majority of the Sabie fish species (O'Keeffe *et al.*, 1996). The cichlids begin to breed as the waters get warmer prior to and irrespective of the increased flow events associated with the onset of the wet season. The increased flows disrupt the breeding cycle of the cichlids and allow the other seasonal species to breed successfully. These events are also important for fish movements.

A pre-processing function within the model is used to analyse the daily hydrological record in order to calculate indices of events to which fish will respond per time step, i.e. categorise the preceding season's daily flow into seasonal classes which form the input to the fish model engine.

Important indices, which require daily flow records to be calculated, are: numbers of freshets, zero flows and flood events. For the purposes of this model, a freshet was defined as a daily discharge which is greater than 2.5 times the average of the preceding three days.

Using this information, each hydrological season, i.e. the fish model time-step, can be classified into three classes *viz.*, dryer than normal ("dry"), normal ("normal") or wetter than normal ("wet").

1. A season (summer or winter), is classified as "dry", if:

 - The number of days on which flow is less than the long-tem 10^{th} percentile value of daily flow is greater than 50

 OR

 - The season's median flow is less than 60% of the long term median flow.

 OR

 (In the case of the wet season (summer))

 - The number of freshets occurring in the season is less than three.

 This in effect is the "failed" wet season.

2. A season (summer or winter) is classified as "wet", if:

- There are 30 or more days on which flow is greater than the long-term 90th percentile daily flow value AND the median flow for that season is greater than the long term median flow.

OR

- The season's median flow is greater than 150% of the long-term median flow.

OR

(In the case of the wet season (summer))

- The number of freshets is greater than 6, AND the median flow for that season is greater than the long-term median flow.

3. In all other cases, the season is classified as normal.

A number of assumptions were made in the development of the set of rules which govern the seasonal classification. A number of these were made in order to "fit" the hydrological season into an ecologist's perception of whether the season in question was "dry", "normal" or "wet". These perceptions were "workshopped" with relevant ecologists. Analysis of the daily flow records shows that values are not normally distributed, but skewed towards the dry end of the spectrum; thus, the use of the 10th percentile daily flow value (i.e. flow that is exceeded 90% of the time in the long-term flow record) to determine whether to classify a season as "dry" whilst the 90th percentile flow value is used to determine if a season is "wet".

Geomorphology

It is recognised that the geomorphological structure of the reach of river under consideration will affect the fish habitat and, thus, the composition of the fish assemblage at that reach. The link between channel geomorphology and fish abundance is made through the development of a fish group specific value of habitat worth, i.e. a factor of microhabitat suitability that quantifies the quality of the available habitat, and then adjusts the target group's abundance (Weeks *et al.*, 1998). For this purpose, a habitat suitability index (HSI) was developed to indicate the suitability of a particular channel type for each fish group, i.e. the HSI is a unitless index of river reach suitability, evaluating that channel type's potential to support each fish group. Thus, the HSI provides the geomorphological input to the model by providing a means to adjust the fish abundance which has been predicted by the hydrological component of the model. For example, the hydrological component of the model may predict a medium abundance of the rock catlet fish group. However, the rock catlet is known to favour rocky stretches of fast flowing water. If the representative reach of interest is a braided or single thread channel type, the HSI for the rock catlet will be very low, and the fish abundance predicted by the hydrological component of the model will be moderated accordingly.

Hydraulics

For the purposes of this model, it was felt that at the scale of the channel type and smaller, simulation and indeed conversion of observed geomorphological data to show water depth and current velocity could not be done accurately given the lack of detailed physical channel information and the potential errors in the hydrological information at fine temporal scales. Thus, the assumption was made that the substratum is an indicator of the flow characteristics of the preceding season. The substratum at particular points in the river bed, is found there because of the flow defined by the physical characteristics at that location. This is an assumption supported by an ASCE Task team on Sediment Transport and Aquatic Habitat who stated "Sediment type serves as an indirect indicator of fish-habitat quality when it provides an integration of the other physical-habitat variables – depth, velocity and cover" (Shields and Milhous, 1992). Furthermore, the substratum size reflects a synthesis of ecologically meaningful hydraulic conditions (Resh, 1979 cited by Shields and Milhous, 1992).

Thus, the hydraulic components that may affect fish abundance are provided implicitly by the HSI. In the rock catlet example above, it can be seen that this assumption is effective at a coarse level. The low HSI for the rock catlet derived for a braided or single thread channel type indicates the lack of bare rock and thus fast flowing water in these channel types. Fast flowing water is needed to scour the bed of the sand, which is typical of the braided or single thread channel type and the HSI based on the substratum present reflects this.

For the purposes of this exercise, all other influences, such as water quality, biological interactions, etc. are ignored. A conceptual diagram of the linkages between catchment hydrology and a geomorphological and fish response at a representative reach of river as used in this modelling system is illustrated in Figure 7.11.

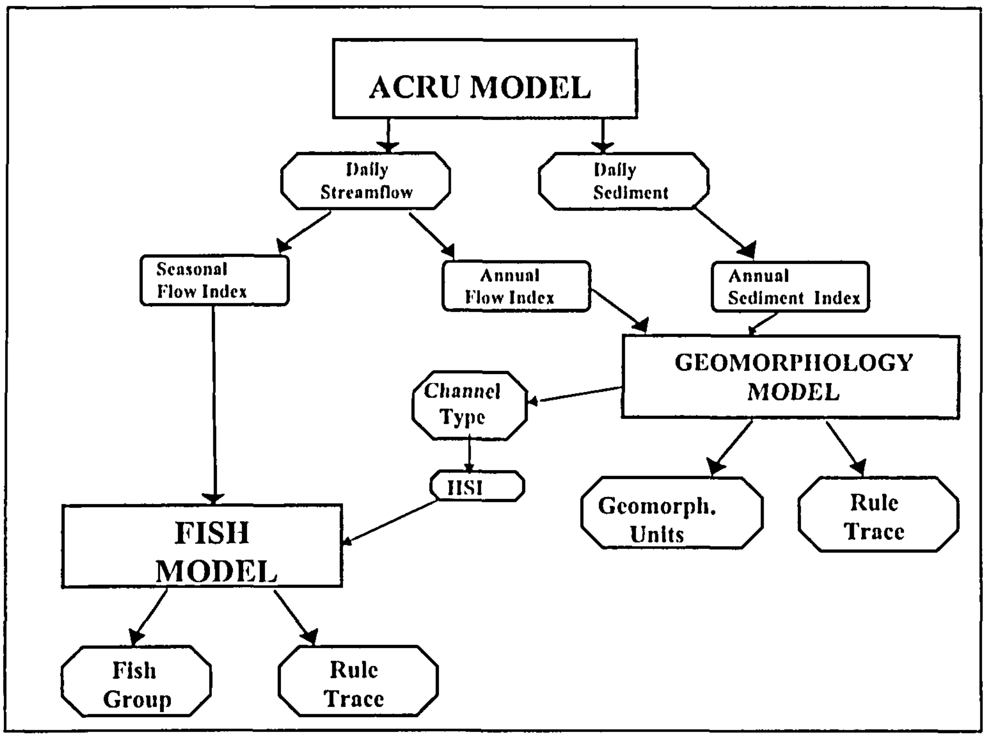


Figure 7.11 Overview of the links in the Fish Model

Model Resolution

The fish groups identified by Weeks *et al.* (1998) and described in Section 7.1.3 are used as the basic predictive units in this model. It is the changing ***patterns*** of abundance established for these groups for different seasonal conditions that form the basis of the predictive model. This is consistent with the macroecological approach suggested earlier and follows on from the ideas of Harris (1996) and Schrader-Frechette and McCoy (1994) who all suggested lowering the resolution of the available information for predictive purposes.

The abundance of each fish group is modelled according to a "state" based approach. According to this methodology, the entity to be simulated is divided into a number of discrete states, each state indicative of a particular phase of that entity's abundance. The fish model utilises numbers of Catch Per Unit Effort (CPUE) as its basis. CPUE represents the amount of effort, usually per time-unit, required when fishing, using generally accepted fishing techniques (Weeks *et al.*, 1998). In keeping with QRBM approach, these states are given qualitative descriptions.

Seven discrete states of abundance were defined for each group of fish as follows (Weeks *et al.* (1998) in Jewitt *et al.* (1998)).

1. Absent
2. Remnant
3. Rare
4. Visible
5. Numerous
6. Abundant
7. Saturation

These states span a semilog scale representative of the exponential growth and decay of the fish groups in which fish respond seasonally to hydrological variation, and in the longer term to changes in the geomorphic template.

Input to the model is provided by parameters describing the hydrological status of the preceding season (i.e. wet, dry or normal) and a description of the available fish habitat provided by the geomorphology model by way of an HSI.

Temporal Scale

The model operates at a twice-annual time step, thus accounting for different fish responses according to a "wet" or "dry" season. Input to the model, however, are daily values of streamflow for the representative reach of interest.

In the early stages of development, attempts were made to use an annual time step for the model engine, operating from May to May each year. However, the three and a half year study of Weeks *et al.* (1996), showed that the responses of the fish in the Sabie-Sand system are primarily seasonal. Using an annual time step would obscure this pattern. In addition, analysis of the hydrological record shows that classifying a year as "wet" or "dry" would completely obscure seasonal patterns of flow. For example, the 1995-1996 hydrological record shows both some of the highest and some of the lowest daily flow values recorded occurring in the same year.

Each year, fish data were collected at quarterly intervals corresponding to the climatic seasons. Model development at the same three monthly scale was attempted, but found to be impossible due to inconsistencies (noise) in the available data. Conveniently, quarterly data could be lumped into two six month periods that corresponded well with the identified hydrological seasons. This enabled the simulation of fish responses to the preceding wet or summer season and the preceding dry or winter season to be modelled. Geomorphic input is provided annually, utilising the concept of asynchronous time-steps explained in Section 5.6.

Spatial Scale

As in the case of the geomorphology model, the fish model has no finite spatial scale. Simulations are applicable to all channel types in the Lowveld regions of the Sabie catchment represented by the representative reach selected. At this scale, the seasonal hydrological effects dominate all other factors that may be affecting the responses of these fish. It is debatable if available habitat acts as a controlling factor affecting fish population at any spatial scale, in the way that seasonal hydrological response dominates at the regional scale (Weeks *et al.*, 1998).

7.4.3 The Riparian Vegetation Model

The riparian vegetation model is a QRBM that predicts a response of riparian vegetation to geomorphological change, as a result of an altered hydrological regime. Vegetation distribution ***patterns*** and the identified relationships of these patterns with fluvial geomorphology have played a major role in the definition of rules that govern vegetation response in the model. A full description of the model is provided by Mackenzie *et al.* (1998).

Hydrological Input

No direct hydrological input is provided to the model.

Geomorphological Input

An estimate of the abundance of each of the geomorphic units present in the channel type represented by the selected Representative Reach forms the geomorphological input to the model.

Model Resolution

The vegetation types identified by Van Coller and Rogers (1995) and described in Section 7.1.4 were selected as response units for the model instead of species. As in the case of the fish model, this is consistent with the philosophy of sacrificing detail to reveal patterns which may be predictable.

For the purposes of the model, the geomorphic unit composition of the representative reach that forms the input to the models is aggregated into five groups of geomorphic unit according to their functionality and ability to support vegetation. These five functional groupings of geomorphic units are:

1. bedrock outcrop
2. consolidated bars with alluvial influence
3. consolidated bars with bedrock influence
4. unconsolidated bars with alluvial influence
5. macro channel bank.

The model rules then relate the prevalence of these functional groups to a state of abundance for each of the vegetation types. Thus, model output consists of a state of abundance for each of the vegetation types listed above. These vegetation states were defined for each of the vegetation types, and range through "not present", "uncommon", "intermediate", to "abundant".

7.5 PRESENTATION OF MODEL OUTPUT AND MODEL VERIFICATION

The models are all operated from the ICIS (aspects pertaining to the integration of the models with the ICIS system are explained in the following chapter). Several new tools for the display and presentation of data in colourful, user-friendly format were developed during the course of the project.

The need for QRBMs to be transparent in their workings, and the ability of a trace feature to make the internal workings of the model easy to follow was discussed in Section 5.2. Thus, model output consists of an hypertext trace of the rules invoked at each time step, and for example, a file of, for example, fish state for each fish group at each time step. The files are presented to the user using a hypertext browser, in the case of the rule trace, and a colour area graph and pie-charts in the case of the fish state information. A typical view of model output is shown in Figures 7.12a) and Figure 7.12b) and Figure 7.13.

Although the same detailed information is not available in the case of the geomorphology and riparian vegetation models, Heritage *et al.* (1998) and Mackenzie *et al.* (1998) believe that the predicted responses are all in accordance with current understanding and data.

Scenario Modelling

The eventual role of these models beyond the prototype stage, is to provide catchment managers, planners and stakeholders with information which will assist them in quantifying the amount of water required by the aquatic ecosystems of the KNP and to assess the suitability of various catchment planning scenarios in achieving this desired state. The use of the Integrated Modelling System to predict the potential impacts of various development scenarios has been reported in detail by Jewitt *et al.*, (1998).

Models to Serve Management Needs

Recently, the development of an objectives hierarchy for management of the Kruger National Park has been completed (Rogers and Bestbier, 1998). This hierarchy begins at a broad level with the overall vision for management of the Park i.e. that managers "maintain biodiversity in its natural facets and fluxes and to provide human benefits in keeping with the National Park, in a manner which detracts as little as possible from the qualities of the KNP" (Braak, 1997). This vision has been progressively broken down into a series of objectives of increasing focus, rigour and achievability (Rogers and Bestbier 1998, Rogers and Biggs 1998). The lower level goals are scientifically based, spatially and temporally bounded targets of ecosystem condition and are known as "Threshholds of Probable Concern" (TPC's) and act as warnings to managers of possible unacceptable environmental change.

Mackenzie *et al.*, (1999) have adopted the TPC philosophy and have used TPCs developed for geomorphology and riparian vegetation implicitly in a "pragmatic approach" to modelling by using these TPCs to guide the development of models that are useful to management. Rather than developing a large multipurpose model that reflects as much of the system dynamics as possible, they use TPCs as a filter. Such a filter acts as a constraint so that only the components of the system that are relevant to management needs, as defined by the TPCs are included in the final model. The result is a suite of relatively simple problem specific models that produce output useable by managers within their operational framework.

This is consistent with the views of other researchers who recommend that where there is a large degree of parameter uncertainty, relatively simple models should be used (James, 1997).

By extending the argument, it is also evident that relatively simple models may be selected in situations where field data are seriously lacking. This reinforces the discussions in Chapter 3, where it was noted that predictability increases at broader scales.

Chapter Eight

RESOLVING SCALE AND INTEGRATION ISSUES IN AN INTEGRATED MODELLING SYSTEM FOR THE KNPRRP

In the KNPRRP, abiotic hydrological and geomorphological processes, such as flow events, which mobilise sediment, and fish and riparian ecological response patterns, such as changes in population, are linked. These biotic responses are observed at the spatial and temporal scales deemed important by the scientists studying these phenomena. As explained in Chapters 2 and 3, these scales are rarely the same.

The need to incorporate multiple process models in an Integrated Modelling System implies a need to incorporate multiple scales of resolution, both spatial and temporal. The Integrated Modelling System described, therefore, needs to operate at spatial scales that allow simulation of the processes affecting biotic responses at the scale at which those processes occur, as well as being able to output information at the observation scale of the biotic response patterns. Thus, linking of these abiotic components to a biotic response requires the ability to simulate at varying spatial and at asynchronous temporal scales (methods for meeting this need were explained in Section 4.4).

The models developed in the Abiotic-Biotic links project have become known as the **B**iotic **LINK** (BLINK) models. With the addition of the ACRU, VTI and HSPF model output, these models form an Integrated Modelling System for the Sabie River. An overview of the modelling system and the links between the different models is given in Figure 7.3 in the previous chapter. These links are discussed further in the following sections, where we re-visit the issues pertaining to decision support for ICM raised in Chapter 2, *viz;*

i) issues of integration of models, and

ii) scale issues and linking catchment abiotic and biotic components

and we explain how they have been resolved in the KNPRRP modelling system.

8.1 MODEL INTEGRATION

Integration of the models into the KNPRRP ICIS follows a combination of the series and parallel linking methods discussed in Section 4.4.

The ICIS system includes hydrological simulations available from the ACRU, VTI and HSPF models. Figure 8.1 illustrates the linkages between the different components of the system on both the UNIX and PC platforms. Output from the ACRU and HSPF models as well as available hydrometeorological data are stored in the Sabie WDM on the CCWR UNIX system. The ICIS user operating on a PC is able to select the time series required by way of the ICIS GUI. This selection invokes a series of scripts which enables the required data to be downloaded to the PC system from the CCWR mainframe computer. This output may then be manipulated, plotted, analysed or used as input to the BLINK models.

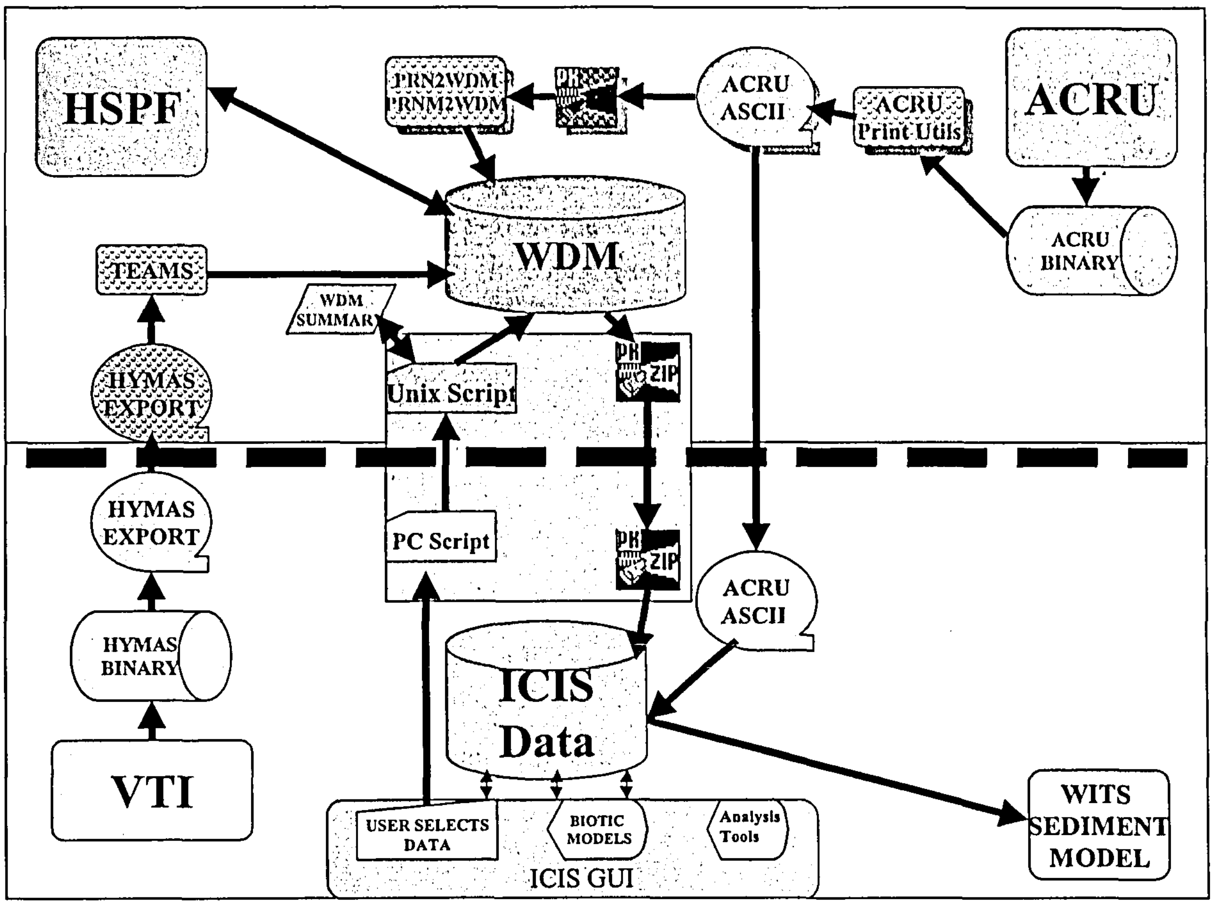


Figure 8.1 Organisation of the components of the Integrated Modelling System on the UNIX and PC platforms as at December 1997.

The BLINK models form two separate executable programs embedded within the Sabie ICIS as illustrated by Figure 8.2.

Daily sediment and flow values generated by the ACRU model, once operation is complete, are converted from the ACRU output format into the *ASCII* format used within the ICIS database. The BLINK models then utilise these data as input, reading directly from the ICIS database. The ACRU model and the BLINK models therefore, have a series or "loose" link, as explained in Section 4.3.2.

The geomorphology and fish models, however, are linked in parallel forming one executable program, with the model components embedded in the program as sub-routines. Each model has a separate component which accesses the database and derives the seasonal hydrology index (in the case of the fish model) and the annual flow and sediment indices (in the case of the geomorphology model). The rule bases form the model "engines". These are accessed seasonally in the fish model, and annually in the geomorphology model. The HSI forming the geomorphic input to the fish model thus changes annually, and is provided as input to the fish model at the end of each wet season.

The riparian vegetation model is linked in series with the geomorphology model and commences its operation once output from the geomorphology model is available. Geomorphology model output is stored in a database within the ICIS system and then accessed by the riparian vegetation model once the geomorphology model has completed its operation. Although feedback between the riparian vegetation and geomorphology components is recognised by this project, no direct feedback could be accommodated in the existing models for two reasons:

i) The feedback mechanism is not yet adequately understood (Mackenzie, 1998).

ii) The time available for model development prevented deeper analysis of this issue.

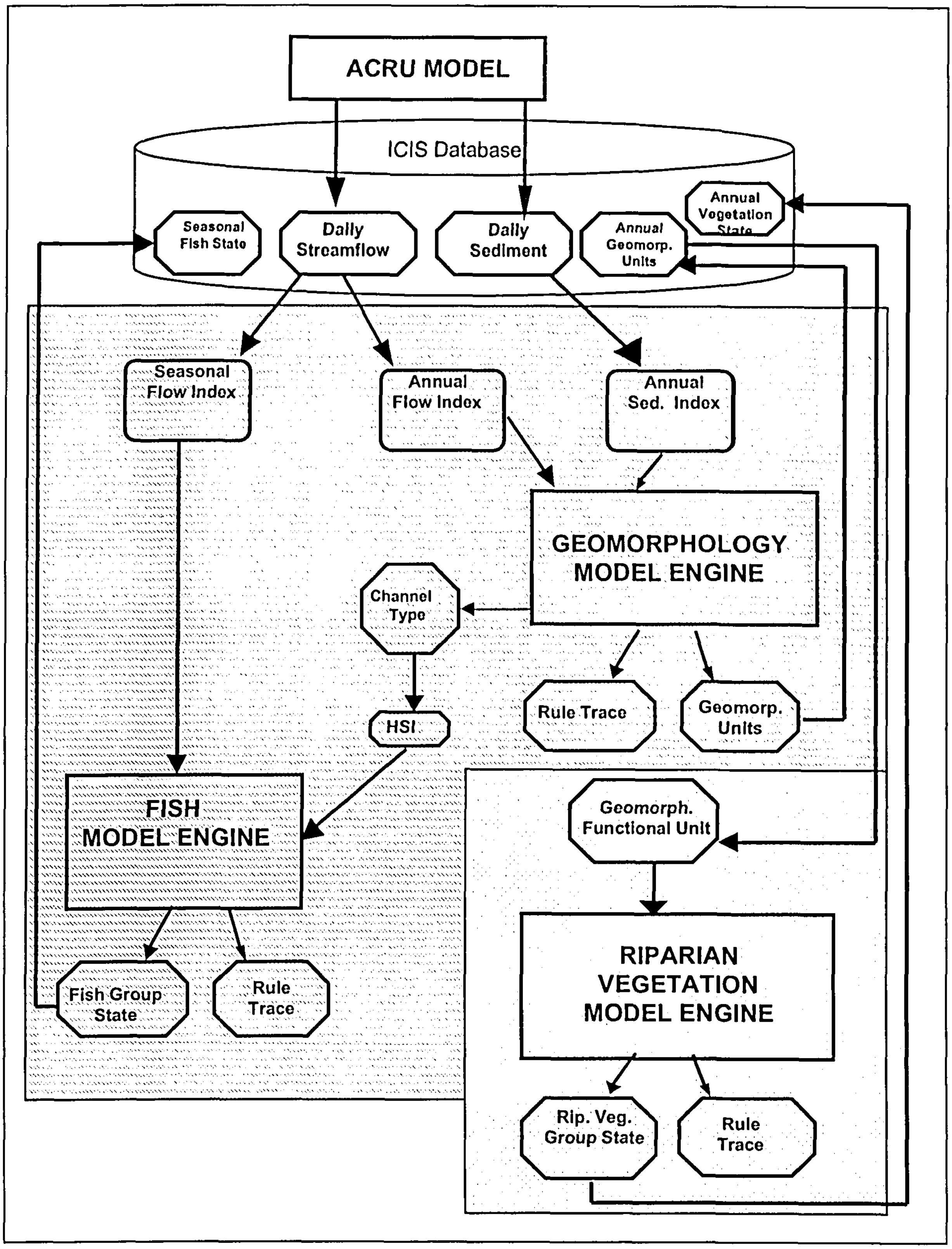


Figure 8.2 Integration of components of the Integrated Modelling System.

It is recognised, however, that the increase of riparian vegetation will create further opportunities for sediment to be trapped, which in turn provides further habitat for riparian vegetation growth.

A further integration issue regarding these models is their integration within the Sabie ICIS. The models, the time series data forming their input and output, the output rule-trace and the tools to display this information are included in the ICIS system. The models are included as executable files, and the ICIS GUI has been modified to allow the user seamless access to these and their output tools using methods explained in Section 5.2.1. To facilitate this integration, the BLINK models utilise the same database structure as the other time series stored within the ICIS system, as was explained in Section 5.2.2.

8.2 RESOLVING SCALE ISSUES IN THE BLINK MODELS

The series of QRBMs that have been developed in order to link biotic responses to abiotic stimuli in the Sabie River Catchment are described in the preceding Chapter. This section describes some of the more important aspects of selecting suitable operational scales for integration of these models with an hydrological model, in this case the ACRU model. All of these models focus on a sacrifice of detail in order to reveal broader scale spatial and temporal ecological patterns. The broad operational scales used have been selected to optimally integrate the various process and observation scales involved. Therefore, much of the work done in this project involves the development of methodologies to scale up information from the observation scale to the operational scales selected for the purposes of modelling (see Figure 2.5 for the identification of commonly used spatial scales in the context of the KNPRRP). In addition to adapting a broad scale perspective, the operational scales have been selected so that they fit within the "zone of predictability" identified by Wiens (1989) and illustrated in Figure 3:12. The scales, both spatial and temporal, as well as the model resolution of the BLINK models are summarised in Table 8.1 and described in the following sections. In what follows, there is a certain amount of repetition of scale aspects already discussed in Chapter 7 in the individual model descriptions. However, in the interests of a cohesive description, such overlap is deemed unavoidable in this Chapter.

Table 8.1 Spatial and temporal scales and resolution of models included in the Sabie IMS.

Model	Spatial Scale (See Fig. 2.5)			Temporal Scale (time step)			Model Resolution (complexity/no. of parameters)		
	Input	Internal	Output	Input	Internal	Output	Input	Internal	Output
Hydrology	Sub-catchment	Sub-catchment	Point	Daily	Daily	Daily	Many	>1000 algorithms	Many
Geomorphology	RR	Geomorphic Unit	Geomorphic Unit	Daily	Daily/Annual	Annual	2 (Flow (4 possible values) and sediment indices (4 possible values)	>1000 rules (rules for each geomorphic unit (12) for each channel type(5))	% geomorphic unit (12) per channel type (5)
Fish	RR	RR	RR	Daily	Daily/Seasonal	Seasonal	2 Streamflow (3 possible values) and HSI	36 rules (3 rules per fish group (6) per season (2))	Coarse (state of abundance (7) per fish group (6))
Riparian Vegetation	Geomorphic Unit	Geomorphic Group	RR	Annual	Annual	Annual	1 Geomorphologi cal Units	35 (1 rule per geomorphic group (7) per vegetation type (5) per year)	Coarse (state of abundance (3) per vegetation type (5))

RR – Representative Reach

8.2.1 Model Resolution

Consistent with the simplification of input requirements at broad spatial and temporal scales, is the idea of coarse resolution models, or what Starfield (1996) referred to as Simple Pragmatic Models. Model resolution in this context refers to the detail of the input and output parameters of the models and the complexity of internal operations. The QRBMs may all be termed simple models. Input and output are of a coarse resolution and internal complexity is low.

As explained in Sections 7.1.2 and 8.1 and summarised in Table 8.1 above, inputs to the geomorphology model engine are annual indices of sediment input and flow (once these have been generated from the daily input). These annual indices may have only one of four possible values indicative of the hydrological or sediment state of the year in question. The geomorphic units identified in the Sabie River by Van Niekerk *et al.* (1993) have been grouped so that only 12 geomorphic units are considered. These 12 groups are grouped further to form 6 functional units for input to the riparian vegetation model as described by Mackenzie *et al.* (1998) and explained in Section 7.1.4. Although the fish model operates at a twice-yearly timestep, hydrological input is restricted to three possible seasonal states, *viz.* "wet", "dry" or "normal". The most common fish species have been classified into six different groups according to their life-style attributes as explained by Weeks *et al.* (1996) and discussed in Section 7.1.3. The riparian vegetation and fish models provide output in broad states roughly analogous to qualitative descriptions of abundance, such as "rare", "abundant", "absent" etc. Clearly, many simplifying assumptions have been made, and the resolution of the models is extremely coarse when considering the complex interactions that could be applicable to each of them.

An important aspect of coarse-resolution models is the sensitivity of the output to the input parameters. For example, the fish model has three possible input parameters for each time step of one season, i.e. dry, normal or wet, and these may result in one of seven possible output states of abundance for each fish group. Although moderating rules are built into the model to prevent extreme changes between timesteps, the model output is highly sensitive to the input value. Sensitivity analyses show extreme sensitivity to dry seasons with little immediate response to normal seasons. An increase in the number of possible input values will decrease the sensitivity of the output to them. However, the required level of understanding of the processes is then concomitantly higher.

However, there are distinct advantages to this approach of constructing coarse resolution models. These include the rapid development of prototype models, ease of understanding by non-specialists and the ease of coding and sequentially modifying the rules of the models in a computer programming language.

8.2.2 Spatial Scale and Temporal Scale

Different terminology is used by different disciplines to describe scale and their observations and analyses proceed at differing and varying scales. As identified in Section 2.4.4, it was thus a primary challenge for the project team to identify coherent scales and hierarchical levels for integrating these interdisciplinary analyses. Once the terminology pertinent to scales of interest had been clarified (Figure 2.5) as was done in Chapter 3, it was recognised that the scales at which the different disciplines operate would not easily be matched. Figure 8.3 is a scope diagram illustrating the apparently disparate scales at which the different disciplines of KNPRRP operated. Hydrological research and models relevant to this project operate at the sub-catchment level over a daily time step. Geomorphology research is focused on the channel type, with measurements made at a seasonal level, or at the geomorphic unit scale with measurement of hydraulic components such as flow depth and velocity. Riparian Vegetation research involves the collection of data seasonally at the spatial scale of the geomorphic unit. Fish ecology data are gathered at the biotope scale with point measurements of substratum, flow depth and flow velocity.

However, it was realised that the *extent* of these studies, rather than the *grain*, does provide some overlap between the different disciplines, as illustrated in Figure 8.4. The fish ecology studies were carried out over the entire catchment, at a seasonal time step for a number of years (Weeks *et al*, 1996). Geomorphology studies spanned decades through the use of historical photographs (Heritage *et al*, 1994). Riparian vegetation studies could be extended by the same techniques, and could be applied at the level of the channel type. The continuous daily hydrology information could be aggregated to larger time steps. All the models developed in this project utilise the concept of the Representative Reach in an effort to address problems associated with spatial scale. As discussed in Section 3.3.3 within a river zone, there are a number of reaches which are similar to each other in having the full range of biotopes and geomorphological features found in that zone (King and Tharme, 1993b; Heritage *et al.*, 1998).

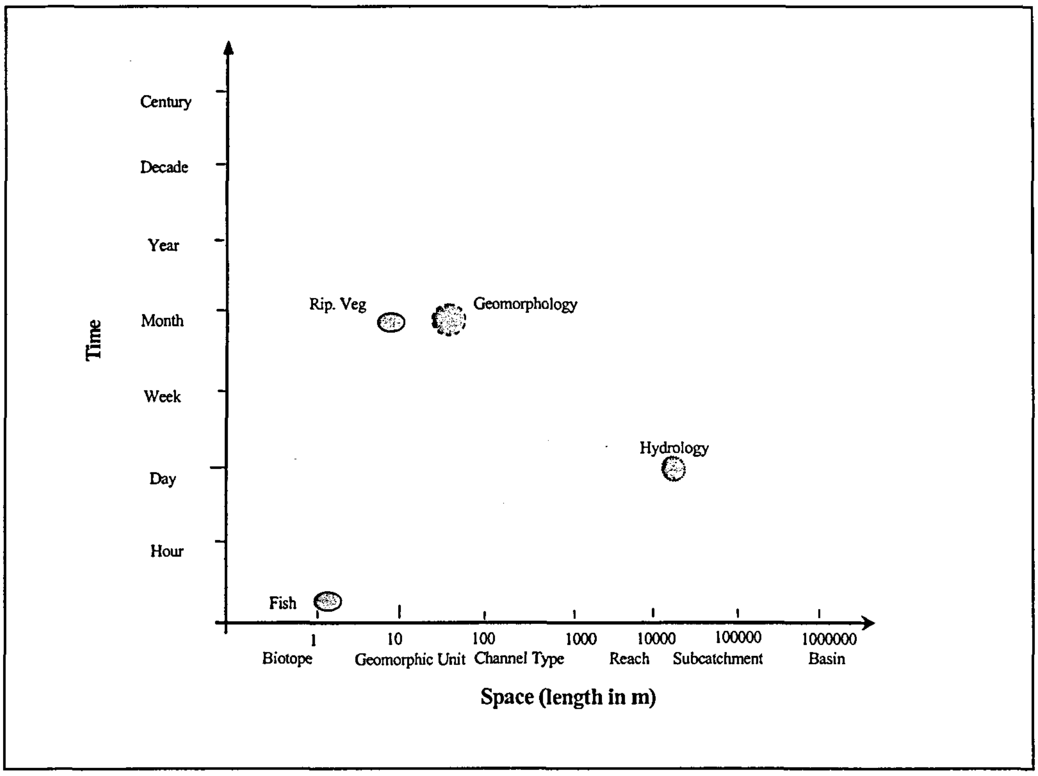


Figure 8.3 Scope diagram illustrating scales (grain) of hydrological, geomorphological, fish and riparian vegetation studies in the Sabie River.

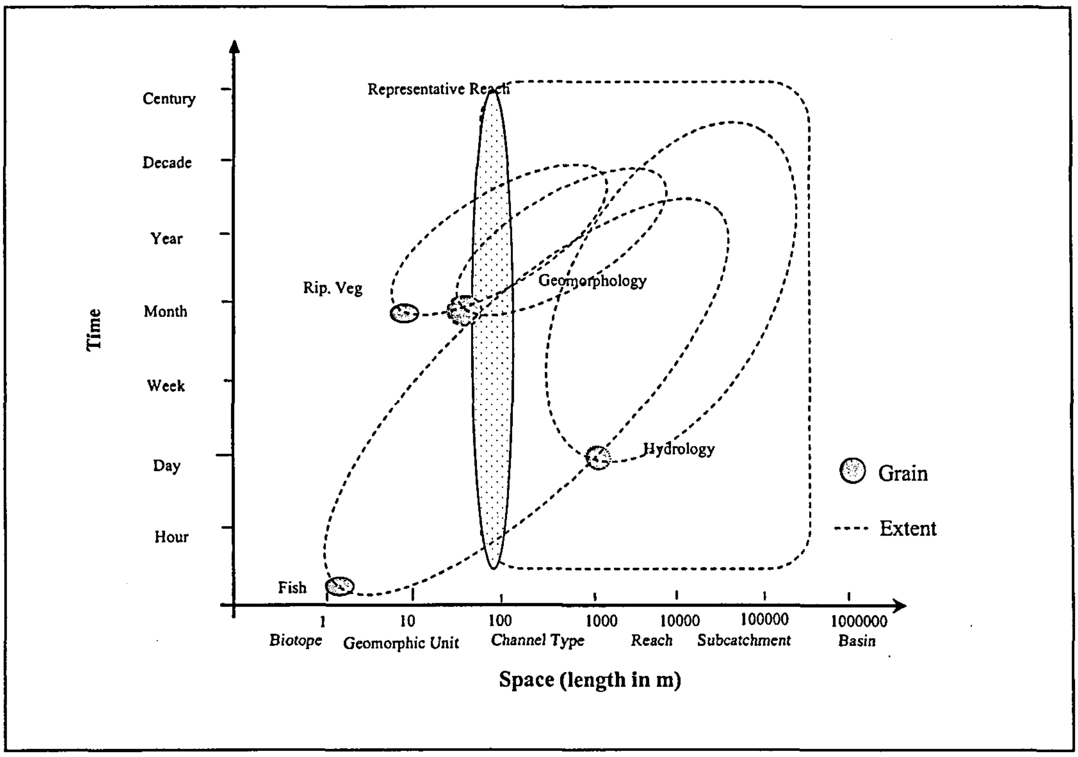


Figure 8.4 Scales of KNPRRP components in terms of grain and extent.

A single reach may then be selected as being representative of the river zone in question. Thus, the Representative Reach appears to offer an extent that provides some overlap of all the studies that need to be considered. The spatial extent of the Representative Reach is also shown in Figure 8.4, and it is postulated that its grain is analogous to the channel type. The use of the Representative Reach together with broad temporal scales, places the models developed in the BLINK project within the zone of predictability identified by Wiens (1989) and illustrated previously in Figure 3.12. The Representative Reach is also a spatial scale at which a hydrological model output may be used with confidence.

Therefore, it is assumed that reaches at which model estimates will be made are representative of all such reaches in the system, and not of any specific section of channel. Electing to run the models at a pool-rapid Representative Reach will produce results applicable to all Lowveld pool-rapid reaches in the Sabie-Sand system rather than results applicable to Cross-section X at Location Y. Thus, the Representative Reach seems to provide a scale that maximises the effectiveness of the models by balancing the conflicting trends of variability in the data and process predictability with varying scale.

The BLINK models are based on the recognition that using an operational scale broader than the scale of the observations improves their predictive reliability by averaging out some of the chaotic behaviour brought about by local perturbations.

Matching Spatial Scales

Early attempts by the project team in making this link between channel morphology and fish habitat, focused on the channel type. However, there are several problems inherent in working at the scale of the channel type. A major difficulty was that the fish data and geomorphological data available were collected from different sites and at different spatial scales. The fish data are usually collected and analysed at a spatial scale of $1m^2$, both a practical and a meaningful scale to the fish ecologist. At this scale, the processes that determine fish habitat are identifiable and, at the practical level, electro-fishing techniques provide a sample from an area of approximately 1 m^2. On the other hand, reaches were mapped by geomorphologists at the scale of the geomorphic unit ranging from 10-100 m^2. Much of the data gathered was not immediately applicable to the Representative Reach. Geomorphic response to hydrological stimuli in a channel needed to be predicted at the level of the geomorphic unit. However, links between fish habitat and geomorphology could not be forged at the level of the geomorphic unit, as habitat-specific fish information was only collected at the biotope scale, which included point measurements of flow depth and velocity, as well as bed substratum and cover. In many ways, this is indicative that factors affecting fish response to flow or habitat conditions operate at different scales to those important to geomorphic processes. The aims of the respective geomorphic and fish field work focuses at scales appropriate to them.

Preference curves reflecting fish preferences to specific water depths and current velocities and preferred substratum at the biotope scale are typically produced as part of ecological studies (Weeks *et al.,* 1996), an example of which is shown in Figure 8.5.

Figure 8.6 shows a hierarchy of "building blocks" used by the geomorphology and ecology disciplines. It can be seen from the figure that substratum is identified as a "building block" common to both the geomorphic unit and the biotope. This implies that the substratum can be used as a "common language" for geomorphological and fish ecology scientists in the KNPRRP.

Consequently, by means of data compiled by the KNPRRP's fluvial ecologist, the idea of substratum as "common language" was developed further, by reducing each geomorphic unit into habitat sub-categories, each of which was assigned a specific substratum and cover code combination. Thus, geomorphic units are classified in terms of sediment size and cover, whether visual and/or velocity cover. Visual cover relates to visibility to predators and can be both direct (instream object) or indirect (overhead shading) while velocity cover relates to physical shielding from current (Weeks *et al.*, 1996). In this exercise, only underwater geomorphology is defined (by area) while sedimentary deposits and banks adjacent to the river are treated as a linear strip a meter wide. It is then possible to convert a geomorphological map of the study reach into a substratum based habitat availability map (Figure 8.7) and to calculate the percentage availability of each habitat category present.

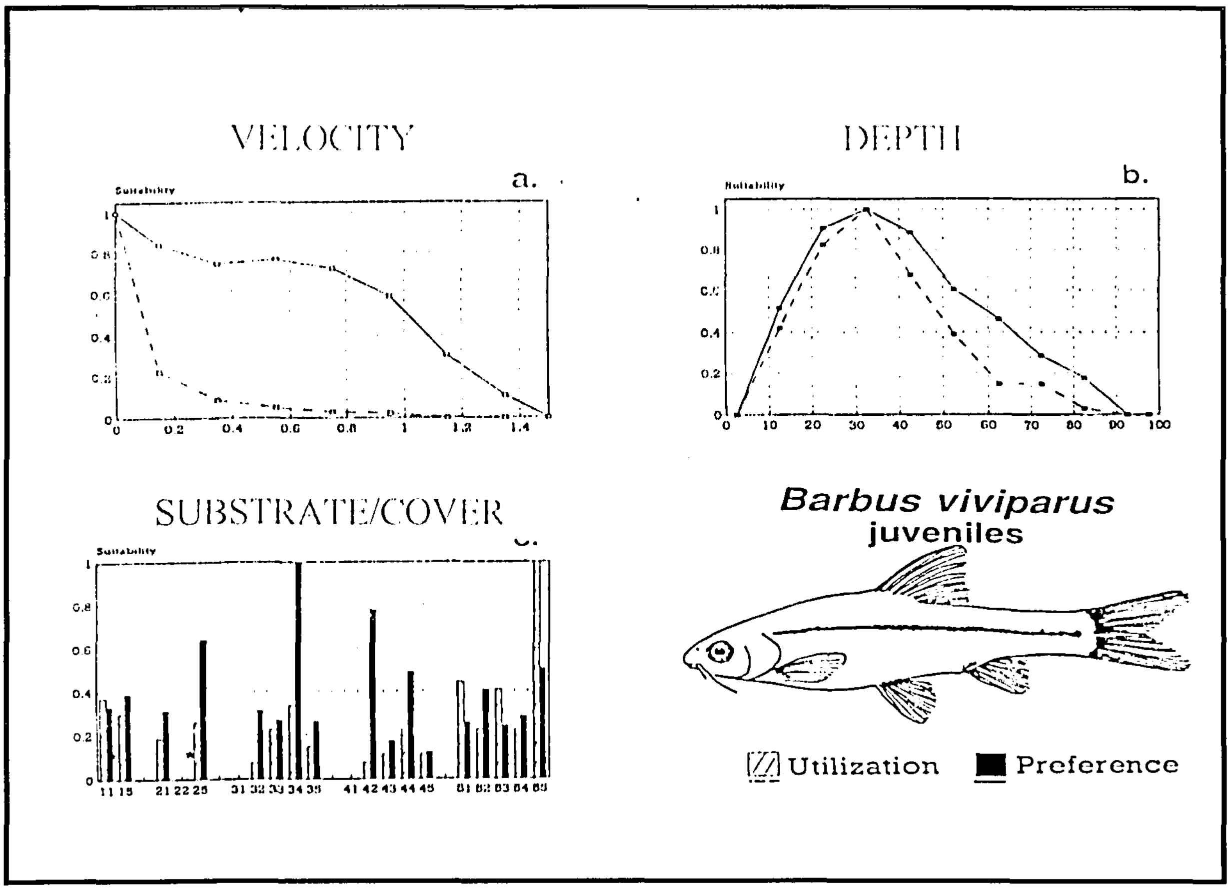


Figure 8.5 Micro-habitat preference for *Barbus viviparus* (after Weeks *et al.*, 1996).

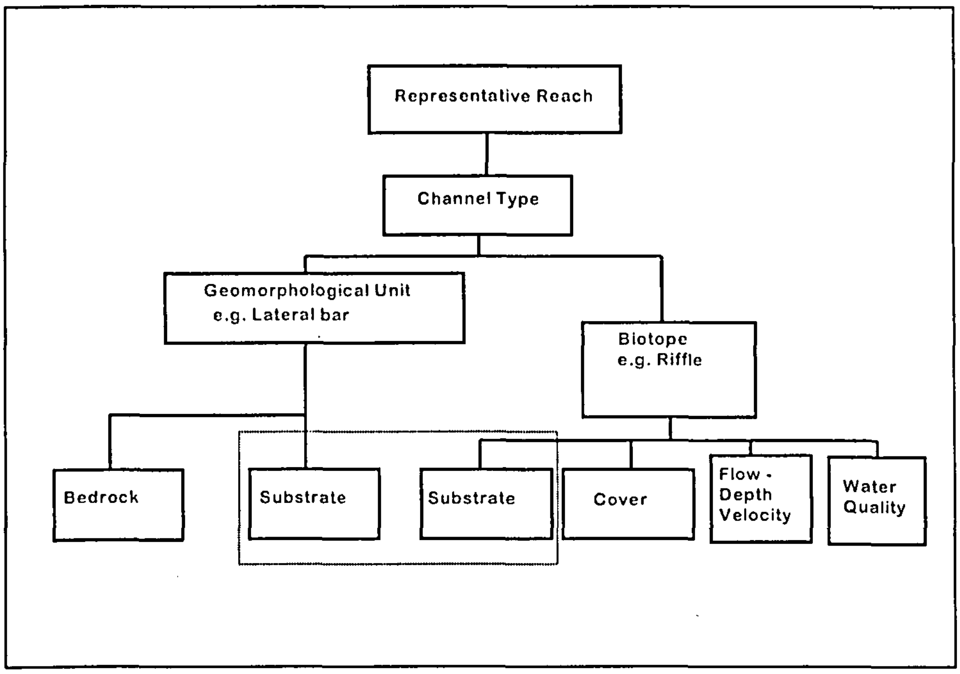


Figure 8.6 Hierarchy of units for links between fish and geomorphology.

Finally, this can be related to the habitat substratum part of the preference curves generated for each of the species present in the river to estimate the preference of each fish group for the Representative Reach under consideration, and thus produce a HSI. By quantifying and analysing the associations of substratum with the geomorphic units making up the channel type, a prediction of change in the channel type means that the change in substratum/cover and thus HSI, can be estimated. This process is covered in detail by Weeks *et al.* (1998) and Heritage *et al.* (1996).

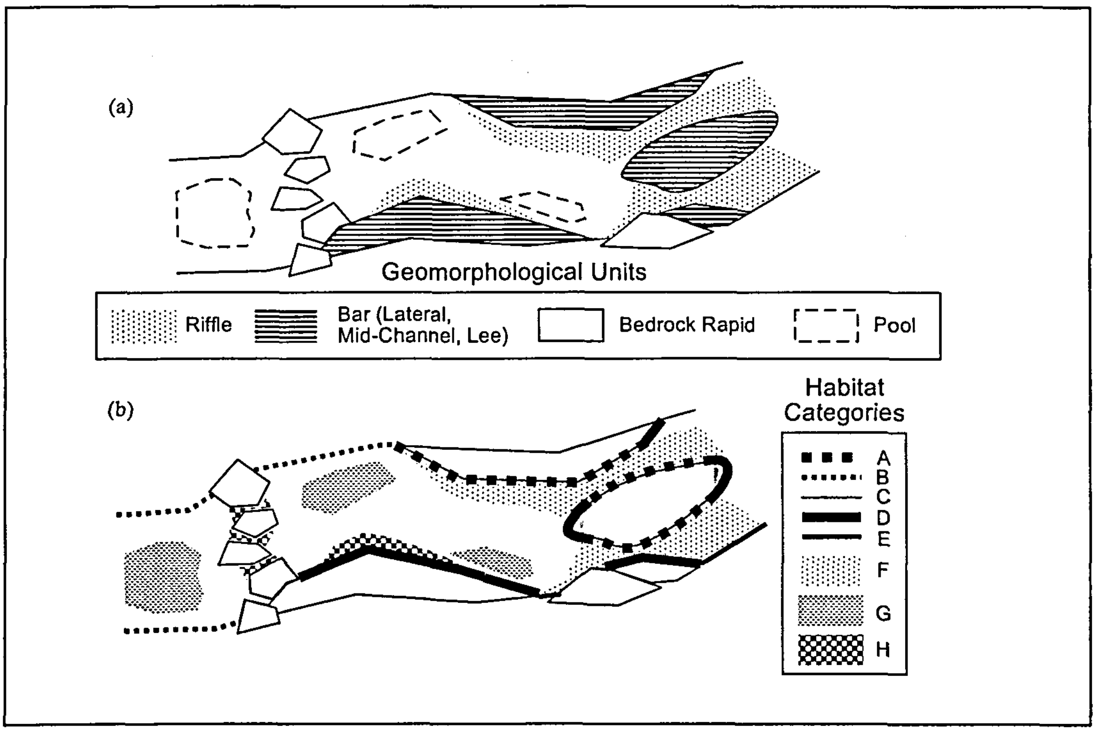


Figure 8.7 Geomorpholog units (a), translated into related fish habitat (b) (after Heritage *et al.*, 1996).

The use of the substratum as a common building block has several inherent advantages. Substratum is identified as the least temporally variable of the micro-habitat variables used for HSI development (Figure 8.4). It is also the most easily measured of these components and thus, its association with geomorphic units is most easily and accurately quantified. Furthermore, by using the substratum to forge the biotic-abiotic link, this link may be applied to the geomorphic unit scale and then to the channel type by means of aggregation. Thus, even if no information regarding fish habitat is available for a particular channel type (e.g. braided/single thread), because fish habitat preference is linked to geomorphic substratum and then mapped at the level of the geomorphic unit, this link can be applied to these channel types (made up of a combination of these geomorphic units and thus substrata) using information which was derived from, say, a pool-rapid channel type.

Ultimately, utilisation of the geomorphological template to predict fish habitat operates at three scales in the model (Figures 8.8 and 8.9). Initially the channel type (represented by the Representative Reach) is recognised (e.g. pool-rapid); secondly geomorphic units are identified and thirdly these units are in turn characterised by a sub-set of cover and substratum categories. It is at this lowest level that fish preferences are related to the geomorphology. Thus, the process of model development has required that fish and geomorphology information are first matched at a fine scale by use of the substratum as a common language between the two data sets. This information is then scaled up to the level of the Representative Reach through the hierarchy shown in Figure 8.8 with the use of a HSI. At this level, output from the ACRU model may be used to provide the hydrological input to both the fish and geomorphological models.

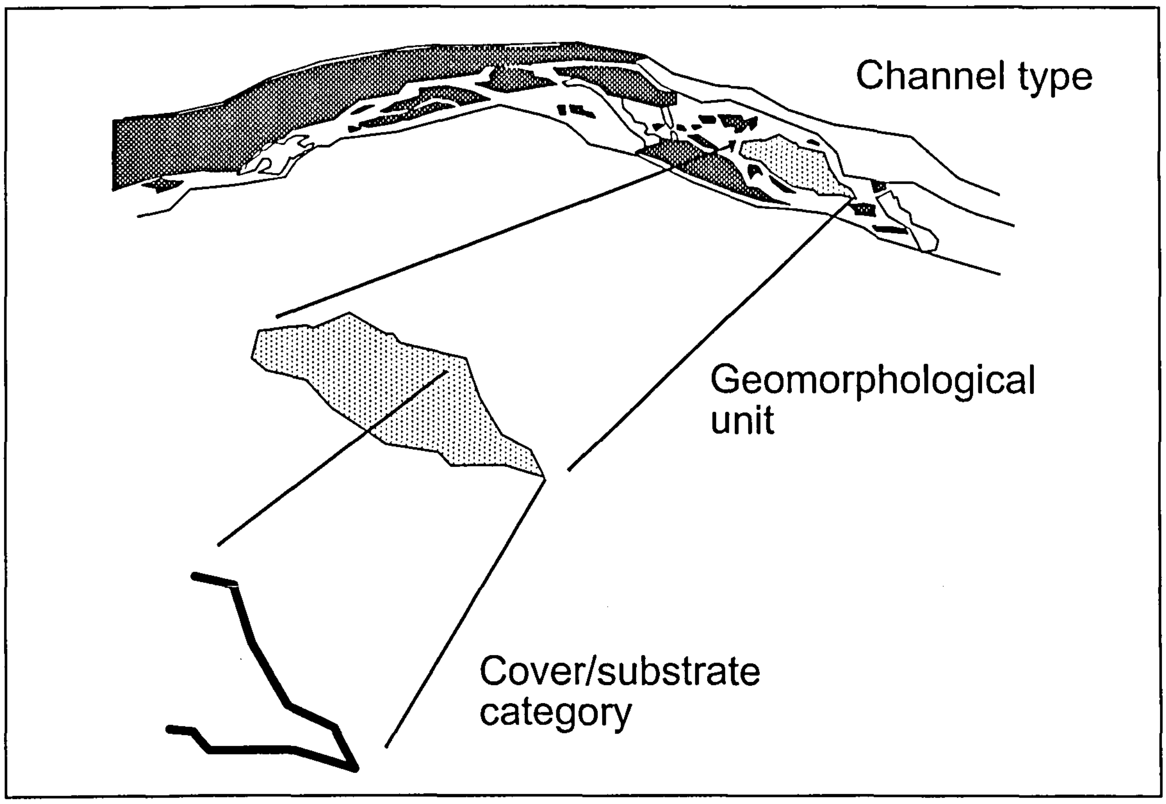


Figure 8.8 The fish model linkage to the geomorphology model operates at three scales (Heritage *et al.*, 1998).

As explained in Section 7.1.4, available riparian vegetation information allowed responses to be predicted at the level of a functional geomorphic unit, a broader scale than the geomorphic unit itself. Consequently, the link between geomorphology and riparian vegetation is made at a further scale, that of the so-called "functional unit". In this case, the geomorphic units simulated by the geomorphology model are aggregated to form units more directly applicable to the association formed by Van Coller *et al.* (1995) (and discussed in Section 7.1.4). The five functional units applicable to riparian vegetation form a fourth important spatial scale of operation of the modelling system and a further hierarchical level within the Representative Reach. A breakdown of the levels of the hierarchy used in the modelling system and making up the Representative Reach is illustrated in Figure 8.9.

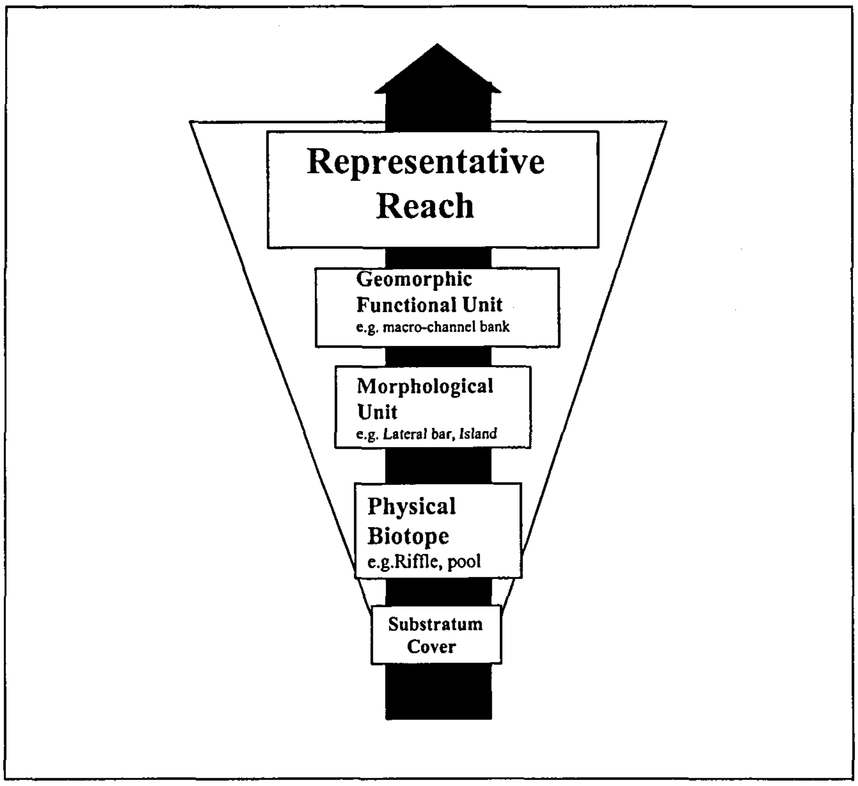


Figure 8.9 Hierarchical levels used in the BLINK Integrated Modelling System

Temporal Scale

These models all utilise a simplified form of "discrete event simulation" and asynchronous time steps to optimise the temporal scales used. The temporal operational scales for these models had to be selected so that abiotic processes could be the dominant cause of the biotic responses observed, i.e. a scale was needed at which clear temporal patterns of biotic responses could be identified.

The fish model operates at a twice-annual time step, producing predictions of fish response in May and in November. These periods are selected to provide an estimate of fish response for the preceding six-month period representative of wet (summer) and dry (winter) seasons respectively. In early stages of development, an attempt was made to use an annual time step, operating from May to May each year. However, according to Weeks *et al.* (1996), within the study period, the responses of the fish in the Sabie-Sand system were primarily seasonal. As explained in Section 7.1.3, the use of an annual time step would obscure this important pattern.

Geomorphic input is provided annually as output from the geomorphology model. The dry season has little impact on the geomorphic composition of the channel as streamflow is reduced and the river does not have the ability to move much sediment. Output at the six-monthly level is unnecessary.

Classification of the flow regime into the categories used as input to these models requires analysis of the hydrological model at a daily level. For example, a freshet, although not a direct input to the fish model, is an important component of a "normal" season. Analysis of a flow regime represented only by average conditions over that period would not allow the detection of freshets, thus, a daily flow sequence is required.

Thus, use is made of the concept of asynchronous time-steps as explained in Section 5.6.1, i.e. in the fish model, the model engine operates twice-yearly, geomorphic input is provided annually and hydrological input is provided on a daily basis.

Although the riparian model produces output annually, the output is often unchanged from the preceding year; the model is only operative if a significant change in the input is recognised by the model. This will then trigger a response and a change in predicted riparian vegetation composition may result, i.e. discrete event simulation.

Thus the modelling system utilises the concepts of "discrete event analysis" and "asynchronous timing", in order to adequately accommodate the complexities of models for which no single temporal scale is appropriate.

Scaling by Simulation Model

It must also be noted that the models used and developed in this project effectively act as mechanisms for scaling the information they assimilate in different directions, both spatially and temporally. This is illustrated by Figure 8.10. The ACRU model is largely driven by point scale information (e.g. precipitation measured at a rainguage). This data is extrapolated to the extent of a subcatchment, although output is then supplied at a particular subcatchment outflow point or Representative Reach. In this project, the ACRU model effectively downscales information from the catchment to the Representative Reach, or the channel type it represents i.e. from model extent to grain (Figure 8.4).

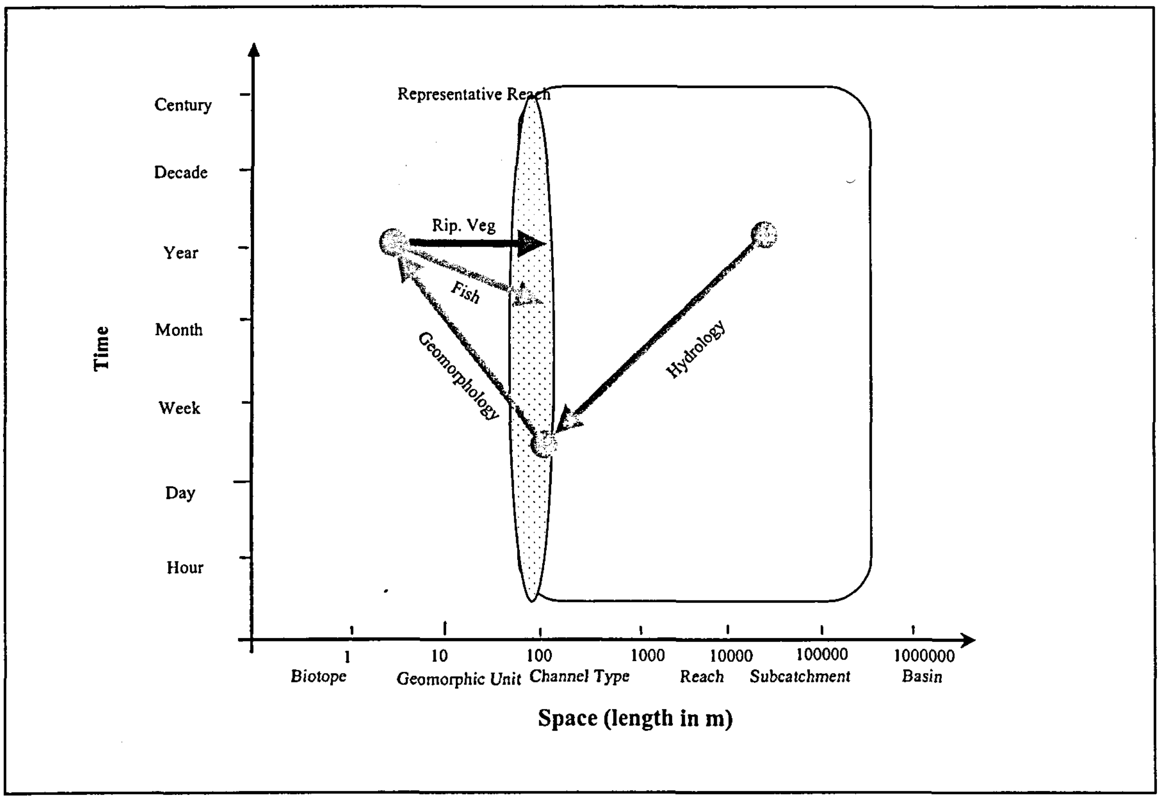


Figure 8.10 Scope diagram illustrating the scaling effects of the different BLINK models.

The functions in the fish and geomorphology models provide methods for scaling daily information to seasonal and annual indices. It has already been noted that the geomorphology operates at three spatial scales internally and that the riparian vegetation model adds a fourth spatial scale to these. Thus, in the KNPRRP BLINK project, the necessary scale matching and transformation requirements were first identified and understood, as explained above. Much of the process of up- or down-scaling is then done by the models themselves.

Chapter Nine

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The modelling system developed in this project incorporates both "traditional" rainfall-runoff modelling techniques, in the form of the ACRU, VTI and HSPF models and knowledge based systems represented by the fish, geomorphology and riparian vegetation models. These have been integrated into a single modelling system forming part of the KNPRRP ICIS.

A number of difficulties have been encountered with the use of the large multi-component models in this project, both HSPF and to a lesser extent ACRU. These difficulties may arise as a result of using large complex modelling systems as interdisciplinary communication tools (Section 4.2), in trying to obtain adequate data to implement and calibrate them (Section 7.2) and finally in the procedures related to linking them. It should also be recognised that the Sabie River catchment may have been an unsuitable choice for the implementation of the ACRU-HSPF system, given its dearth of meteorological and water quality data.

If, however, the focus falls on the feasibility of such a linkage of two available models for utilitarian purposes, then this project highlights the typical problems, and their solutions, associated with linking models from different sources. These are:

Should models be linked in series or parallel?	Ideally in parallel, though this is not always possible and requires an depth of working knowledge of both models.
Do common time-series databases facilitate model linkages?	In the case of serial links, ensuring that the models to be linked share a common database does simplify model linking.
Linking two large models in their entirety adds complexity to the simulation task.	This problem may be alleviated by linking only the required components of one of the models in parallel with the other.
Parallel integration requires that spatial and temporal scales of operation are compatible.	In series linkages, the models may act as scaling mechanisms.

9.1 CONCLUSIONS

A number of conclusions can be drawn from the experiences described and discussed in this document:

- A key step in the process of successful interdisciplinary research and, thus, in the development of the modelling system described in this document, is the successful resolution of scale issues. Methods of resolving such scale issues have been described in this document, and the use of structured hierarchies, together with consistent use of terminology, has been recommended.
- Interdisciplinary research requires that a system be studied from various viewpoints within a hierarchy, because the different disciplines focus their studies at different scales. This is a difficulty when linking models, but provides a better perspective to the aim of the interdisciplinary study, as the established domain of a discipline, in general, may limit the perspective to problems that its members judge as "appropriate" to study.
- A sacrifice of detail to reveal broad predictable patterns in available biotic data is necessary before models can be developed to describe these patterns. It has been noted in this study that the movement to higher levels of the catchment hierarchy at which these predictable broad scale patterns are recognisable, is not possible without the detailed knowledge gathered by the different disciplines. Sound discipline-based work is needed to complement and form these higher-perspective views. Furthermore, good quality data (e.g. detailed fish or geomorphology data) gathered over several years and the fieldwork associated with this is critical to the development of these higher perspective views.

9.2 RECOMMENDATIONS

It is recommended that future integrated catchment modelling exercises adopt the idea of a core catchment hydrology model with basic water quality functions, which may be coupled with a suite of pragmatic models, governed by some form of filter represented by management needs, such as the TPCs mentioned in Chapter 8. "Traditional" modelling paradigms are not always appropriate to this approach. Thus the use of Qualitative Rule Based Models is recommended where appropriate.

It is further recommended that future linkages of hydrology and hydraulic components of models follow the embedded option described in Section 4.3.3. This has the advantage of minimising the complexity of the modelling system, allowing feedback between the linked components and increasing functionality of the system.

The development of models, such as those in the BLINK project, may guide future research in a way that this research may be more compatible with the development of a predictive capacity to aid management. It is recognised that collaborative planning of research projects will benefit interdisciplinary projects. However, there is little recognition that researchers should focus their projects at scales deemed important by managers, or at scales which would appear to assist in collaboration with other researchers. Although there are technical complexities associated with matching the operating and process scales important to the different disciplines, with strategic planning these can be overcome. It is the issues that surround interdisciplinary collaboration that will be most difficult to resolve.

The following recommendations are made for further research:

- The suite of models developed in this project is only partially verified. Further refinement of these models and verification over a wider range of conditions is required.

- The work reported in this document is of a scientific nature. Consequently, the manner of the transfer or use of these models, or their results, for ICM support is another area in which further research is required.

- The participants in this project have all benefited from their exposure to the paradigms, work ethics, thought processes, methodologies and personalities involved in scientific disciplines other than their own. Although scientists are increasingly seeing the need for collaboration, this is a process that requires careful nurturing and proactive development. Such development should be the subject of planned programmes by South Africa's research funding institutions.

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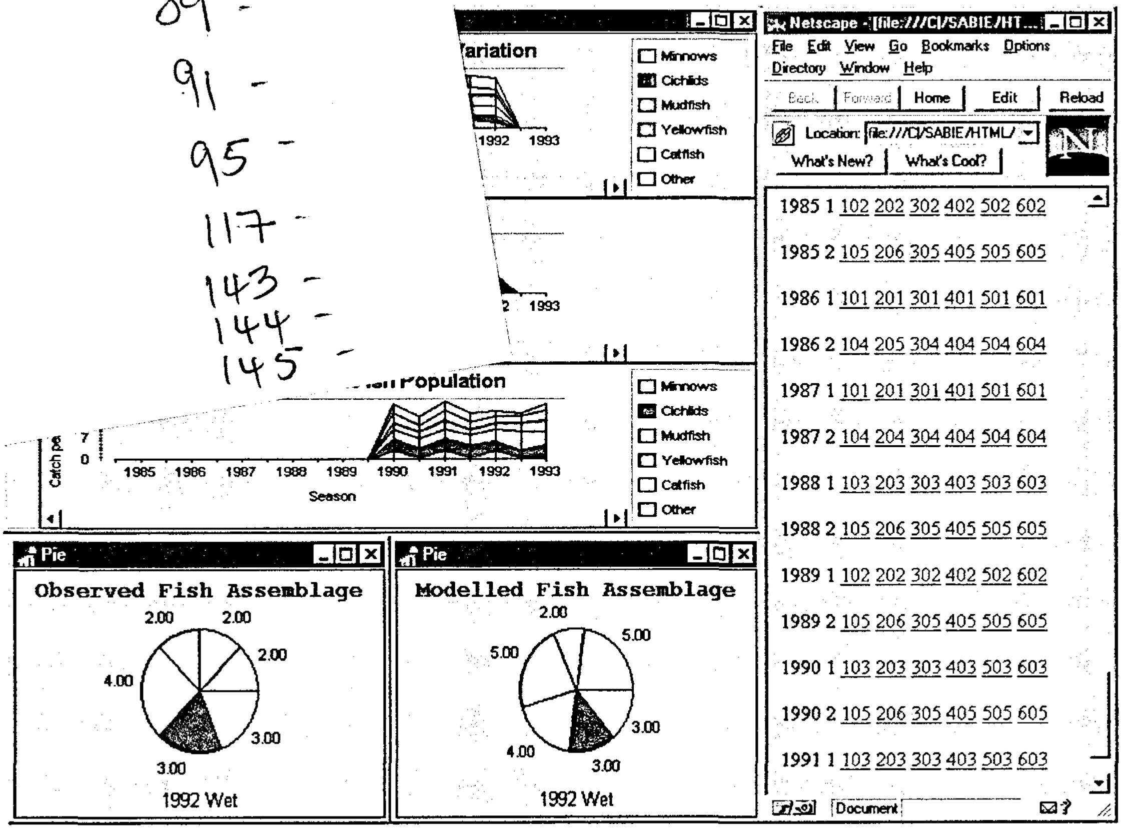

Figure 7.12a) Sample output of the fish model.

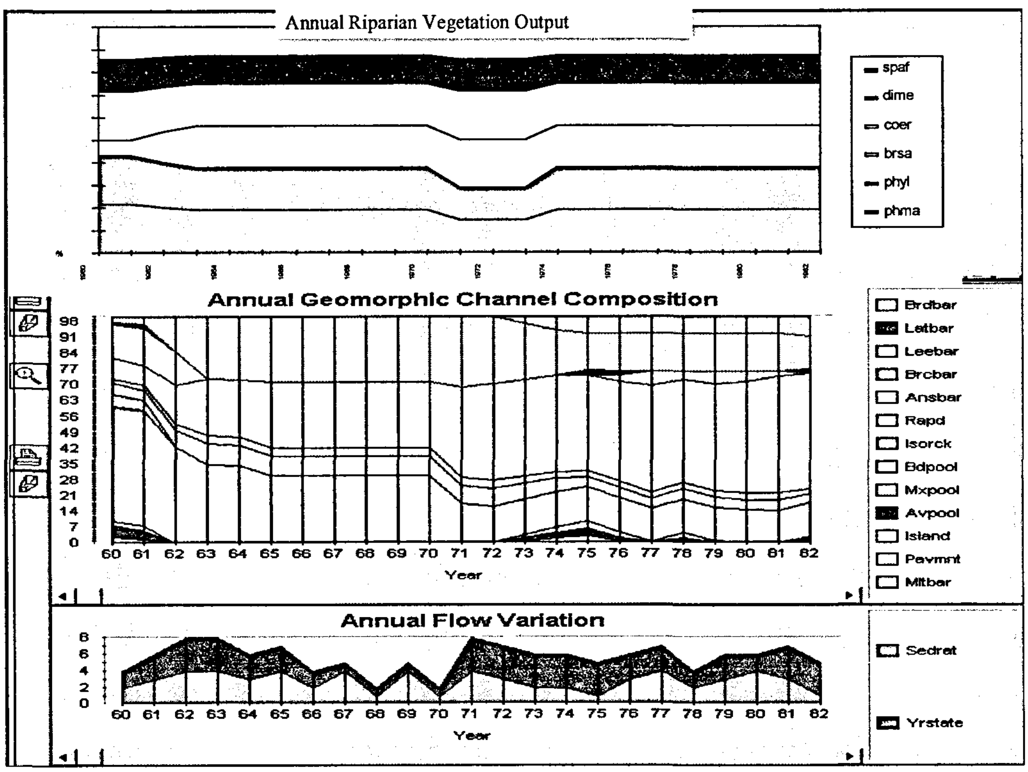

Figure 7.12b) Sample output of the geomorphology and riparian vegetation models.

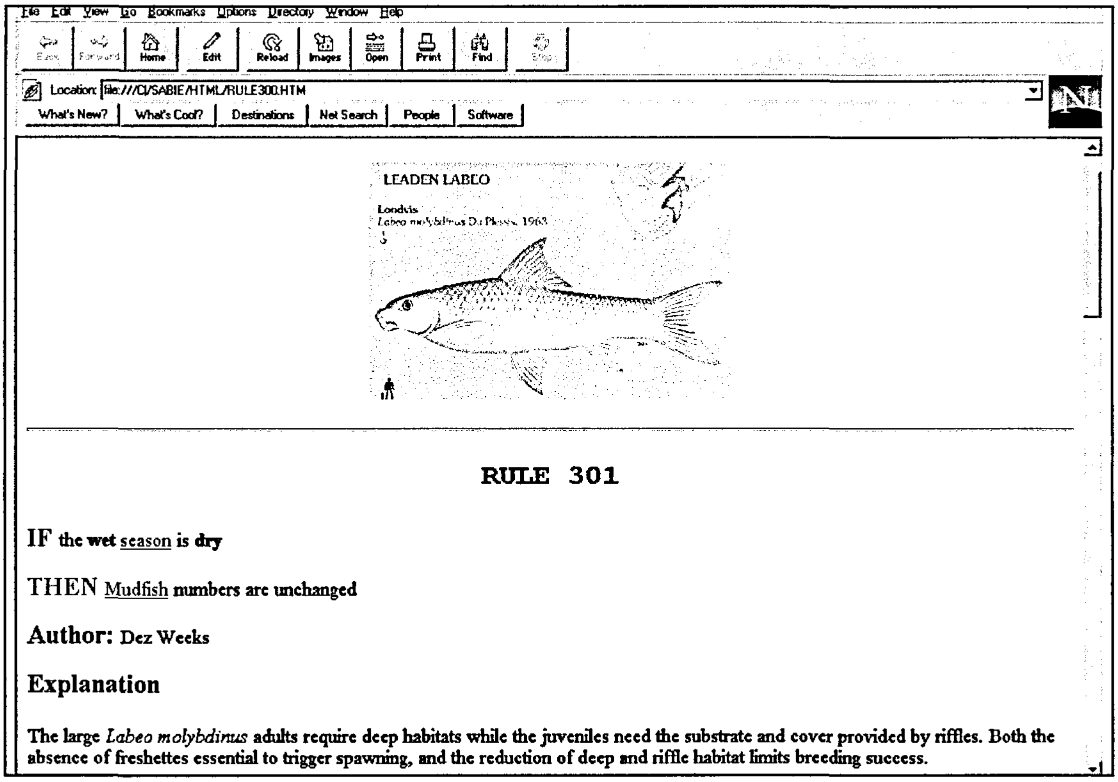

Figure 7.13 Sample of hypertext explanation of a fish rule.

Although the expert knowledge used in the development of these models was gleaned from many years of published information, the models were created based on field data collected over a fairly limited period of time, i.e. 1990-1996. In order to use the models outside the scope of the knowledge used in its development, some form of verification is necessary. In many ways, the acceptance of a knowledge-based system and the results it produces by other experts in the field is an important form of model verification. If experts, other than those involved in the development of the model, are able to accept the rules that drive it, one form of verification is complete. Thus, it is important that assumptions made in the development of the model are known and understood. By presenting dual model output, i.e. simulated results and the rule trace, the aim has been to provide the user with a great deal of information regarding the internal workings of the model and its output. In this manner, a transparent system which supplies the user with information, rather than a system which merely generates numbers is produced. This information includes explanations of the geomorphic units used, grouping of the fish and riparian vegetation, the classification of each season as hydrologically "wet", "dry", or "normal" etc. Model output for the geomorphology and riparian vegetation models follows in this line (Jewitt *et al.*, 1998).

The fish model output produced does show close resemblance to observed data collected for Pool-Rapid reaches (Figure 7.12a). However, this short (3-year) period of observed data does not offer an adequate data set for a verification exercise. Possibly of more significance is that the model output does agree with observations made over many years by other fish ecologists (Deacon, 1997). In particular, it is noted that in dry cycles, cichlids (blue in Figure 7.12a) tend to dominate the fish assemblage and fish numbers in general are reduced. In wetter periods, minnows (green in Figure 7.12a) tend to dominate the fish assemblage and fish numbers increase. These responses predicted by the model tend to agree with expert opinion.

Study of Figure 7.14, which shows model output for the same period and same hydrological variation, but for different channel types, shows the effect of the geomorphic habitat template on the simulated fish response. For example, the Rock Catlet (yellow, Figure 7.14) show their highest level of abundance in bedrock anastomosing and pool-rapid reaches. Their numbers are greatly reduced in braided/single thread reaches. This is consistent with habitat preferences for this fish, which is known to prefer fast flowing rocky sections of the river, very few of which are provided by alluvial sections of river such as braided/single thread reaches. Cichlids (blue, Figure 7.14) do not show much variation across channel types, which is consistent with their less specialised microhabitat requirements (Weeks *et al.*, 1998).

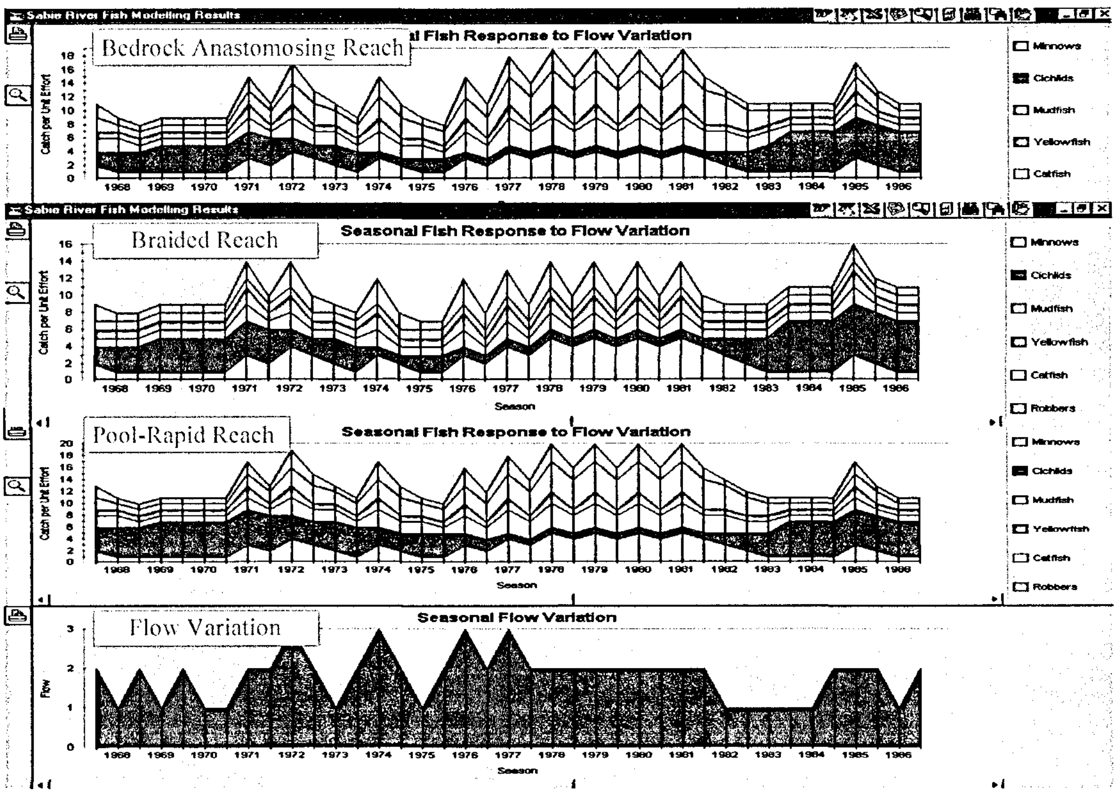

Figure 7.14 Fish model output showing effect of geomorphic template

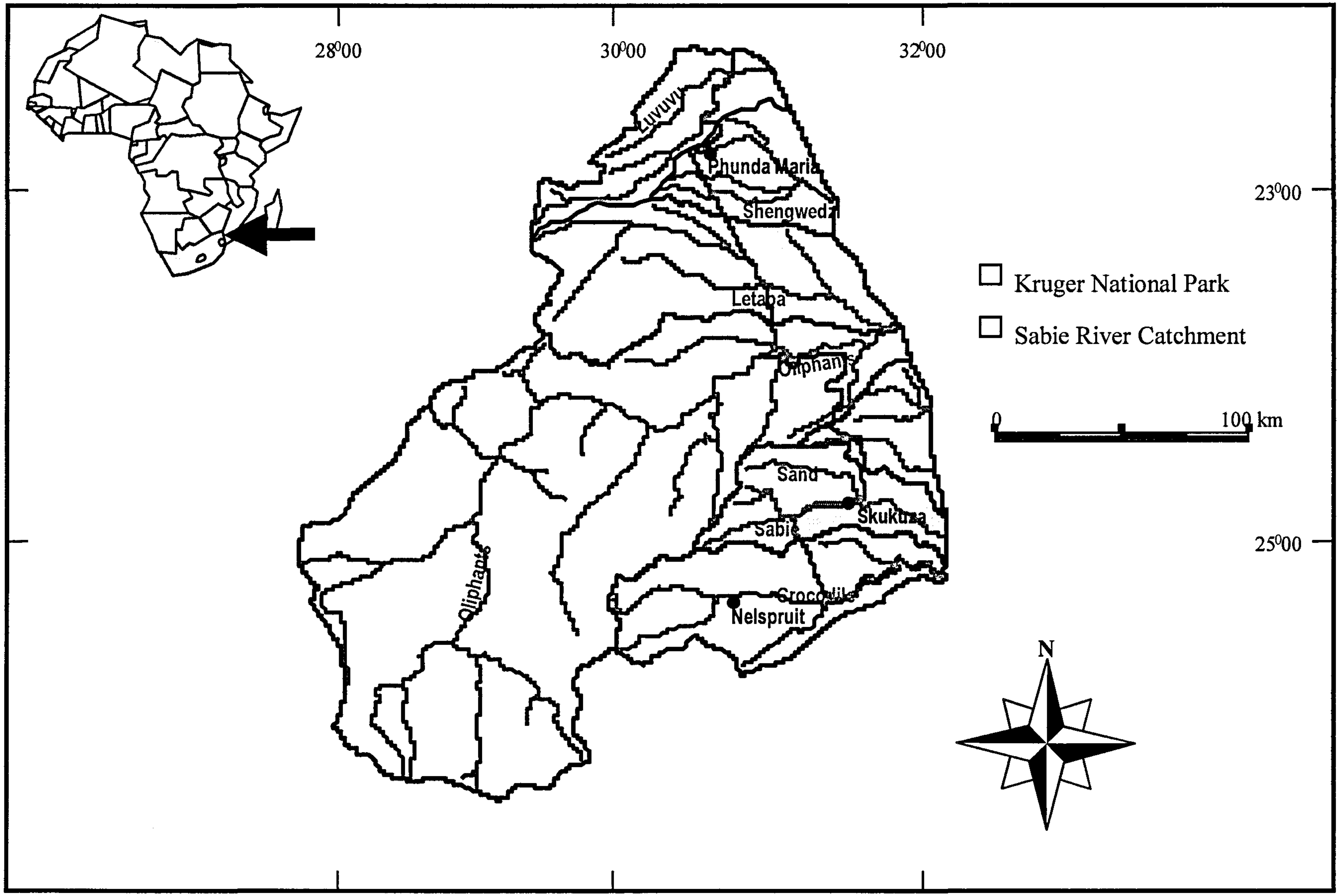

Figure 2.1 Location of the Kruger National park with the Sabie River catchment highlighted.

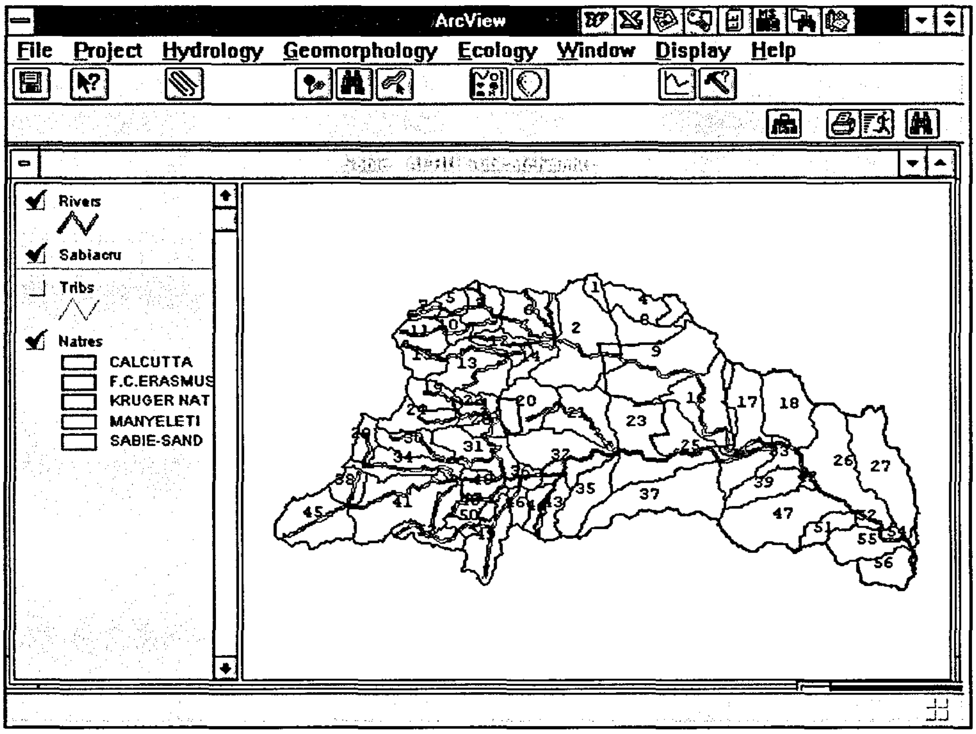

Figure 5.3 The ICIS Graphical User Interface

5.3.2 Databases

Two types of databases exist in the ICIS, *viz.* local and remote. The local database consists of a loose arrangement of files in ASCII or tabular format. Future enhancements to the ICIS should allow the organisation of many types of data used into a single unified relational database. Several data types need to be incorporated or linked in a system such as this one. These include;

- the coverages relating to catchment spatial information and utilised by the GIS,
- metadata relating to many aspects of the catchment under consideration, such as that stored in the system developed by Biggs (1995) as part of the KNPRRP. This may include catalogues of relevant (paper) publications, contact addresses, photographs, etc.,
- other metadata relating to explanation of rules used in ecological predictions, geomorphological site descriptions and descriptions of biota, etc., and
- time series of observed data and simulated time-series for the catchment, such as, rainfall, runoff, sediment, etc.

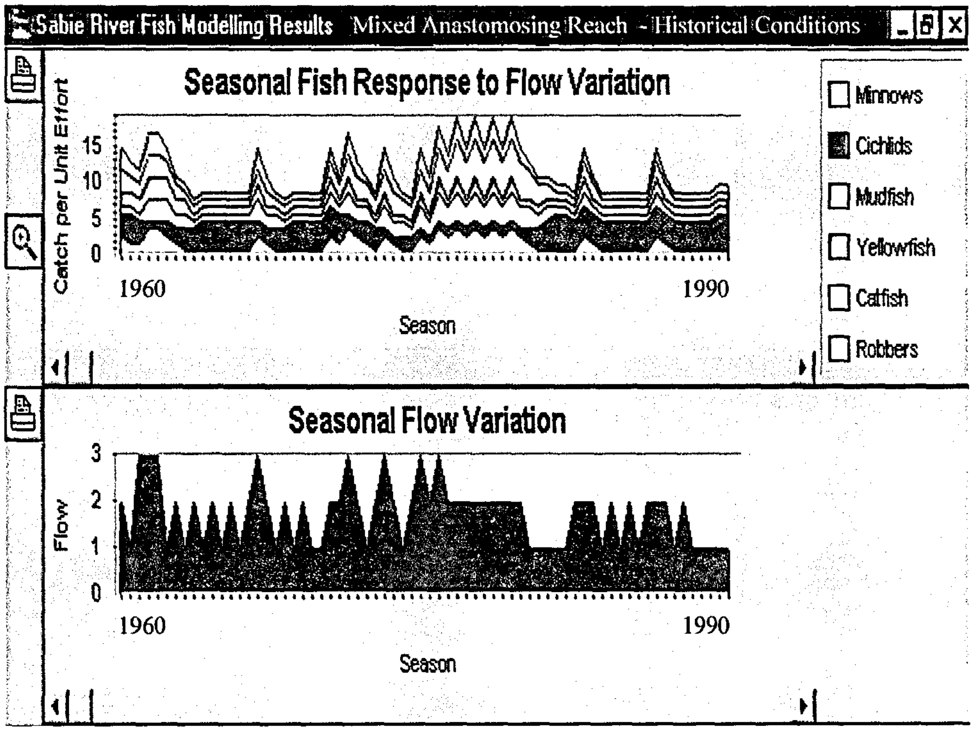

Figure 5.4 Sample output from the models included in the ICIS

5.3.4 Networking Tools

As stated previously, the ICIS is part of a decision support system which makes use of ARCVIEW and a range of other software on a PC and larger host computers at remote sites. The ability to connect the system to other computers on the wide area networks was vital in the context of the KNPRRP, where the participating scientists are scattered geographically and yet are required to communicate continuously (Dent, 1996).

Connectivity to wide area networks, most notably the Internet, are available through Telnet, X.25 or Kermit. The latter two methods are utilisable through dial-up modems, thus the user need not be resident at an organisation with a direct Internet link.

5.4 FUTURE ICIS DEVELOPMENTS

The ICIS is not a static system, but one which is under constant development. This is in line with the evolving needs of the user community who are intimately involved in its use and feedback as its development progresses (Dent, 1998).

An essential element in the systems' future usefulness and acceptability is that users feel that their needs have been accommodated within the software. For this reason the ICIS

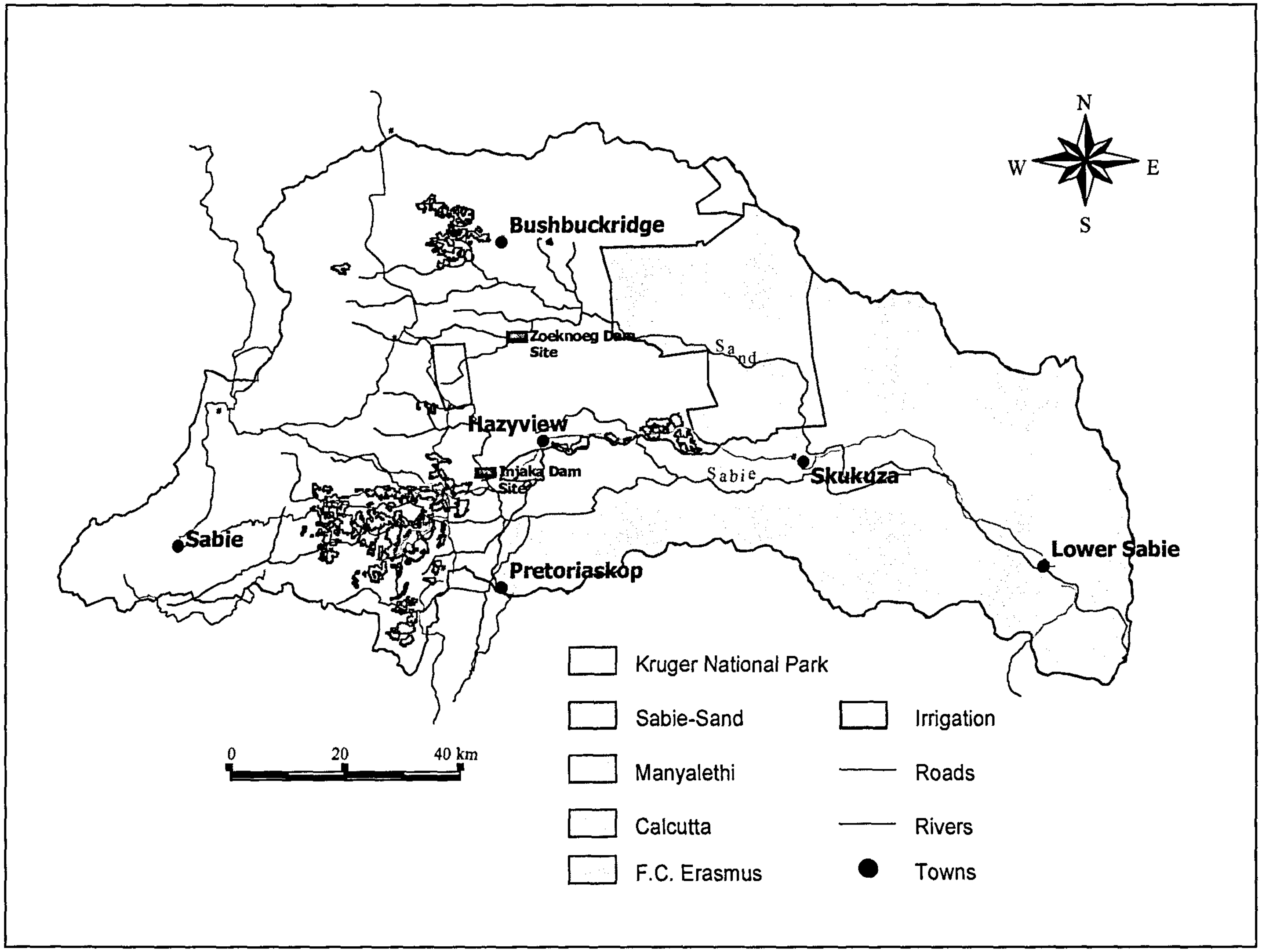

Figure 6.1 Selected Landuses of the Sabie catchment

REFERENCES

Abel, D.J., Kilby, P.J. and Davis, J.R., 1994. The systems integration problem. International Journal of Geographical Information Systems, 8:1-12.

Allen, T.F.H. and Hoekstra, T.W., 1992. Toward a unified ecology. Columbia University Press, New York.

Allen, T.F.H., 1987. Hierarchical complexity in ecology: a non-euclidean conception of the data space. Vegetatio, 69: 17-25.

Angstrom, A., 1924. Solar and terrestrial radiation. Quart. Journal of the Royal Meterological Society, 50:121-126.

Ashley, G. M., Renwick, W. H. and Haag, G. H., 1988. Channel form and process in bedrock and alluvial reaches of the Raritan River, New Jersey. Geology, 16: 436-439.

Australian Scales Workshop, 1995. Australian Symposium on Spatial and Temporal Scaling of Ecological Processes in Freshwater Systems. Hosted by the CRC for Freshwater Ecology, Dec 10-11, 1995. Monash University, Melbourne.

Ball, G.L., 1994. Ecosystem modelling with GIS. Environmental Management, 18: 345-349.

Ball, G.L., Zeigler, B.P., Sclichting, R., Marefat, M. and Guertin, D.P., 1996. Problems of multi-resolution integration in dynamic simulation. Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modelling, National Center for Geographic Information and Analysis, Sante Fe.

Bathurst, B.J., 1986. Sensitivity analysis of the Systeme Hydrologique Europeen for an upland catchment. Journal of Hydrology, 87: 103-123.

Bella, D.A. and Williamson, K.J., 1996. Conflicts in interdisciplinary environmental research. Journal of Environmental Systems, 62:105-124.

Beuster, J., Shand, M.J. and Stoffberg, F., 1997. Development of a water balance model for Eastern Cape water resources assessments. In: Proceedings of the Eighth South African National Hydrology Symposium, University of Pretoria, Pretoria.

Beven, K., 1987. Towards a new paradigm in hydrology. Journal of Hydrology, 87:393-403.

Beven, K., 1989. Changing ideas in hydrology – the case of physically-based models. Journal of Hydrology, 105:157-172.

Beven, K., Warren, R. and Zaoui, J., 1980. SHE: Towards a methodology for physically-based distributed forecasting in hydrology. In: Hydrological Forecasting, Proceedings of the Oxford Symposium. IAHS Publ. 129, 133-137.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigian, A.S. and Johanson, R.C.,1996. Hydrological Simulation Program - FORTRAN. User's manual for release 11. U.S. EPA Environmental Research Laboratory, Athens, GA, in cooperation with U.S. Geological Survey, Office of Surface Water, Reston, VA.

Biggs, H., 1995. Kruger National Park Rivers Research Programme Meta-DataBase http://aqua.ccwr.ac.za/knprrp/knp.html

Blöschl G. and Sivapalan M., 1995. Scale issues in hydrological modelling: A review. Hydrological Processes 9:251-290.

Blöschl, G., 1996. Scale and Scaling in Hydrology. Habilitationsschrift, Institute for Hydraulics, Vienna Technical University, Vienna.

Bovee, K. D., 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12, FWS/OBS-82/26, Co-operative Instream Flow Group, US Fish and Wildlife Service, Office of Biological Services.

Breen, C., Quinn, N.W. and Deacon, A., 1994. A description of the Kruger National Park Rivers ramme, second phase. Foundation for Research Development, Pretoria.

Breen, C., Quinn, N.W. and Mander, J., 1997. A description of the Kruger National Park Rivers Research Programme, third phase. Foundation for Research Development, Pretoria.

Brookes. A.,1992. River channel change. In: Petts, G. and Calow, P., [eds.] River flows and Channel Forms: Selected Extracts from the Rivers Handbook, Blackwell Science, Oxford. pp221-242.

Chunnet, Fo urie and Partners, 1990. Kruger National Park Rivers Research Programme, Water for Nature, Hydrology, Sabie River Catchment. DWAF Report No. P.X.300/00/0390. Department of Water Affairs, Pretoria.

Clark, M.J. and Gardiner, J., 1994. Strategies for handling uncertainty in integrated river planning. In: Kirkby, C. and White, W.R. [eds.], 1994. Integrated River Basin Development, Institute of Hydrology, Wallingford, John Wiley.

Cobban, D. Dent, M.C., Horn, M., Van Rensburg, J., Silberbauer, M. and Buescher, K., 1995. Integration of a catchment based water quality model with query and display on a

GIS, Poster presented at the SASAQS Conference, June 28-30. Rhodes University, Grahamstown.

Cortner, H.J., and, Moote, M.A., 1994. Trends and issues in land and water resources: Setting the agenda for change. Environmental Management, 18: 167-173.

Costanza, R. and Maxwell T., 1993. Resolution and predictability: An approach to the scaling problem. Landscape Ecology, 9:47-57.

Costanza, R. and Maxwell, T., 1995. Spatial ecosystem modeling using parallel processors. Ecological Modelling, 58: 59-183.

Costanza, R., Kemp, M. and Boynton, W., 1993. Predictability, scale, and biodiversity in coastal and estuarine ecosystems: Implications for management. Ambio, 22:88-96.

Cox, D.J., 1990. The art of scientific visualization. Academic Computing, 46:20-56

CSIRO, 1994. The Catchment Management Support System. Demo program. CSIRO, Sydney, Australia.

Da Costa, J.R., Lacerda, M. and Jesus, H.B., 1995. The Portuguese water resources information system: Using OOP to integrate time series and GIS. Proceedings of the ESRI Users Conference 1995. http://www.esri.com/users/

Davies, J.R., Abel, D.J., Zhou, D. and Kilby, P. (1994). HYDRA: A Generic Design for Integrating Catchment Models. In Press: ASCE J. Water Resources Planning and Mgmt.

Davis, J.R., Abel, D.J., Zhou, D. and Kilby, P., 1994. HYDRA: A generic design for integrating catchment models. Draft of paper submitted to ASCE Journal of Water Resources Planning and Management.

Davis, J.R., Nanninga, P.M., Hoare, J.R.L. and Press, A.J., 1989. Transferring scientific knowledge to natural resource managers using artificial intelligence techniques. Ecological Modelling, 46:73-89.

Deacon, A., 1997. Personal Communication, National Parks Board, Skukuza.

Dent, M.C., 1996. Individual and Organisational Behavioural Issues Relating to Water Resources Simulation Modelling and its Role in Integrated Catchment Management in Southern Africa. Unpublished MBL thesis, University of South Africa, Pretoria.

Dillaha, T.A., 1990. Role of Best management practices in restoring the health of the Chesapeake Bay. CBP/TRS41/90, Chesapeake Bay Program, USEPA, WASHINGTON, DC.

Donigian, A. S. and Crawford, N. H., 1976. Modeling pesticides and nutrients on agricultural lands. EPA-600/3-76-043. Environmental Research Lab., Athens, Ga, USA.

Donigian, A.S., Bicknell, B.R., Patwardhan, A.S., Linker, L.C., Alegre, D.Y., Chang, C. Reynolds, R. and Carsel, R., 1991. Chesapeake Bay Program. Watershed model application to calculate bay nutrient loadings. U.S. Environmental Protection Agency, Annapolis, Maryland.

Dooge, J. C., 1986. Looking for hydrologic laws. Water Resources Research, 22:46S-58S.

Doolan, J.M., Grayson, R.B. and LLoyd, L., 1993. The use of AEAM in catchment assessment and planning. Unreferenced paper.

Dubayah, R., 1996. The tyranny of scale and the multifractal paradigm. Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling, National Center for Geographic Information and Analysis, Sante Fe.

DWAF and WRC, 1998. A Strategic Plan For The Department Of Water Affairs And Forestry To Facilitate The Implementation Of Catchment Management In South Africa. Water Research Commission, Pretoria.

DWAF, 1996. The Philosophy and Practice of Integrated Catchment Management: Implications for Water Resources Management in South Africa. WRC Report TT 81/96 Water Research Commission, Pretoria.

DWAF, 1997. A white paper on a national water policy for South Africa. Department of Water Affairs and Forestry, Pretoria.

DWAF, 1998. National Water Bill - Eighth Draft. Department of Water Affairs and Forestry, Pretoria.

Fedra, K., 1995. Decision support for natural resources management: Models, GIS and expert systems. AI Applications, 9(3):3-19.

FEMAT, 1993. Forest ecosystem management: an ecological, economic, and social assessment. Report of the Forest Ecosystem Management Assessment Team, pp. I-1 to I-3.

Fitzsimmons, A.K., 1994. Federal Ecosystem Management: A "Train Wreck" In The Making. Policy Analysis No. 217. http://www.cato.org.

Fitzsimmons, A.K., 1996. Sound policy or smoke and mirrors: Does ecosystem management make sense? Water Resources Bulletin, 32(2): 217-227.

Flügel, W.A., 1995. Delineating Hydrological Response Units, HRU's, by GIS analysis for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. Hydrological Processes, 9:423 – 436.

Frissell, C.A., Liss, W.J., Warren, C.E. and Hurley, M.D., 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management, 10(2):199-214.

Gan, K.C. and McMahon, T.A., 1990. Comparison of two computer models for assessing environmental flow requirements. Report to Dept. of Water Resources, Victoria.

Gardner, R.H., and O'Neill, R.V., 1991. Pattern, process, and predictability: the use of neutral models for landscape analysis. In: Turner, M.G. and Gardner, R.H. [eds.] Quantitative methods in landscape ecology. Springer-Verlag, New York.

Gell-Mann, M., 1994. The Quark and the Jaguar: Adventures in the Simple and the Complex. Little, Brown and Co. London.

Geoffrion, A.M., 1996. Integrated modeling systems. Computer Science in Economics and Management, 2:1, 3-15.

Giller, P.S., Hilldrew, A.G. and Raffaelli, D.G., 1994. Aquatic Ecology: Scale, Pattern and Process. Blackwell Scientific Publications.

Glover, J. and McCulloch, J.S.G., 1958. The empirical relationship between solar radiation and the hours of sunshine. . Quart. Journal of the Royal Meterological Society, 84:172-175.

Goodrich, S., 1996. Ecosystem management or an ecological approach to management and rangeland condition. Watershed Management Council Newsletter 5,3. Spring 1996. http://glinda.cnrs.humboldt.edu/wmc/news/wmcnews.htm

Görgens, A.H.M., 1992. Salinity management and planning in a South African irrigation scheme by use of decision support software. Proceedings of the HYDROCOMP '92 Conference, May 1992, Budapest, pp 123 -132.

Görgens, A.H.M., 1994. An Integrated Modelling System for the Sabie River. Research Proposal to the KNPRRP, Water Research Commission, Pretoria.

Gould, S.J., 1994. The Golden Rule: A proper scale for our environmental crisis. In: Eight Little Piggies, Penguin Books.

Grayson R.B. and Doolan, J.M., 1995. Adaptive environmental assessment and management, AEAM and integrated catchment management. Occasional Paper 1/95. LWRRDC, Canberra.

Grayson, R.B., Doolan, J.M. and Blake, T., 1994. Application of AEAM to Water Quality Management in the Latrobe River Catchment. J. of Env. Mgmt. 41: 00

Grayson, R.B., Moore, I.D. and McMahon, T.C., 1992. Physically based hydrological modelling: Is the concept realistic? Water Resources Research, 28: 2639-2658.

Greyling, A.J., 1996. Personal Communication. Ninham Shand Inc. Cape Town.

Haagsma, I.G. and Johanns, R.D., 1994. The interaction of ground water and surface water studied by loosely coupled models. In: Water Down Under 94, 25th Congress of The International Association of Hydrogeologists / Internationial Hydrology & Water Resources Symposium of The Institution Engineers, Australia, Nov. 21-24 1994, Vol. 2 part A pp 93-98, Adelaide.

Harris, G.P., 1994. Pattern, process and prediction in aquatic ecology: A limnological view of some general ecological problems. Freshwater Biology, 32:143-160.

Harris, G.P., 1996. Process, pattern and prediction in aquatic ecology. Seminar presented to the CSIRO Division of Fisheries, Canberra. Http://www.ml.csiro.au/~bradford/public/GHAbstract.html

Harvey, L.E., 1996. Macroecological studies of species composition, habitat and biodiversity using GIS and canonical correspondence analysis. Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling National Center for Geographic Information and Analysis, Sante Fe.

Haufler, J.B., Wilcove, D., Crowe, T., Guustafson, G. and Duppon, D., 1997. Scale phenomena, toward a scientific and social framework for ecologically based stewardship of federal lands and waters. Draft Paper from the Ecological Stewardship Workshop, USDA Forest Service.

Heritage, G.L. and Van Niekerk, A.W., 1994. Morphological response of the Sabie River to changing flow and sediment regimes, In: Proceedings of the 50 Years of Water Engineering in South Africa SAICE, Johannesburg, pp389-402.

Heritage, G.L., Broadhurst, L.J., Van Niekerk, A.W. and Rogers, K.H, in press. The Definition of Representative River Reaches, Draft Report to the Water Research Commission, Pretoria.

Heritage, G.L., Jewitt, G.P.W, Van Niekerk, A.W. and Birkhead, A.L., 1998. The Geomorphology Model. In: Jewitt, G.P.W., Heritage, G.L., Weeks, D.C., Mackenzie, J.A., Van Niekerk, A., Görgens, A.H.M., O'Keeffe, J., Rogers, K. and Horn, M., 1998. Modelling Abiotic-Biotic Links in the Sabie River. WRC Report No. 777/1/98, Water Research Commission, Pretoria.

Heritage, G.L., Van Niekerk, A.W. and Weeks, D., 1996. A model of fish assemblage response to hydraulic and fluvial geomorphological change in a pool-rapid channel type. In: Leclerc, M., Capra, H., Valentin, S., Bordreault, A. and Cote, Y. [eds.] Proceedings of the Second IAHR Symposium on Habitat Hydraulics, Ecohydraulics 2000, pp A355-A366.

Holling, C.S. (ed.), 1978. Adaptive Environmental Assessment and Management. Wiley IIASA International Series on Applied Systems Analysis. John Wiley and Sons, New York.

Holling, C.S., 1976. *Adaptive Environmental Assessment and Management.* Chichester. J. Whiley and sons.

Horn, M., 1997. Personal Communication. Computing Centre for Water Research, University of Natal, Pietermaritzburg.

Hughes, D.A., 1984a. HYMAS v1.0: A Hydrological Modelling Application System: Guide to System and User Manual. Water Research Commission, Pretoria, 80 pp.

Hughes, D.A., 1984b. An isolated event model based upon direct runoff calculations using an implicit source area concept. Hydrological Sciences Journal, 29(3): 311-325.

Hughes, D.A., 1989. Estimation of the parameters of an isolated event conceptual model from physical catchment characteristics. Hydrological Sciences Journal, 34(5): 539-557.

Hughes, D.A., 1995. Personal Communication. Institute of Water Research, Rhodes University, Grahamstown.

Hughes, D.A. and Sami, K., 1994. A semi-distributed, variable time interval model of catchment hydrology - structure and parameter estimation procedures. Journal of Hydrology, 155:265-291.

Hydraulic Engineering Centre, 1977. Scour and deposition in rivers and reservoirs: HEC 6. US Army Corps of Engineers, Davis, California.

IMLAB, 1996. SmartForest: An interactive forest data modeling and visualization tool. Http://imlab9.landarch.uiuc.edu/smartforest/

Isaacs, E.H. and Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, Oxford.

IUCN, 1980. World Conservation Strategy. Gland : IUCN/UNEP/WWF

James, W.J., 1997. Rules for responsible modelling. Unpublished Paper.

Jensen, M.E., Bourgeron, P., Everett, R. and Goodman, I., 1996. Ecosystem management: A landscape ecology perspective. Water Resources Bulletin, 32(2): 203-216.

Jewitt, G.P.W. and Görgens, A.H.M., 1995. Integration of multi-disciplinary predictive tools for management of the rivers of the Kruger National Park - South Africa. In: Proceedings Of The Third Modsim Conference Dec. 4-6, University Of Newcastle, Newcastle.

Jewitt, G.P.W., Heritage, G.L., Weeks, D.C., Mackenzie, J.A., Van Niekerk, A., Görgens, A.H.M., O'Keeffe, J., Rogers, K. and Horn, M., 1998. Modelling Abiotic-Biotic Links in the Sabie River. WRC Report No. 777/1/98, Water Research Commission, Pretoria.

Jewitt, G.P.W., Horn, M., Dent, M.C. and Görgens A.H.M., 1997a. An integrated catchment information system for southern African Rivers. In: Proceedings of the Eighth South African National Hydrological Symposium, Nov. 17-19, 1997, Water Research Commission, Pretoria.

Jewitt, G.P.W., Weeks, D., Heritage, G., Görgens, A.H.M. and O'Keeffe, J., 1997b. The ecological significance of floods in the Sabie River, South Africa: A simulation exercise. In: Proceedings of the Third International Conference on River Flood Hydraulics, Nov. 5-7, University of Stellenbosch, Stellenbosch.

Johansson, R. C., 1995. Personal Communication. c/o Computing Centre for Water Research, Pietermaritzburg.

Johnston, J.M. and Novak, J.H., 1997. A Community Basis for Complex System Modeling: Evolution and Involvement Using Problem Solving Environments, U.S. Department of Commerce.

Kay, J.F., 1993. On the nature of ecological integrity: some closing comments. In: Woodley, S.; Kay, J.F., Francis, G. [eds.] Ecological Integrity and the Management of Ecosystems. St. Lucie Press, Delray, Florida. pp201-210.

King, J.M. and Tharme, R.E., 1993a. River ecologists need hydrological information for assessing environmental water allocations, but what form should it take and why? In: Proceedings of the Sixth South African National Hydrological Symposium. Sept. 8-10, 1993, University of Natal, Pietermaritzburg.

King, J.M. and Tharme, R.E., 1993b. Assessment of the instream flow incremental methodology and initial development of alternative instream flow methodologies for South Africa. WRC Report 295/1/94, Water Research Commission, Pretoria.

Kirmani, S.S. and Le Moigne, G., 1996. Fostering Riparian Cooperation in International River Basins: The World Bank at its Best in Development Diplomacy. World Bank, Washington, D.C.

Kittle, J.L., Flynn, K.M., Hummel, P.R. and Lumb, A.M., 1991. Programmers manual for the Watershed Data Management (WDM) System. USGS Water Resources Investigations Report 91-draft. Reston.

Klêmes V., 1983. Conceptualization and scale in hydrology. Journal of Hydrology, 65:1-23.

Kolasa, J., 1989. Ecological systems in hierarchical perspective: Breaks in the community structure and other consequences. Ecology, 70:36-47.

Kotliar, N.B. and Wiens, J.A. 1990. Multiple scales of patchiness and patch structure: A hierarchical framework for the study of heterogeneity. Oikos, 59:253-260.

Lam, D. C. L., and Swayne, D.A., 1993. An expert system approach of integrating hydrological database, models and GIS: application of the RAISON System, In: Kovar, K. and Nachtnebel, H.P. [eds.] Application of Geographic Information Systems in Hydrology and Water Resources Management, Proceedings of the Vienna conf., April 1993, IAHS Publ. No. 211, pp. 23-34.

Larson, S. M., Cass, G. R., Hussey, K. J., and Luce, F., 1988. Verification of image processing based visibility models. Environmental Science and Technology, 22(6): 629-637.

Lawton, J.H., 1987. Problems of scale in ecology. Nature, 325:206.

Leavesley, G.H., Restrepo, P.G., Stannard. L.G. and Dixon, M.J., 1994. The Modular Modeling System, MMS. - A modelling framework for multidisciplinary research. Unpublished paper. USGS, Denver.

Levin, S.A., 1992. The problem of pattern and scale in ecology. Ecology, 73(6):1943-1967.

Loh, D.K. and Rykiel, E.J., 1992. Integrating resource management systems: coupling expert systems with data-base management and geographic information systems. Environmental Management, 16:167-177.

Loucks, D.P., Kindler, J. and Fedra, K., 1985. Interactive water resources modeling and model use: An overview. Water Resources Research 21(2): 95-102.

Maaren, H. and Dent, M.C., 1995. Broadening participation in integrated catchment management for sustainable water resources development. Proceedings IAWQ Conference on River basin management for sustainable development, Kruger National Park, South Africa. ISBN 0-7970-3155-3.

Mackenzie, J.A., 1998. Personal Communication, Centre for Water in the Environment, University of the Witwatersrand, Johannesburg.

Mackenzie, J.A., Jewitt, G.P.W, Heritage, G.L. and Rogers, K.H., 1998. The Riparian Vegetation Model. In: Jewitt, G.P.W., Heritage, G.L., Weeks, D.C., Mackenzie, J.A., Van Niekerk, A., Görgens, A.H.M., O'Keeffe, J., Rogers, K. and Horn, M., 1998. Modelling Abiotic-Biotic Links in the Sabie River. WRC Report No. 777/1/98, Water Research Commission, Pretoria.

Maidment, D.R., Olivera, J.F., Calver, A. Eatherral, A. and Fraczek, W., 1996. A unit hydrograph derived from a spatially distributed velocity field. Hydrologic Processes, 10(6):831-844.

Mandelbrot, B.B. 1977. Fractals. Form, chance and dimension. W.H. Freeman and Co., San Francisco, CA.

Mandelbrot, B.B. 1983. The Fractal Geometry of Nature. W.H. Freeman and Co., San Francisco, CA.

Mason, S.J., 1995. Climate change over the low Veld of South Africa. Climatic Change, 32(1):35-49.

Maxwell, T. and Costanza, R., 1996. Facilitating High Performance, Collaborative Spatial Modelling. http://kabir.umd.edu/SMP/ecohpc.html

Meentemeyer, V., 1989. Geographical perspectives of space, time and scale. Landscape Ecology, 3:3-4.

Meyer, G. and Scholes, R. J., 1994. Development of an Integrated Catchment Management System for the Crocodile Catchment. Draft report to WRC.

Midgley, D.C., Pitman, W.V. and Middleton, B.J., 1994. Surface Water Resources of South Africa 1990. WRC Report Nos 298/1/94 to 298/6.2/94, Water Research Commission, Pretoria.

Milne, B.T. 1992. Spatial aggregation and neutral models in fractal landscapes. American Naturalist, 139:32-57.

Mitchell, P., 1990. The environmental condition of Victorian streams. Dept. of Water Resources, Victoria.

Mitchell, B. and Hollick, M., 1993. Integrated catchment management in Western Australia: Transition from concept to implementation. Environmental Management 17(6):735-743.

Nicolson, C.R. and James, C.S., 1995. A qualitative approach to river process modeling In: Proceedings of the Seventh South African National Hydrology Symposium, Rhodes University, Grahamstown.

Niu, W., Lu, J.J. and Abdullah, A.K., 1993. Spatial systems approach to sustainable development: A conceptual framework. Environmental Management, 17(2):179-186.

Norberg, J. and Elmgrin, G., 1996. Scale dependencies on ecological process and pattern. http://www.ecology.su.se/norfa.htm

NPB, 1997. The Sabie River in the Kruger Park under threat. South African Nature Conservation Services. Pretoria.

O'Keeffe, J.H., 1995. Abiotic-Biotic links in the Sabie River: The consequences of changing hydrology, geomorphology and water quality on the riverine biota. Research proposal by the KNPRRP to the Water Research Commission, Pretoria.

O'Keeffe, J.H., Weeks, D.C., Fourie, A. and Davies, B.R., 1996. A Pre-impoundment study of the Sabie-Sand River System, Mpumulanga with special reference to predicted impacts on the Kruger National Park. Volume 3: The effects of proposed impoundments and management recommendations. WRC Report No 294/3/96. Water Research Commission, Pretoria.

O'Neill, R.V., Johnson, A.R. and King, A.W., 1989. A hierarchical framework for the analysis of scale. Landscape Ecology, 3:193-205.

O'Neill, R.V., DeAngelis, D.L., Waide, J.L.B. and Allen, T.F.H., 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton, New Jersey.

Onstad, D.W., 1988. Population dynamics theory: The roles of analytical, simulation and supercomputer models. Ecological Modelling, 43:111-124.

Oreskes, N., Schrader-Frechette, K.S. and Belitz, K., 1994. Verification, validation and confirmation of numerical models in the earth sciences. Science, 263(4): 641-646.

Orland, B. and Daniel, T.C., 1995. Impact of proposed water withdrawals on the perceived scenic beauty of desert springs and wetlands: Image generation. http://imlab3.landarch.uiuc.edu/projects/desertspr/more.desertspr.html.

Palmer, R.N., Keyes, A.M. and Fisher, S., 1993. Empowering stakeholders through simulation in water resources planning. In: Hon, K. [ed.] Water Management for the '90s. ASCE, Seattle.

Pattern, B.C., 1994. Ecological systems engineering: Toward integrated management of natural and human complexity in the ecosphere. Ecological Modelling, 75/76: 653-665.

Pegram, G.C, Görgens, A.H.M and Otterman, A.B., 1997., A framework for addressing the information needs of catchment water quality management. Water SA, 23(1): 25-38.

Pike, A.P., Schulze, R.E., Lorentz, S.A., Ballim, F., Taylor, V. and Howes, B., 1997. Simulation of streamflows and sediment yields in the Sand and Sabie catchments: initial results. Report to the KNPRRP, Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Pitman, W.V., 1973. A mathematical model for generating monthly river flows from meteorological data in South Africa. Hydrological Research Unit Report 2/73. University of Witwatersrand, Johannesburg

Punnet, R.E. and Stiles, J.M., 1993. Bringing people, policies and computers to the water bargaining table. In: Hon, K [ed.] Water Management for the '90s. ASCE, Seattle.

Ramsey, R.D., Patraw, K., Biggs, B., Falconer, B., Van Neil, T., Halisky, M., Spencer, R., 1995. GIS for environmental management: A hierarchical database structure. Proceedings of the ESRI Users Conference 1995. http://www.esri.com/users/

Rastetter, E.B., King, A.W., Cosby, B.J., Hornberger, G.M., O'Neill, R.V., and Hobbie, J.E. 1992. Aggregating fine-scale ecological knowledge to model coarser-scale attributes of ecosystems. Ecological Applications, 2(1): 55-70.

Reid, L.M., and Ziemer, R.R., 1997, Basin assessment and watershed analysis. In: L. M. Reid, [ed.] Issues in watershed analysis. PSW General Technical Report. USDA Forest Service Pacific Southwest Research Station, Redwood Sciences Laboratory, Arcat, CA.

Reitsma, R.F. and Carron, J.C., 1997. Object-oriented simulation and evaluation of river basin operations. Journal of Geographic Information and Decision Analysis, 1(1):9-24.

Resh, V.H. 1979. Sampling variability and life history features: Basic consideration in the design of aquatic insect studies. Journal of the Fisheries Research Board of Canada 36:290-311.

Reynolds, K., Saunders, M., Olson, R., Miller, B., Latham, D., Foster, M., Schmoldt, D., Steffenson, J., Cunningham, P., Bednar, L., 1996. Knowledge-based information management for watershed analysis in the Pacific Northwest U.S. AI Applications, 10(2).

Rodriguez-Iturbe I. and Gupta, T.C., 1983. Special Issue "Scale Problems in Hydrology". Journal of Hydrology, 65: 400pp

Rogers, K.H. and Besttbier, R., 1997. Development of a protocol for the definition of the desired state for riverine systems in South Africa. Dept. of Environmental Affairs and Tourism, Pretoria.

Rogers, K.H., 1997. Operationalising ecology under a new paradigm. In: Picket, S.T.A., Ostfeld, R.S., Shachak, M. and Likens, G.E. [eds.] Enhancing the Ecological Basis of Conservation: Heterogeneity, Ecosystem Function and Biodiversity. Chapman and Hall, New York. Pp 60-77.

Rooseboom, A., Verster, E., Zietsman, H. L. and Lotriet, H. H., 1992. The Development of the New Sediment Yield Map of Southern Africa. WRC Report No. 297/2/92. Water Research Commission, Pretoria.

Runkel, R.L. and Restrepo, P.J., 1993. Solute transport modelling under unsteady flow regimes: An application of the Modular Modelling System. Paper presented at the ..

Russell, I.A. and Rogers, K.H., 1989. The distribution and composition of fish communities in the major rivers of the Kruger National Park. In: Proceedings of the Fourth South African National Hydrological Symposium Nov., 20-22 1989, University of Pretoria, Pretoria.

Schenk, G., 1996. Personal Communication. Chesapeake Bay Programme, Annapolis.

Schrader-Frechette, K.S. and McCoy, E.D., 1994. What ecology can do for environmental management. Journal of Environmental Management, 41: 293-304,

Schulze, R.E., 1995. Hydrology, agrohydrology and agrohydrological simulation modelling. In: Schulze, R.E. Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. WRC Pretoria, Report TT69/95, Water Research Commission, Pretoria.

Senge, P., and Lannon-Kim, C., 1991. The Systems Thinker Newsletter, V.2, N.5. P.O. Box 1281, Kendall Square, Cambridge, MA.

Senge, P.M., 1990. The Fifth Discipline: The Art and Practice of the learning Organization. Doubleday/Currency, New York.

Shields, F.D. and Milhous, R.T., 1992. Sediment and aquatic habitat in river systems. Journal of Hydraulic Engineering, 118(5): 669-687.

Silvert, W., 1993a. Object-oriented ecosystem modeling. Ecological Modelling, 68:91-118.

Silvert W., 1993b. The distributed derivative: an aid to modular modeling. Ecological Modelling, 68:293-302.

Smithers J. and Schulze R.E., 1995. ACRU Agrohydrological Modelling System User Manual. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Starfield, A.M., 1996. A pragmatic approach to modelling for wildlife management. Unpublished paper.

Starfield, A.M., Cumming, D.H.M., Taylor, R.D. and Quadling, M.S., 1993. A frame-based paradigm for dynamic ecosystem models. AI Applications in Nat. Res. Management, 7(2&3):1-13.

Starfield, A.M., Smith, K.A. and Bleloch, A.L., 1990. How to Model it: Problem Solving for the Computer Age. McGgraw-Hill Publishing Company. New York.

Tharme, R.E., 1997. Sabie-Sand River System. Instream Flow Requirements. Proceedings of IFR Workshop. Draft report to the Department of Water Affairs and Forestry. Freshwater Research Unit, University of Cape Town, Cape Town.

Thiessen, E.M. and Loucks, D.P., 1992. Computer assisted negotiation of multiobjective water resources conflicts. Water Resources Bulletin, 28:163-177.

Thoms, M.L., James, C.S., Moon, B.P. and Rogers, K.H., 1990. Environmental Problems in South African Rivers: The Need for Expertise in Fluvial Geomorphology. Contract report, Water Expertise in Fluvial Geomorphology. Contract report, Water Research Commission, Pretoria.

Turner, M.G., and Gardner, R.H. [eds.], 1991. Quantitative methods in landscape ecology. Springer-Verlag, New York.

Tyson, P. D., 1987. Climatic change and variability in southern Africa Oxford University Press, Cape Town

USDA, 1996. A national framework: Ecosystem management. Program Aid 1502. U.S.Department of Agriculture, Forest Service. Washington DC.

USGS, 1995. United States Geological Survey, River Systems Management Section. Http://www.mesc.usgs.gov

USNPS, 1994. United States National Parks Service, Water Resources Division. http://www.aqd.nps.gov/natnet/wrd/wrd.htm

Van Coller, A.L. And Rogers, K.H, 1995. Riparian Vegetation on the Sabie River: Relating Spatial Distribution Patterns to Characteristics of the Physical Environment. Centre for Water in the Environment Report No 1/95. University of the Witwatersrand, Johannesburg.

Van Coller, A.L. And Rogers, K.H, 1996. A Basis for Determining the Instream Flow Requirements of the Riparian Vegetation along the Sabie River within the Kruger National Park. Centre for Water in the Environment Report No 2/96. University of the Witwatersrand, Johannesburg.

Van Coller, A.L., Heritage, G.L. and Rogers,K. H., 1995. Linking riparian vegetation distribution and flow regime of the Sabie River through fluvial geomorphology. Proceedings of the Seventh South African National Hydrology Symposium, Rhodes University, Grahamstown.

Van Niekerk, A.W. and Heritage,G. L., 1993. Geomorphology of the Sabie River: Overview and classification, Centre for Water in the Environment Report No: 2/93 University of the Witwatersrand, Johannesburg 257-71

Van Niekerk, A.W., Heritage, G.L. and Moon, B.P., 1995. River classification for management: the geomorphology of the Sabie River. South African Geographical Journal, 77(2):68-76.

Van Rensburg J.D. Janse and Dent, M.C., 1997. Development of a water quality and quantity modelling system which will provide a common currency for communication between researchers in the Kruger National Park Rivers Research Programme. Department of Landscape Architecture, University of Pretoria. Water Research Commission Report, Pretoria.

Voinov, A. and Costanza, R., 1998. Watershed Management over the Web In: Fishwick, P., Hill, D. and Smith, R. [eds.] Proceedings of the 1998 Conference on Web-based Modeling and Simulation, San-Diego.

Wadeson, R.A., 1994. Geomorphological approach to instream flow environment. South African Journal of Aquatic Science, 20: 38-61

Walters, C., 1986. *Adaptive Management of Renewable Resources.* New York. Macmillan.

Waltho, N. and Kolasa, J., 1994. Organization of instabilities in multispecies systems: a test of hierarchy theory. Proc. National Academy of Science 91:1682-1685.

Weeks, D.C., Jewitt, G.P.W., Heritage, G.H., Van Niekerk, A.W., O'Keeffe, J., and Horn, M., 1998. The Kruger National Park Rivers Research Programme Lowveld Fish Model. In: Jewitt, G.P.W., Heritage, G.L., Weeks, D.C., Mackenzie, J.A., Van Niekerk, A., Görgens, A.H.M., O'Keeffe, J., Rogers, K. and Horn, M., 1998. Modelling Abiotic-Biotic Links in the Sabie River. WRC Report No. 777/1/98, Water Research Commission, Pretoria.

Weeks, D.C., O'Keeffe, J.H., Fourie, A., and Davies, B.R., 1996. A pre-impoundment study of the Sabie-Sand River system, eastern Transvaal with special reference to predicted impacts on the Kruger National Park. Volume 1: The ecological status of the Sabie- Sand river system. WRC report 294/1/96, Water Research Commission, Pretoria.

Wiens, J.A., Crawford, C.S and Gosz, J.R., 1985. Boundary dynamics: a conceptual framework for studying landscape ecosystems. Oikos, 45:421-427.

Wiens J.A., 1989. Spatial scaling in ecology. Functional Ecology, 3: 385-397.

Wiens, J.A. 1997. Scientific responsibility and responsible ecology. Conservation Ecology. [online]1(1): 16. http://www.consecol.org/vol1/iss1/art16

Wiens, J.A., 1992. Commentary on Ecology 2000: An essay on future directions in ecology. Ecology Society Of America Bulletin, 73(3):165-170.

WMC, 1996. Watershed Management Council Newsletter 7(2): Summer 1996. http://glinda.cnrs.humboldt.edu/wmc/news/wmcnews.htm

Wohl, E. E., 1992. Bedrock benches and boulder bars: Floods in the Burdekin Gorge of Australia. Geological Society of America Bulletin, 104: 770-778.

Yin Y. and Pierce, J.T., 1993. Integrated resource assessment and sustainable land use. Environmental Management, 17(3): 319-327.

Young, W.J. Personal Communication. CSIRO Division of Water Resources, Canberra.

Young, W.J., Davis, J.R., Bowmer, K.H. and Fairweather, P.G., 1995. The Feasibility of a Decision Support System for Environmental Flows. CSIRO Consultancy Report No. 95/19, Murray-Darling Basis Commission, Canberra.

Young, W.J. and Davis, J.R., 1995. Proposed environmental flows decision support system. In: Proceedings of the Third MODSIM Conference Dec. 4-6, University of Newcastle, Newcastle.

Zeigler, B.P., 1976. Theory of Modelling and Simulation. John Wiley, New York.

SIMULATION OF STREAMFLOWS AND SEDIMENT YIELDS IN THE SAND AND SABIE CATCHMENTS : INITIAL RESULTS

Report to Kruger National Park Rivers Research Programme (KNPRRP)

***ACRU*cons Report 17**
May 1997

A Pike, RE Schulze, SA Lorentz, F Ballim, V Taylor and BJ Howe

Department of Agricultural Engineering
University of Natal
Pietermaritzburg

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Report to Kruger National Park Rivers Research Programme (KNPRRP)

May 1997

Andrew Pike, Roland Schulze, Simon Lorentz, Faeeza Ballim, Valerie Taylor and Brad Howe

Department of Agricultural Engineering
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Pietermaritzburg

BACKGROUND

The Department of Agricultural Engineering at the University of Natal was commissioned by NSI on behalf of the Kruger National Park Rivers Research Programme (KNPRRP) to undertake a hydrological simulation of the steamflows and sediment yields of the Sand and Sabie catchments in Mpumalanga (hereafter referred to as the KNPRRP water resources study), using the *ACRU* modelling system. These catchments comprise 25 Department of Water Affairs and Forestry Quaternary Catchments, nine making up the Sand River catchment and 16 making up the Sabie River catchment, all within the borders of South Africa.

The findings of this study are presented in the form of an Executive Summary comprising of brief descriptions of the procedures followed, together with maps of relevant information and graphical representations of results. Tables of model input data and more detailed descriptions of procedures have been included in Appendices to this report.

OBJECTIVES OF THE KNPRRP WATER RESOURCES STUDY

The overall objectives of the water resources study were to simulate, in a scientifically objective and transparent manner, and using state-of-the-art modelling techniques, the streamflows and sediment yields under present land use conditions of the Sand and Sabie catchments within the borders of South Africa. This required daily flow sequences to be estimated at predetermined locations within the Sand and Sabie catchments and an assessment to be made on where within these catchments streamflow and sediments are generated, in terms of both magnitude and seasonality.In order to undertake such a simulation, an agrohydrological computer model is used. Such a model requires ***INPUT*** of known, calculable or measurable, factors including information on:

* climate (daily rainfall in different parts of the catchment; temperature, potential evaporation and their variations over the catchment and within seasons)
* soils (spatial variations and distributions of horizon depths; soil water retention constants; drainage characteristics; erodibility indices)
* agricultural land uses (hydrologically relevant above and below ground attributes of, e.g. afforestation, with species distribution and levels of site preparation; commercial crops, with management levels considered; subsistence farming; land cover influences on soil loss)
* other land uses (e.g. hydrological responses characteristics of formal urban areas; informal settlements)
* runoff (stormflow generation mechanisms; baseflow depletion rates; flow attenuating characteristics)
* sediment yield production (daily stormflow generation and associated peak discharges; erodibility indices of soils; land cover, land management and topographic indices)
* dams (capacities; surface areas; releases; abstractions; evaporation rates; storage-surface area relationships)
* irrigation practices (crop type and seasonality, with mode of scheduling, areas, source of water, application efficiencies accounted for)
* other abstractions (e.g. amounts; sources of water; seasonality) and
* inter-basin transfers (from where; to where; amounts; seasonal differences).

This information is ***UTILISED*** in the model by considering

* the climate, soil, vegetative, hydrological, agricultural and human *subsystems* and
* how they *interact* with one another;
* what *thresholds* need to be exceeded for responses to take place
* how the various responses *lag* and are *attenuated* at different rates and
* whether there are *feedforwards* and *feedbacks* which allow the system to respond in a forward or reverse direction.

The model then produces ***OUTPUT*** of the unmeasured variables to be assessed, e.g.

* streamflows (from different parts of the catchment; including stormflow and baseflow on a daily basis; return flows) and low flows
* recharge of water through the soil profile into the subsurface vadoze zone
* reservoir status and
* sediment yield (on an event-by-event basis)

on which risk analyses (month-by-month and annual statistical analysis, including flows under median conditions and for the driest flow in, say, 5 or 10 years; flow variability; low flow analyses), as well as daily flood volume analyses for different recurrence intervals, may be undertaken. Monthly totals of daily streamflows and monthly totals of sediment yields under present land use conditions were considered in this study.

The *ACRU* agrohydrological modelling system (version 325) was selected for this purpose.

THE *ACRU* AGROHYDROLOGICAL SIMULATION MODEL

ACRU is a daily time step, physical-conceptual model revolving around multi-layer soil water budgeting. It is a multi-purpose model (Figure 1) with options to output, *inter alia*, daily values of streamflow, peak discharge, sediment yield, recharge to groundwater through the soil profile, reservoir status, irrigation supply and demand, irrigation and other return flows as well as seasonal crop yields, at any location within the catchment.

The model is structured (Figure 2) to be hydrologically sensitive to catchment land use and changes thereof, including the impacts of commercial and subsistence agriculture, the construction and operation of reservoirs, inter-basin transfers, formal and informal urbanised areas, irrigation practices, river flow abstractions and of afforestation.

To facilitate an analysis of streamflows and sediment yields in response to land use practices the model requires input on location, climate, soils, catchment physiography, land uses, hydrological response parameters, irrigation demand and supply, reservoirs, abstractions and inter-basin transfers.

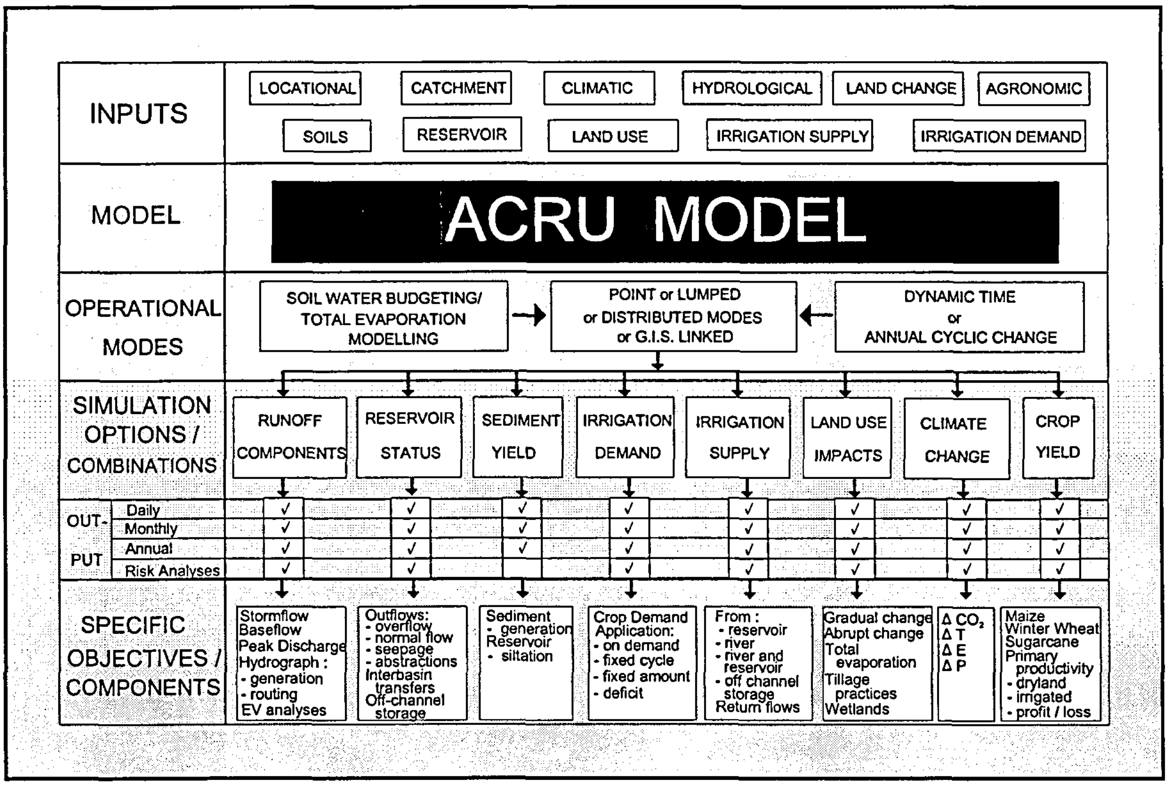


Figure 1 *ACRU* : Concepts of the modelling system (Schulze, 1995)

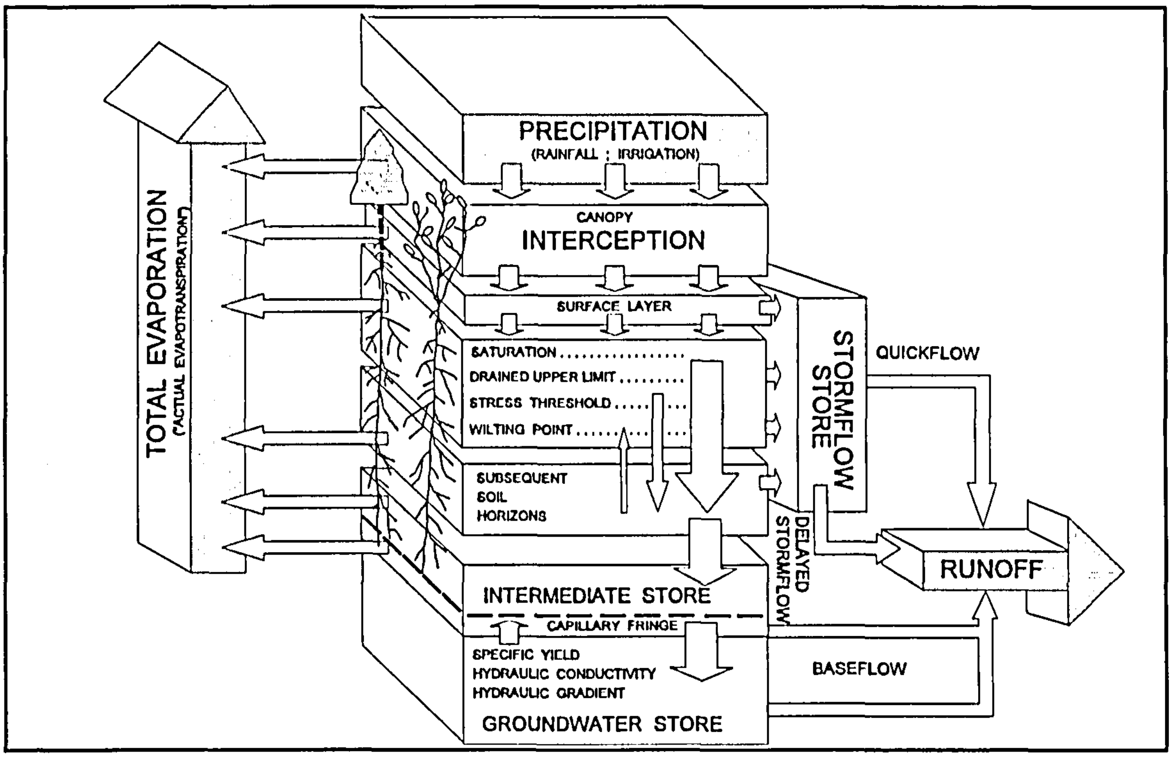


Figure 2 *ACRU*: Model structure (Schulze, 1995)

ACRU MODEL INPUT

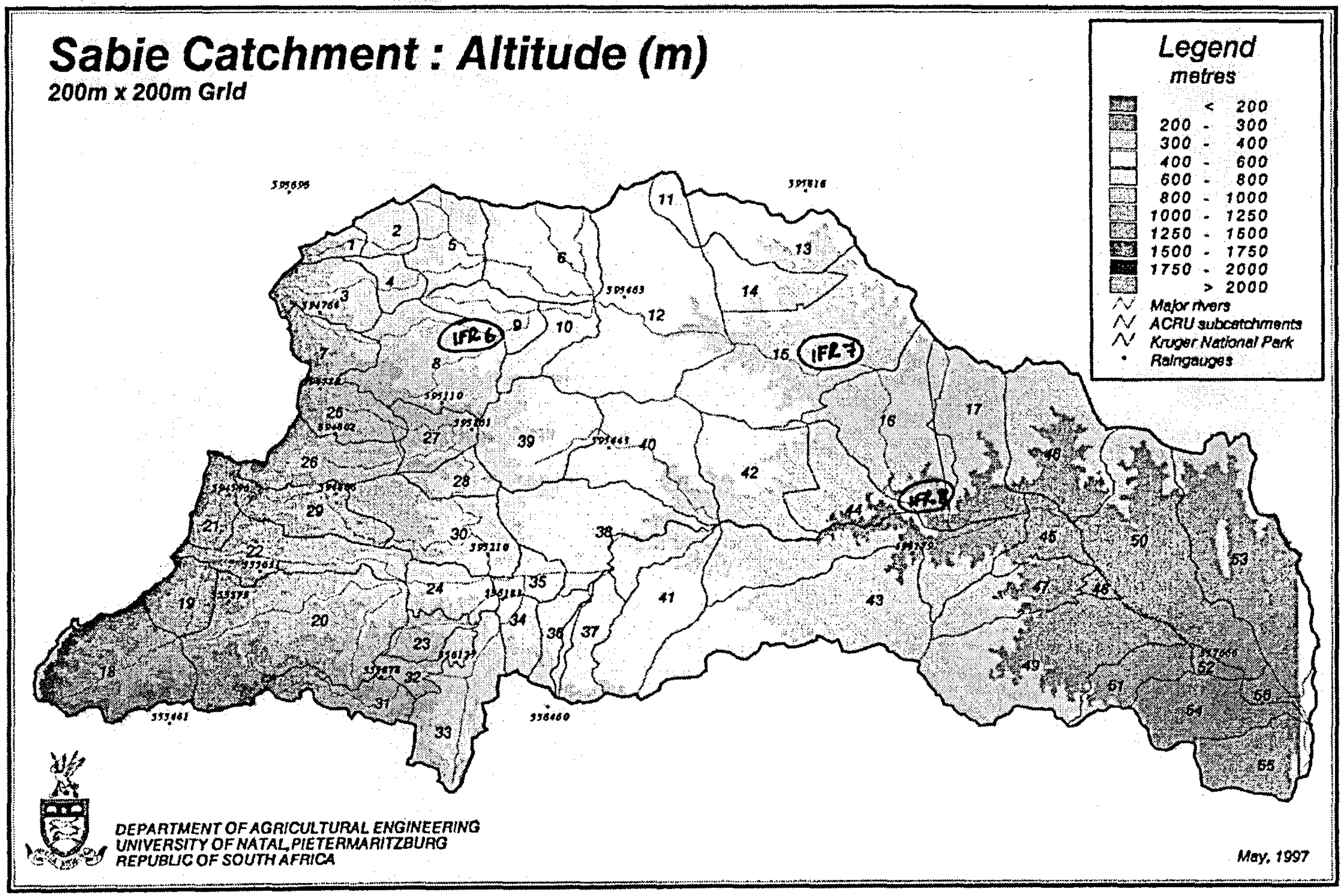
(a) Location

The two catchments as defined for this simulation cover an area of 6260.36 km^2. They are located north of Nelspruit in Mpumalanga in an area which stretches latitudinally from 24°30' to 25°15' S and longitudinally from 30°40' to 32°10' E, while altitudinally the area ranges from 150m in the east to over 1800 m in the west (cf. Figure 3; also Appendix A). The catchments consist of two major river basins, from north to south the

* Sand river basin (1910.02 km^2) made up of Quaternary Catchments X32A to X32J and the
* Sabie river basin (4350.34 km^2) made up of Quaternary Catchments X32A to X32M and below the confluence with the Sand, Quaternary Catchments X33A to X33D (Appendix A).

A dolomitic area runs from north to south through the upper reaches of the Sand and Sabie catchments. Runoff processes associated with Karst Hydrology were expected to dominate the production of streamflows in subcatchments falling within this area.

Figure 3	KNPRRP water resources study : Altitude, Quaternary and subcatchment boundaries and major stream networks


Sabie Catchment : Altitude (m)
200m x 200m Grid
Legend
metres
< 200
200 - 300
300 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1250
1250 - 1500
1500 - 1750
1750 - 2000
> 2000
Major rivers
ACRU subcatchments
Kruger National Park
Raingauges
IFR 6
IFR 7
IFR 8
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May, 1997

(b) Delimitation of the Area into Subcatchments

The 25 Department of Water Affairs and Forestry (DWAF) Quaternary Catchments (QCs) making up the area were selected as the basic spatial units of the Sand and Sabie systems when subdividing them into more homogeneous hydrological regions. Owing to the range of soils, land uses, reservoir locations and climatic variation, the QCs were subdivided into 17 and 39 subcatchments for the Sand and Sabie catchments respectively, with each subcatchment having its own unique climate and other inputs. The delineation of subcatchments was performed on 1:50 000 topographic maps. Area, altitude and rainfall information on the 56 subcatchments (ranging in area from 8.51 to 311.72 km^2) and corresponding DWAF Quaternary Catchment numbers are given in Appendix A. The manner in which the subcatchments are interconnected hydrologically (i.e. configured) is shown in Figures 4, 5 and 6. Coverages of altitude, together with main catchment boundaries and major stream networks, mean annual and median annual rainfall, soils and present land uses are illustrated in Figures 3, 7, 8, 9 and 11 respectively.

Subcatchment mean altitude was derived by averaging grid point values of altitude from the Department of Agricultural Engineering's 1' x 1' of a degree latitude/longitude (i.e. 1.6 x 1.6 km) grid of altitudes for southern Africa.

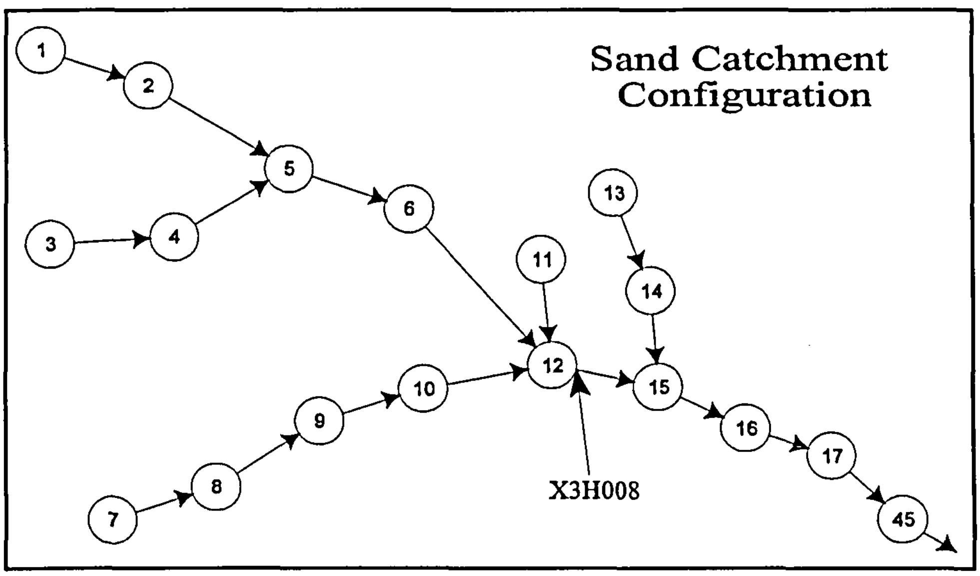


Figure 4 KNPRRP water resources study : Sand catchment configuration

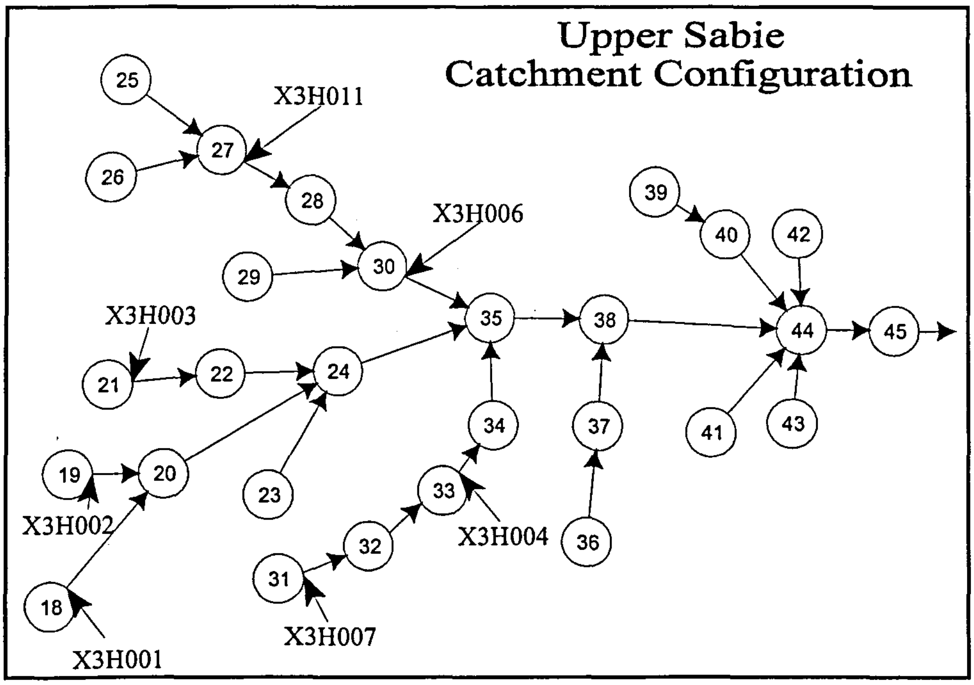


Figure 5 KNPRRP water resources study : Sabie catchment configuration upstream of its confluence with the Sand river

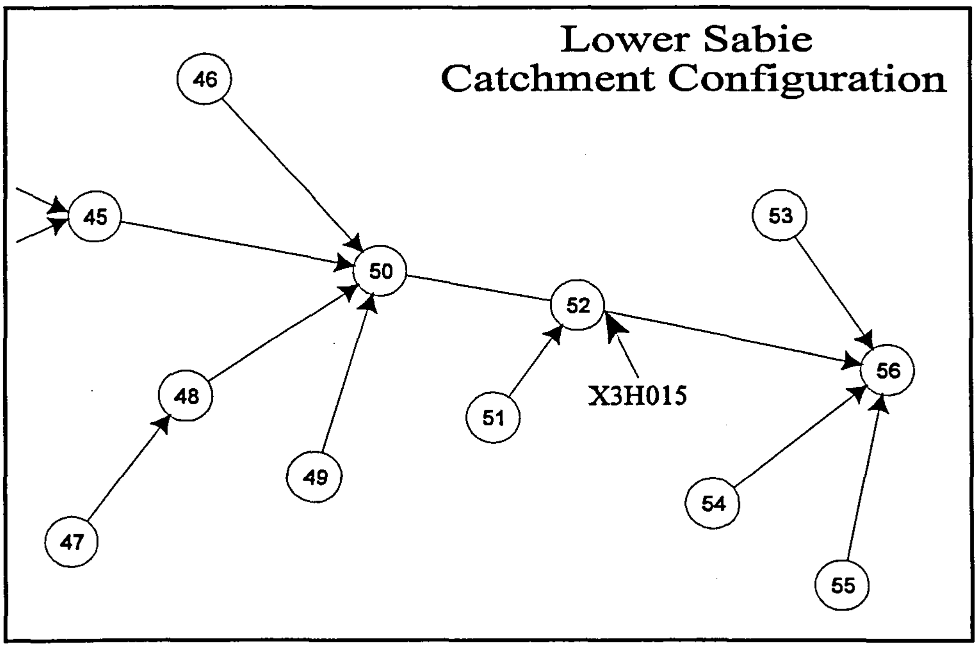


Figure 6 KNPRRP water resources study : Sabie catchment configuration downstream of its confluence with the Sand river

(c) Rainfall

Hydrological responses, in nature and also in a daily model such as *ACRU*, are highly sensitive to rainfall input, with an error in rainfall estimation often resulting in a doubling (or more) of the error in runoff estimation (Schulze, 1995). A major effort was therefore expended in obtaining subcatchment rainfall values which could be considered to be as realistic as possible, both spatially and temporally.

An initial selection of rainfall "driver" stations for each subcatchment identified many stations which did not adequately represent the subcatchments to which they were assigned. It was therefore decided to reassess the availability of daily rainfall records for the entire catchment area.

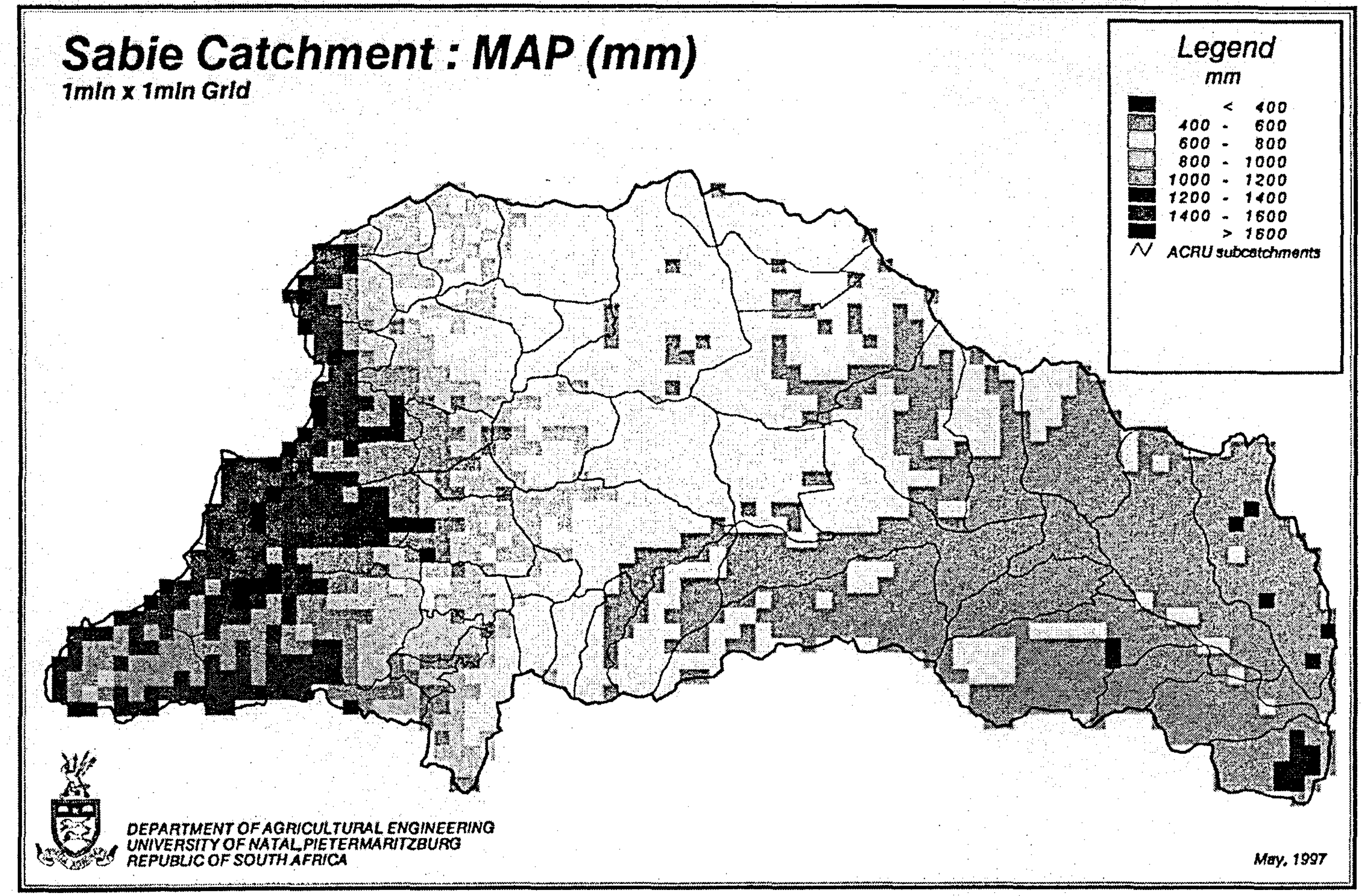
To account for the regional, seasonal and daily diversity of rainfall, rainfall stations with daily data in and immediately adjacent to the study area were extracted from the Computing Centre for Water Research (CCWR) rainfall database. The 21 stations which were finally selected had any missing daily data infilled (patched) for the concurrent period 1 January 1940 to 31 December 1995 using an Inverse Distance Weighting (IDW) technique developed in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg (Appendix B). A precipitation adjustment factor was entered for each subcatchment to account for differences between the subcatchment's rainfall and that of the rainfall station. This adjustment was in the form of a multiplicative correction factor applied to each daily rainfall amount from the driver station for a specific subcatchment to obtain representative daily rainfall values for each of the subcatchments. The adjustment factor was obtained by comparing the median monthly rainfalls for each subcatchment (obtained from the Department of Agricultural Engineering's 1'x1' gridded database) with the median monthly rainfalls from the driver station in each month of the year (Figure 8).

Figure 7	KNPRRP water resources study : 1'x1' latitude and longitude grid interval estimates of Mean Annual Precipitation (mm)

Figure 8	KNPRRP water resources study : 1'x1' latitude and longitude grid interval estimates of Median Monthly Precipitations (mm)

(d) Temperature and Potential Evaporation

ACRU requires monthly mean values of daily maximum and minimum temperatures and monthly totals of A-pan equivalent values as its reference for estimating the potential evaporation, E_r. Month-by-month subcatchment area-weighted values of monthly means of daily maximum and minimum temperatures and mean A-pan equivalent potential evaporation were determined from 1' x 1' of a degree latitude by longitude gridded values using techniques developed by Schulze and Maharaj (1991; revised in 1996). Examples of the range of month-by-month temperature and potential evaporation values in the KNPRRP study area are given in Appendix C. For both temperature and potential evaporation values there are significant spatial variations within the Sand-Sabie catchment on a month-by-month basis.


Sabie Catchment : MAP (mm)
1min x 1min Grid
Legend
mm
< 400
400 - 600
600 - 800
800 - 1000
1000 - 1200
1200 - 1400
1400 - 1600
> 1600
ACRU subcatchments
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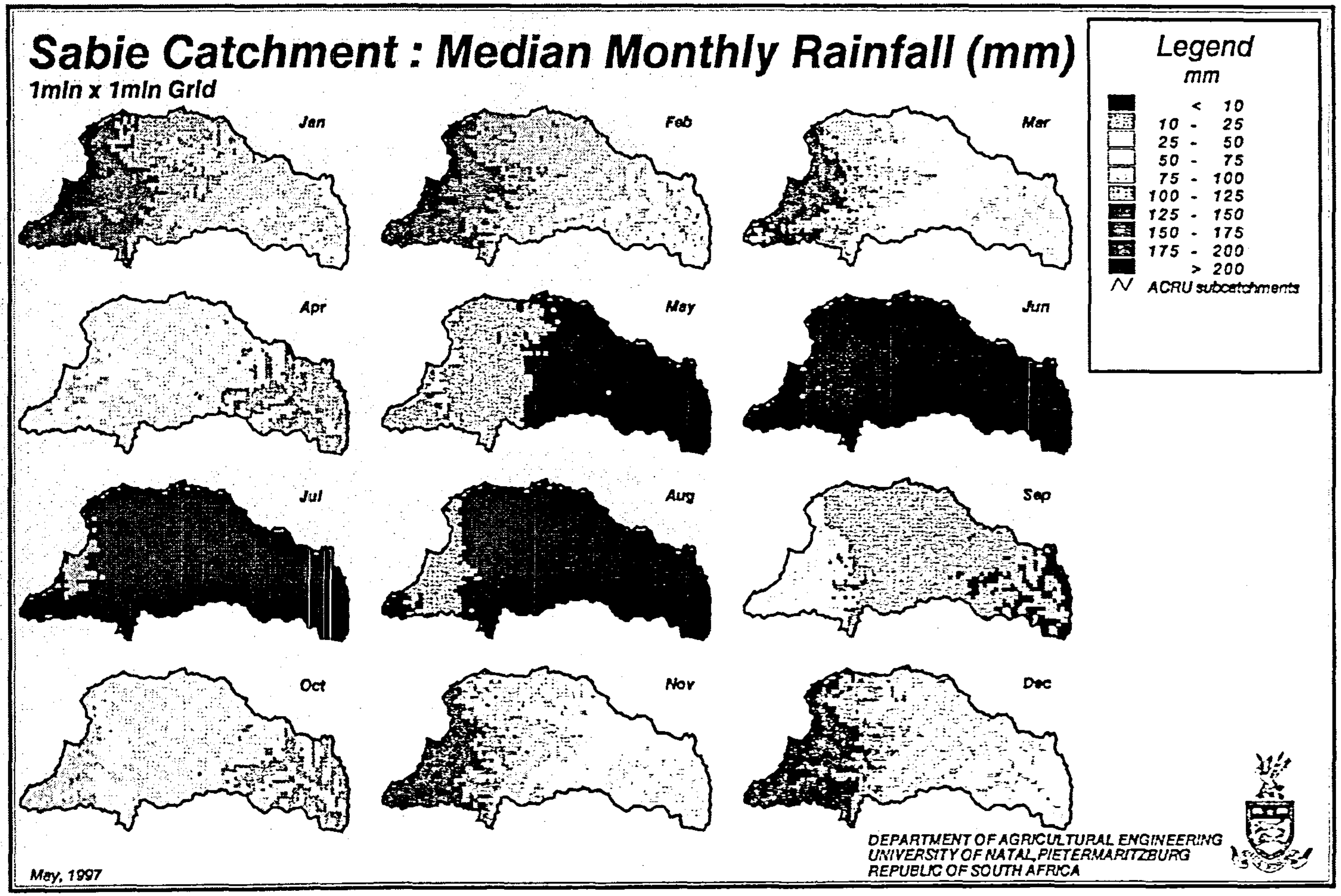
Sabie Catchment : Median Monthly Rainfall (mm)
1min x 1min Grid
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Legend
mm
< 10
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
150 - 175
175 - 200
> 200
ACRU subcatchments
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(e) Soils

Soils play a crucial role in catchments' hydrological responses by facilitating the infiltration of precipitation, and thereby largely controlling stormflow generation, by acting as a store of water which makes soil water available to plants and by redistributing water, both within the soil profile and out of it, by evaporation and transpiration processes and by drainage below the root zone and eventually into the groundwater zone which feeds baseflow.

For the KNPRRP study area the GIS coverage of soil Land Types was obtained from the Institute for Soil, Climate and Water (ISCW). In total 39 Land Types, grouped into 9 broad soil mapping units, were identified in the Sand and Sabie catchments. The distributions of the major soil mapping units are shown in Figure 9, while some hydrological attributes of the 39 Land Types are listed in Table D1 of Appendix D.

For each Land Type in Table D1, a vast amount of information on percentages of soil series per terrain unit, soils depths, texture properties and drainage limiting properties was provided by the ISCW. This Land Type information had to be "translated" into the hydrological soils input properties for a two-horizon soil profile, as required by *ACRU*. This translation takes place via a Soils Decisions Support System computer program called AUTOSOIL (Appendix E), developed by Pike and Schulze (1995) from information contained in Schulze (1995). For each subcatchment the output from the AUTOSOIL translation program for the KNPRRP study area is shown in Appendix E. Information for each of the 56 subcatchments includes soil texture, top- and subsoil horizon thicknesses, retention constants at critical soil water contents, drainage rates and percentages of impervious areas.

Figure 9	KNPRRP water resources study : Major soil mapping units

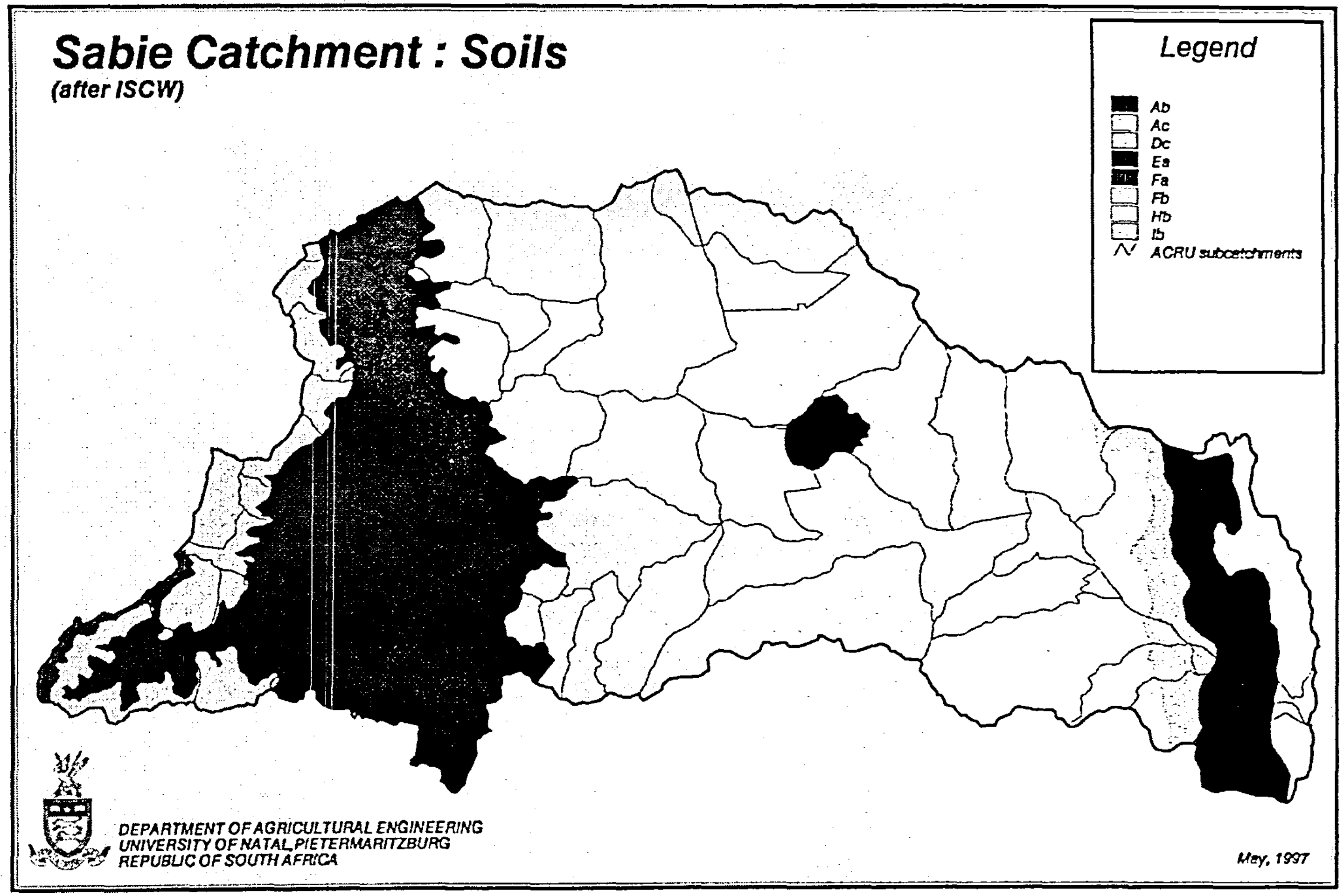
(f) Land Cover and Land Use

In order to determine the present land use of the KNPRRP study area a LANDSAT TM satellite image of 1993 land cover was obtained from the CSIR. This image was classified into 15 land cover classes, as shown in Figure 10. For simulation purposes these categories were regrouped into 11 land uses and the percentages of each is tabulated for the 56 subcatchments in Appendix F. Month-by-month model input variables for each of the 11 land uses are also presented in Appendix F.

Figure 10	KNPRRP water resources study : Present land cover

(g) Irrigation

The types of irrigation schemes, irrigated crops, and their modes of scheduling were obtained from a Chunnett, Fourie and Partners consulting report (1990). It was found that irrigation of perennial, summer and winter crops occurs in 17 of the 56 subcatchments of the KNPRRP study area. The


Sabie Catchment : Soils
(after ISCW)
Legend
Ab
Ac
Dc
Ea
Fa
Fb
Hb
Ib
ACRU subcatchments
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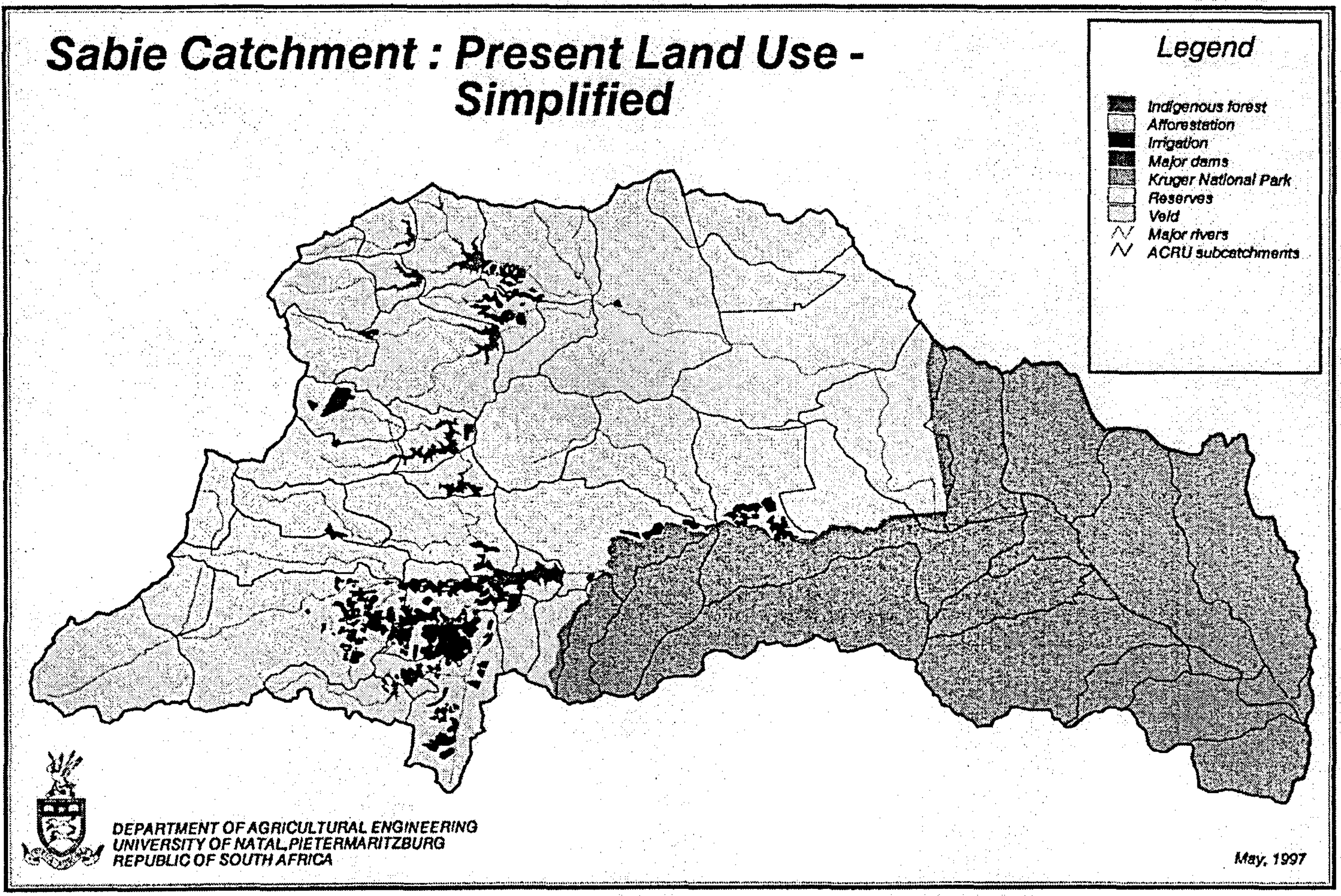
Sabie Catchment : Present Land Use - Simplified
Legend
Indigenous forest
Afforestation
Irrigation
Major dams
Kruger National Park
Reserves
Veld
Major rivers
ACRU subcatchments
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areas under irrigation, the source of water for irrigation, information on soils, agronomic, irrigation efficiency parameters and the monthly crop water use related input variables used in *ACRU* for the irrigated crops in the KNPRRP areas are given in Appendix G. Where irrigation abstractions were taken from the simulated run-of-river, the supply of irrigation water depended on sufficient streamflows in the river.

(h) Runoff

In determining daily runoff, the *ACRU* model distinguishes between stormflow generation and baseflow generation. Further explanation of the generation of runoff and values of the parameters which determine the amount of runoff and the disaggregation of stormflow and baseflow (e.g. coefficients of initial abstractions, critical soils depths, impervious areas, drainage rates, baseflow decay rates, stormflow delay factors) are given in Appendix H. Since daily flows were routed along stream channels and through reservoirs, information on subcatchment and channel slope and other channel dimensions relevant to Muskinghum-Cunge flow routing procedures also had to be determined. This channel information is also given in Appendix H.

(i) Afforestation

While most of the *ACRU* model input regarding afforestation is presented in Tables F1 and F2 of Appendix F, Appendix I contains certain aspects which require special emphasis (e.g. assumptions on age, site preparation, canopy and surface properties, physiological response).

(j) Dams

In order to model the reservoir's water status and the influence of dams on downstream water resources, information is required on each dam's location, its full supply capacity, surface area, storage:surface area relationships, legal (normal) flow releases, seepage, surface water evaporation, dead storage, spillway width, abstractions and inter-basin transfers into or out of the dam. Information on dams was obtained from the following sources, *viz.*

* the 1993 LANDSAT TM satellite image
* the WRSM90 Memoirs for South African Quaternary catchments (Midgley, Pitman and Middleton, 1994)
* 1:50 000 topographic maps and
* the Chunnett, Fourie and Partners (1990) consulting report.

Internal dams were lumped to form a single reservoir, located at the outlet of the relevant subcatchment and having a capacity and surface area of the combined reservoirs. All the inputs on dams, as required for the *ACRU* model, are summarised in Appendix J. Five dams with capacities exceeding 1 million m^3 were identified, the largest being the Da Gama Dam (13.6 million m^3).

(k) Sediment Yield

The Modified Universal Soil Loss Equation within the *ACRU* modelling system was used to estimate individual subcatchment sediment yields on an event-by-event basis. This equation requires the following information as input for each subcatchment:

* event-by-event stormflow volume and peak discharge
* weighting parameters for stormflow and peak discharge
* a maximum and minimum soil erodibility factor
* a slope length and steepness factor
* monthly vegetation/ surface cover factors
* a management practice factor and
* the fraction of the event based sediment yield from the subcatchment that reaches the outlet on the day of the event.

The sediment yield option requires that the peak discharge option be invoked. The Schmidt and Schulze (1984) method of calculating catchment lag was selected. In addition to subcatchment area and MAP this method also requires the following information as input:

* average slope (%) of each subcatchment and
* the 2-year return period value of the 30-minute duration rainfall intensity ($\bar{I}_{30}$, $mm.h^{-1}$).

The average subcatchment slopes were calculated from a 200 m altitude grid using *ARC/INFO* GIS routines. Tables K1 and K2 of Appendix K contain information on the soil erodibility and cover factors for each subcatchment in the KNPRRP study area while the $\bar{I}_{30}$ values were calculated from information given in the *ACRU* User Manual (Smithers and Schulze, 1995).

(l) Domestic and Livestock Abstractions

Human, livestock and game populations were determined from 1985 census figures provided in the Chunnett, Fourie and Partners (1990) report. These human population figures were projected to 1996 values by a 5% per annum (compounded) increase to account for population growth before being used to estimate per capita daily water consumption (Appendix L). Allocations of 10 $l.person^{-1}.day^{-1}$ for humans, and 45 $l.head^{-1}.day^{-1}$ for livestock and game were assumed (Chunnett, Fourie and Partners, 1990). The lower volume assumed by Chunnett, Fourie and Partners (1990) for human demands is due to the return flows to the hydrological system in the form purified waterborne sewerage and percolation from pit latrines into the groundwater. Projected human populations, estimates of livestock and game populations and the associated water consumptions are listed in Tables L1 and L2 of Appendix L.

(m) Inter-Basin Transfers

There are two water transfer schemes in Subcatchment 35 where 600 000 $m^3.a^{-1}$ and 500 000 $m^{-3}.a^{-1}$ are pumped out of the Sabie catchment area to supply water to Pretoriuskop and KaNgwane respectively. These transfers are summarised per subcatchment in Tables L1 and L2 of Appendix L.

HOW REALISTICALLY DOES THE *ACRU* MODEL SIMULATE STREAMFLOWS IN THE KNPRRP STUDY AREA? AN INITIAL STUDY

(a) The basis of verification studies with the *ACRU* model

As a physical-conceptual model, physically realistic and observationally derived variables on climate, soils, land use, catchment channel characteristics, irrigation and other water transfers and dams are input in *ACRU*. Structurally and conceptually *ACRU* has, therefore, been designed specifically to simulate scenarios based on land use impacts. *ACRU* is *not* a parameter fitting model which is calibrated until simulated values mimic observed values; rather, it is a deterministic model structured to give realistic answers for hydrologically valid and correct reasons.

One nevertheless needs to have the assurance that the modelled streamflow values reflect observed values. For this purpose a verification study of the model output was conducted, where the simulated streamflow values from the model were compared to an observed streamflow data record for the same period.

(b) Problems with the verification study

Table 1 shows the quality of the data collected at the nine gauging weirs in the Sand and Sabie catchments. The shaded rows identify seven weirs where it is strongly suspected that overtopping of the structures occurs during flood events without the relevant flags for suspect data appearing in the data record (e.g. Figure 11).

Table 1 Quality of observed daily streamflow records for the nine weirs in the Sand and Sabie catchments

Catchment	Sub-catchment	Weir Identification Code	Monitoring Period	Number of Months Monitored	Number of Months of Reliable Data	% of Months With Reliable data
SAND	12	X3H008	1/11/1967 - 31/12/1995	338	213	63.0
SABIE	18	X3H001	1/11/1948 - 31/7/1995	561	532	94.8
	19	X3H002	1/5/1964 - 31/12/1995	380	208	54.7
	21	X3H003	1/11/1948 - 30/9/1995	563	556	98.8
	27	X3H011	1/1/1979 - 31/11/1995	203	184	90.6
	30	X3H006				
	31	X3H007	1/1/1964 - 31/8/1991	332	297	89.5
	33	X3H004	1/11/1948 - 31/12/1995	566	551	97.3
	52	X3H015	1/1/1988 - 28/2/1993	62	62	100.0

Data for weir X3H006 (Subcatchment 30) was unavailable at the time of this study and weir X3H004 (Subcatchment 33) records streamflows from a contributing area (Subcatchments 31, 32 and 33) which contains in excess of 1700 ha of irrigation in summer and 1450 ha in winter (Figure 5; Table G2). The plot of simulated vs observed values of monthly totals of daily streamflows for the full

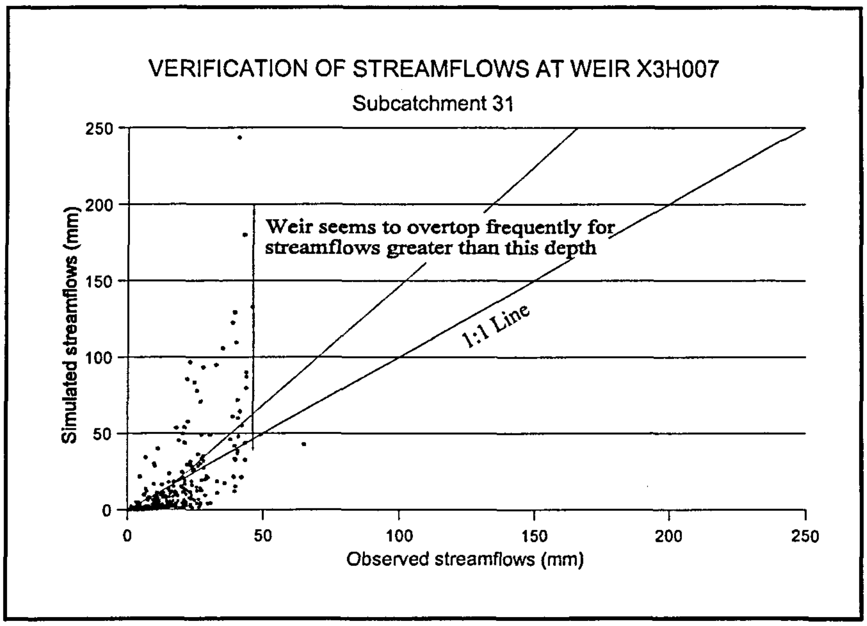


Figure 11 Plot of simulated vs observed monthly totals of daily streamflows at weir X3H007 for the full period of observed record, showing oversimulation as a result of overtopping of the structure

period of observed record and the monthly and accumulated streamflows for weir X3H004 are included in Figures 12 and 13 respectively. These figures highlight the problems of conducting verification studies in catchments where uncertainties related to both the volume of irrigated water applied and the exact extent of irrigation exist (in this case Subcatchments 31, 32 and 33) and where the representativeness of rainfall data from the selected "driver" station (A0556460) is not satisfactory (Table B2). These problems resulted in the verification study of output from the *ACRU* model been restricted to weir X3H001 at the outlet of Subcatchment 18, where the monthly medians of the daily rainfall values of "driver" station A0555461 represent the median monthly rainfalls of Subcatchment 18 (obtained from the Department of Agricultural Engineering's 1'x1' gridded database) to within 10% in all summer months except for the month of March (where the median monthly rainfall measured for March underestimates the gridded median monthly value by 11% - cf. Table B2).

(c) Verification of streamflows at weir X3H001

Figure 14 shows the plot of simulated vs observed values of monthly totals of daily streamflows for the full period of observed record while Figure 15 shows both the monthly and accumulated simulated and observed streamflows for weir X3H001 for the period 1972 to 1995.

Months with high flows are well simulated on a monthly totalled basis (Figures 14 and 15). Figure 15 also highlights several potential anomalies in either the rainfall or the streamflow data record where extraordinarily high streamflows are recorded but very little response is simulated (eg. the summers of 1979, 1982, 1986, 1987, 1993 and 1994) or visa versa (eg. the summers of 1974, 1992and 1995). The verification also identifies potential problems in the timing of either the

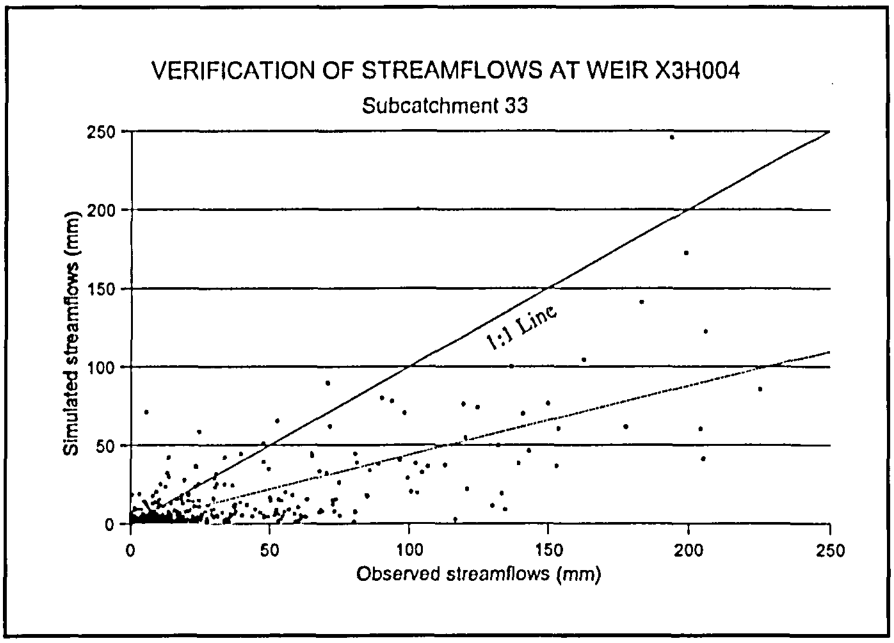


Figure 12 Plot of simulated vs observed monthly totals of daily streamflows at weir X3H004 for the full period of observed record, showing undersimulation as a result of uncertainties in irrigation abstractions

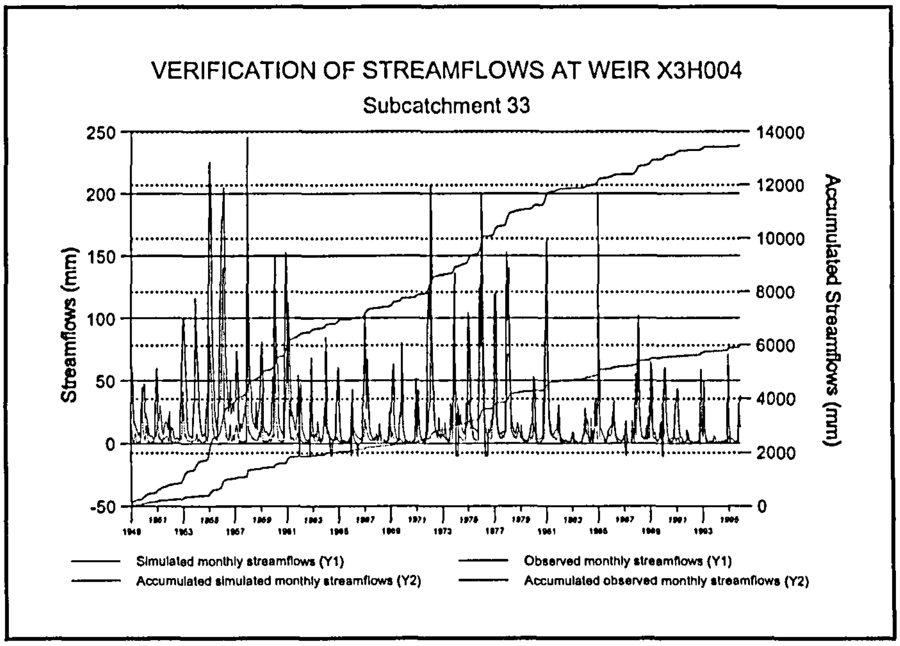


Figure 13 Accumulated and monthly simulated and observed streamflows at weir X3H004 for the full period of observed record

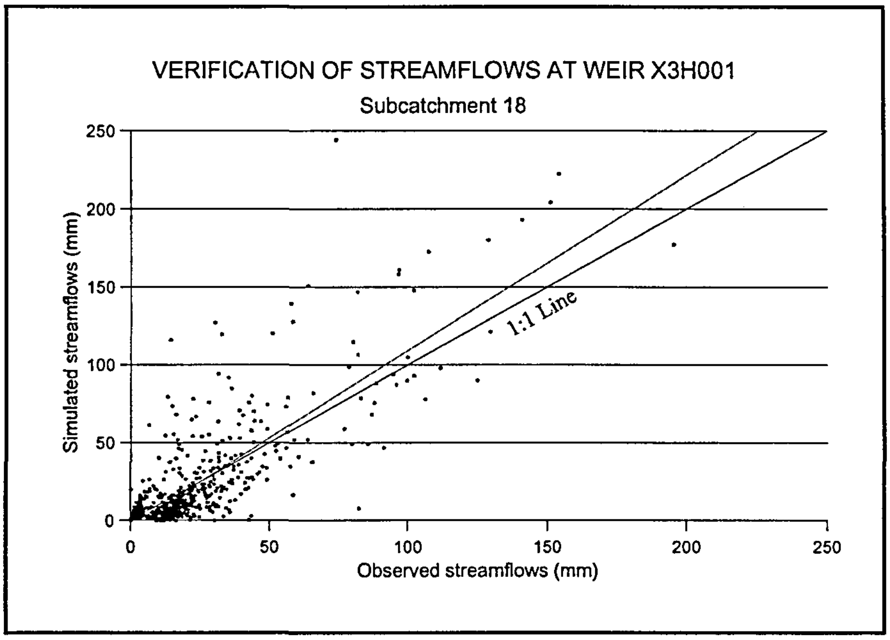


Figure 14 Plot of simulated vs observed monthly totals of daily streamflows at weir X3H001 for the full period of observed record

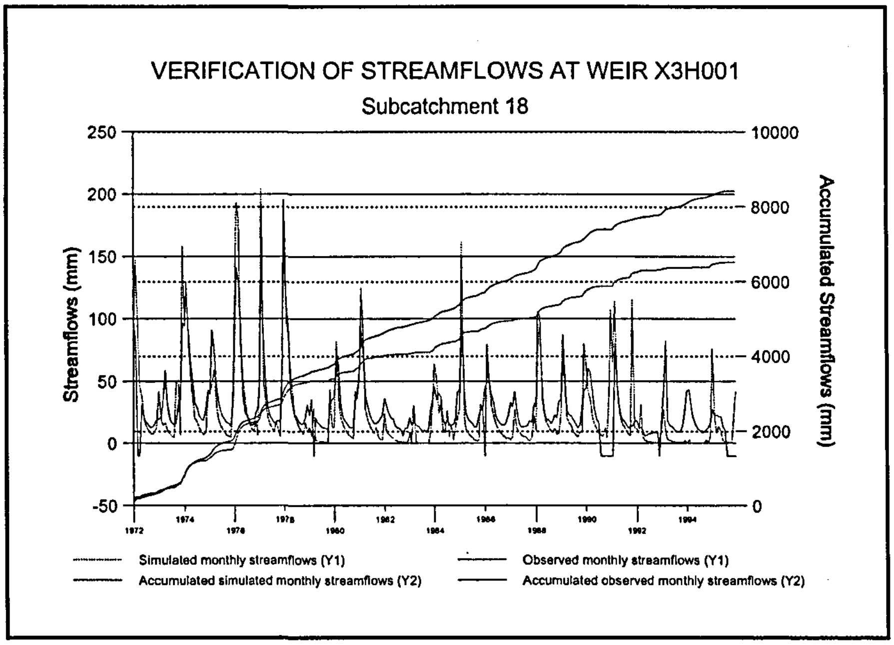


Figure 15 Accumulated and monthly simulated and observed streamflows at weir X3H001 for the period 1972 to 1995

rainfall or streamflow data (eg. the summers of 1973 and 1990). The *ACRU* model tends to underestimate autumn and winter low flows (Figures 14 and 15). These verifications together with some of the problems encountered in the accurate simulation of low flows and suggestions for future research are discussed in the conclusions and recommendations.

On the whole, these results engender confidence that the various scenarios run with *ACRU* would be expected to give realistic results. Further monthly and accumulated streamflow plots resulting from the verification study for weirs X3H003, X3H011 and X3H007 are provided in Figures M1, M2 and M3 respectively of Appendix M.

SIMULATION RUNS

After checking model input, undertaking random spot checks on daily printouts and monthly summaries and completing the initial verification study at streamflow gauging station X3H001, the final *ACRU* simulation was performed. Each simulation was conducted for the period 1 January 1940 to 31 December 1995. The following scenario was considered:

* Streamflows and sediment yield under present land uses, including present afforestation and irrigation/dams and domestic, livestock and game abstractions.

Monthly totals of daily simulated streamflows at the outlets of Subcatchments 21, 31 and 52 are shown in Figures 16, 17 and 18 while the annual coefficients of variation for each subcatchment are shown in Figure 19. Subcatchments in the west, characterised by higher annual rainfall, and subcatchments receiving upstream flow contributions display lower annual coefficients of variation than primary subcatchments and subcatchments in the east, which receive less rainfall. Subcatchment 41 in the south is characterised by a very high annual fluctuations in streamflow which may be associated with the low MAP of 592 mm (see Table A1).

Median annual sediment yields per subcatchment are shown in Figure 20. The simulated sediment yield is closely related to land cover and slope, with the steeper subcatchments producing more sediment than those characterised by shallower gradients. The well conserved areas in the Kruger National Park produce less sediment loadings than the cultivated areas and the former independent homelands (cf. Figures 3 and 10).

The purpose of this scenario was to assess the streamflows and sediment yields resulting from present-day land use. With the data files in place and the modelling framework complete the impact of any future land use scenarios on present-day hydrological responses may be assessed with relative ease.

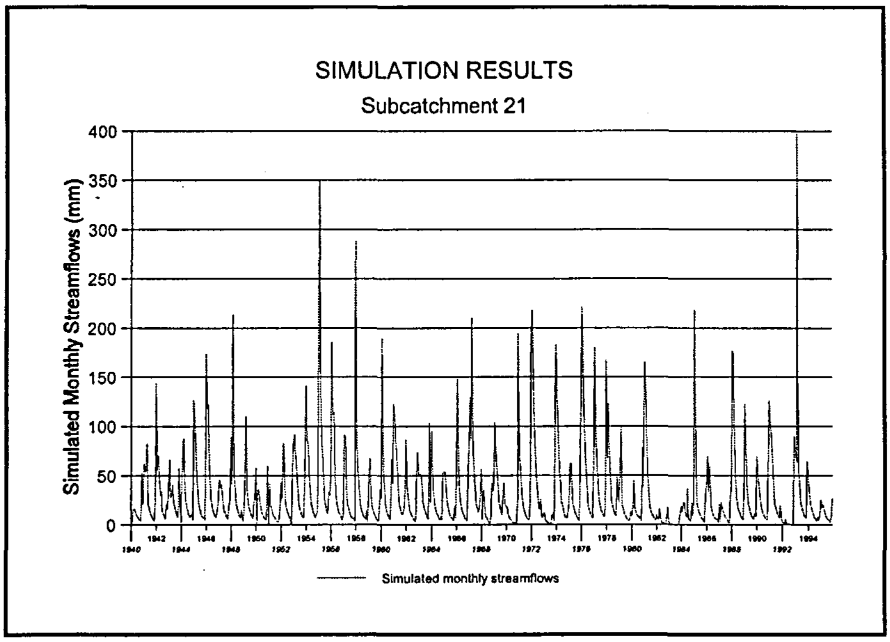


Figure 16 KNPRRP water resources study : Monthly totals of daily simulated streamflows (mm) at Subcatchment 21

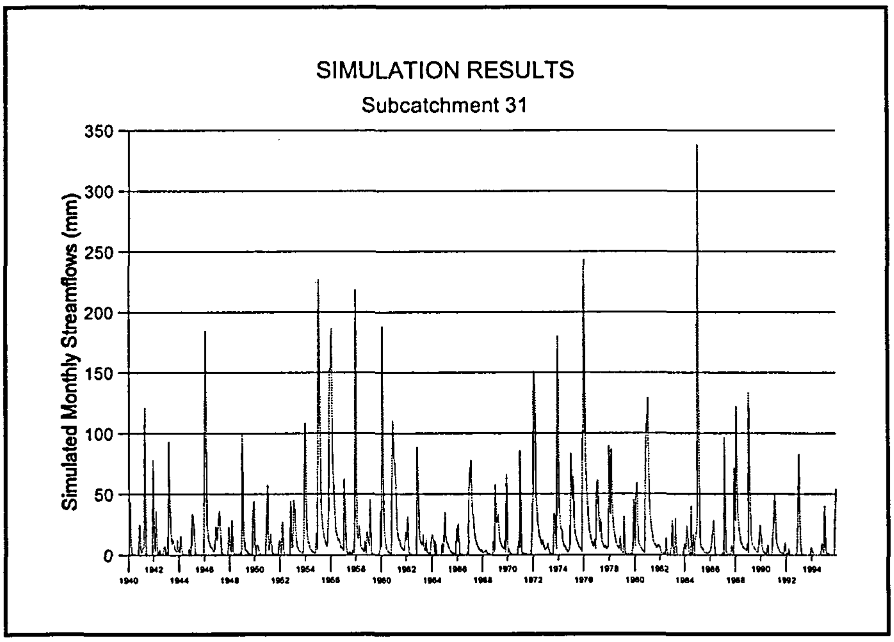


Figure 17 KNPRRP water resources study : Monthly totals of daily simulated streamflows (mm) at Subcatchment 31

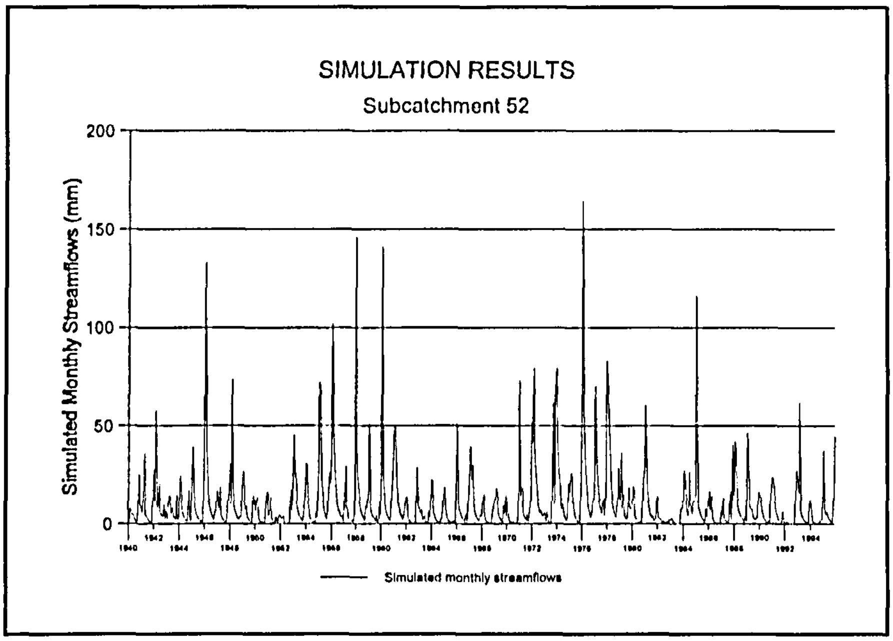
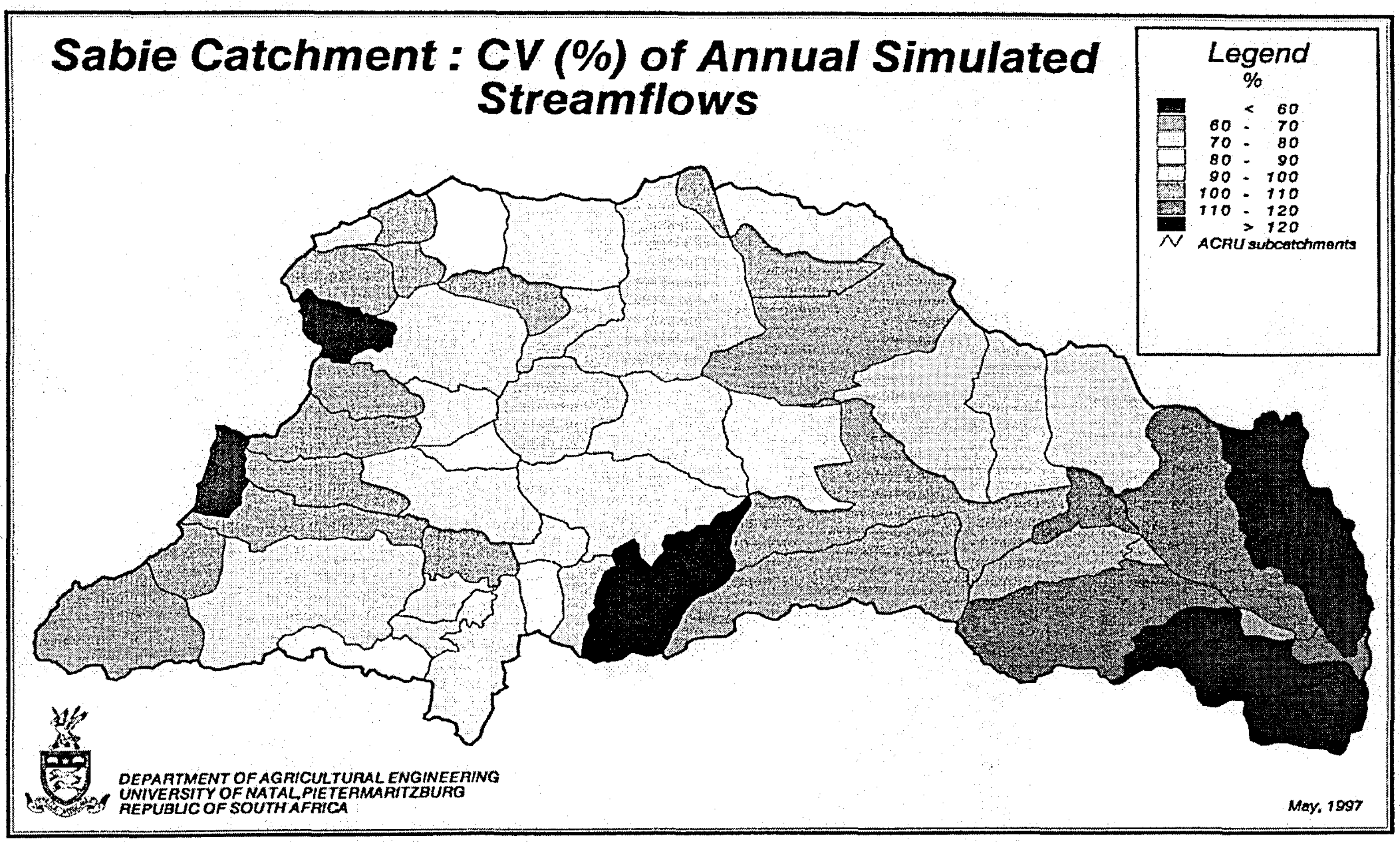
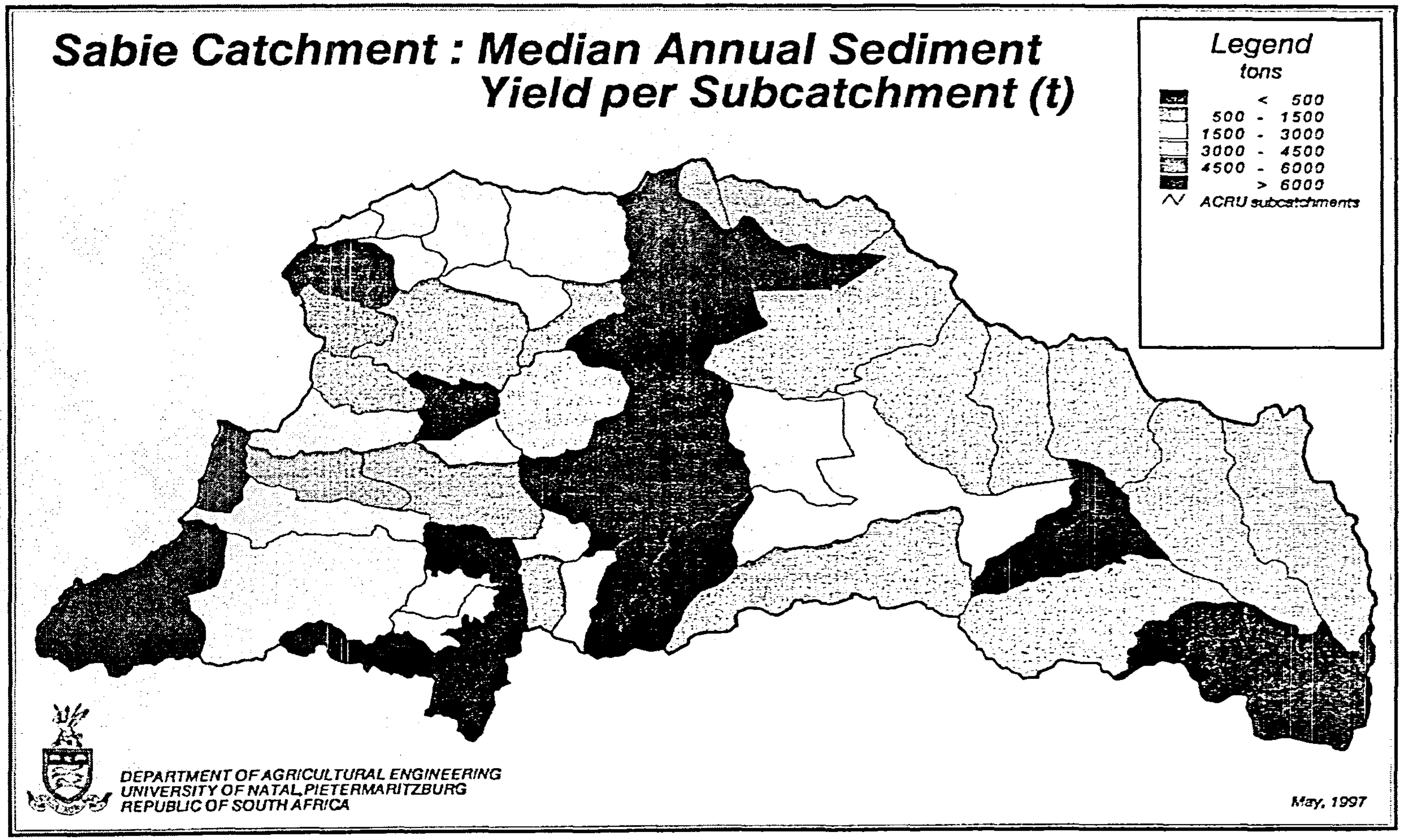


Figure 18 KNPRRP water resources study : Monthly totals of daily simulated streamflows (mm) at Subcatchment 52

Figure 19 KNPRRP water resources study : Coefficients of variation of annual simulated streamflows (%) for each subcatchment

Figure 20 KNPRRP water resources study : Median annual sediment yield (t) per subcatchment


Sabie Catchment : CV (%) of Annual Simulated Streamflows
Legend
%
< 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
> 120
ACRU subcatchments
DEPARTMENT OF AGRICULTURAL ENGINEERING
UNIVERSITY OF NATAL, PIETERMARITZBURG
REPUBLIC OF SOUTH AFRICA
May, 1997


Sabie Catchment : Median Annual Sediment
Yield per Subcatchment (t)
Legend
tons
< 500
500 - 1500
1500 - 3000
3000 - 4500
4500 - 6000
> 6000
ACRU subcatchments
DEPARTMENT OF AGRICULTURAL ENGINEERING
UNIVERSITY OF NATAL, PIETERMARITZBURG
REPUBLIC OF SOUTH AFRICA
May, 1997

CONCLUSIONS AND RECOMMENDATIONS

From experience in other catchment studies, from the Sabie X3H001 verification (cf. Figures 11, 12 and 13) and the many other published verification studies of various hydrological processes (Schulze, 1995), the compilers of this report consider the results from the KNPRRP simulations with the *ACRU* model to be realistic. However, as is the case with any modelling, results should never be taken to be definitive or absolute. Output from a model, assuming the model to be structurally sound, can at most only be as good as the input, and with some of the input values in this KNPRRP study there are some concerns.

* The flow regime of the KNPRRP study area is a highly seasonal one. This is evident from the verification study and is highlighted in Figures 12 and 13 of this report by the seasonal distribution of month-by-month simulated streamflows at the outflows of Subcatchment 18 for median flow conditions (50th percentile), as well as for flows in the driest years in 5 (20th percentile) when simulating hydrological responses under current land use conditions. Of importance in these seasonal distributions is the frequency of occurrences of streamflows of less than 5 $mm.month^{-1}$. The accurate simulation of these low flows is crucial for determining whether the instream flow requirements for the preservation of various aquatic flora and fauna habitats are satisfied. Four main sources of inaccuracies in the simulation of low flows were identified in this study, viz.
  - the occurrence of dolomitic areas with a magnesium limestone substructure within the upper reaches for the Sand and Sabie catchments, the hydrological response of which is very difficult to simulate as it falls within the specialised realm of Karst Hydrology;
  - the uncertainties pertaining to the timing and amount of water abstracted for irrigation and domestic and livestock consumption and the return flows from these areas;
  - the operating rules of the dams including minimum legal releases, planned 'flushes' of water and seepage, which are not always known; and
  - the problem of transmission losses and disconnected ground water tables in the Sand catchment, where considerable recharge to the water table is believed, from field observations, to occur from the river channel.

  These hydrological processes were not modelled satisfactorily by the *ACRU* model and further research is required in these fields.

* Reliable rainfall and observed streamflow data are prerequisites for the reliable verification of model results. The state of available observed streamflow data in the KNPRRP study area and the aforementioned uncertainties regarding domestic and livestock abstractions, irrigation applications and return flows and operating rules of dams did not allow for either an accurate verification of the simulation, or for any research to be undertaken to understand the hydrology of subcatchments characterised by dolomitic parent material.

It is recommended that the above-mentioned issues, among many others, be examined jointly by the main stakeholders concerned in these KNPRRP catchments as well as by relevant governmental departments and parastatal organisations, to the mutual benefit of all parties subscribing to an integrated management of this catchment.

ACKNOWLEDGEMENTS

All observed streamflow data were extracted and reformatted by staff at the Computing Centre for Water Research (CCWR). Furthermore, all computer simulation runs as well as all GIS work were undertaken at the CCWR. We express our sincere acknowledgement to the CCWR for providing the resources and expertise required for this study.

REFERENCES (EXECUTIVE SUMMARY)

ARC/INFO 1991. Cell-based Modelling with GRID. Environmental Systems Research Institute, Inc., Redlands, USA.

Chunnett, Fourie and Partners, 1990. Water Resources Planning of the Sabie River Catchment. Study of the development potential and management of the water resources. Catchment Study Report. *Department of Water Affairs and Forestry*, Pretoria, *Report P.X300/00/0490.* Volumes 1 to 10.

CSIR, 1993. LANDSAT-TM images of the KNPRRP study area. CSIR, Pretoria.

Midgley, D.C., Pitman, W.V. and Middleton, B.J. 1994. Surface Water Resources of South Africa 1990. *Water Research Commission*, Pretoria, *Report* 298/6.1/94. Volume 6.

Pike, A. and Schulze, R.E. 1995. AUTOSOIL Version 3 : A Soils Decision Support System for South African Soils. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Schmidt, E.J. and Schulze, R.E. 1984 Improved estimations of peak flow rates using modified SCS lag equations. *Water Research Commission*, Pretoria, *Report* 63/1/84. pp142.

Schulze, R.E. 1995. Hydrology and Agrohydrology : A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. *Water Research Commission*, Pretoria. *Technology Transfer Report* TT69/95. pp 552.

Schulze, R.E. and Maharaj, M. 1991. Mapping A-pan equivalent potential evaporation over southern Africa. *Proceedings, 5th South African National Hydrology Symposium*, Stellenbosch. NSI Cape Town. 4B-4-1 to 4B-4-9.

Smithers, J.C. and Schulze R.E., 1995 ACRU Agrohydrological Modelling System : User Manual Version 3.00. *Water Research Commission*, Pretoria. *Technology Transfer Report* TT70/95.

REFERENCES (APPENDICES)

Chunnett, Fourie and Partners, 1990. Water Resources Planning of the Sabie River Catchment. Study of the development potential and management of the water resources. Catchment Study Report. *Department of Water Affairs and Forestry*, Pretoria, *Report P.X300/00/0490.* Volumes 1 to 10.

CSIR, 1993. LANDSAT-TM images of the KNPRRP study area. CSIR, Pretoria.

Midgley, D.C., Pitman, W.V. and Middleton, B.J. 1994. Surface Water Resources of South Africa 1990. *Water Research Commission*, Pretoria, *Report* 298/6.1/94. Volume 6.

Schulze, R.E. 1995. Hydrology and Agrohydrology : A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. *Water Research Commission*, Pretoria. *Technology Transfer Report* TT69/95. pp 552.

Schulze, R.E., Dent, M.C., Lynch, S.D., Schäfer, N.W., Kienzle, S.W. and Seed,A.W. 1995. Chapter 3, *In* Schulze, R.E.. 1995.

REFERENCES (APPENDICES, Continued)

Smithers, J.C. and Caldecott, R.E. 1993. Hydrograph routing. *In*: Schulze, R.E. 1995. Hydrology and Agrohydrology : A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. *Water Research Commission*, Pretoria. *Technology Transfer Report* TT69/95. pp AT13-1 to AT13-16.

APPENDICES TO THE REPORT TITLED

SIMULATION OF STREAMFLOWS AND SEDIMENT YIELDS IN THE SAND AND SABIE CATCHMENTS : INITIAL RESULTS

Report to Kruger National Park Rivers Research Programme (KNPRRP)

***ACRU*cons Report 17**
May 1997

A Pike, RE Schulze, SA Lorentz, F Ballim, V Taylor and BJ Howe

Department of Agricultural Engineering
University of Natal
Pietermaritzburg

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Appendix A

KNPRRP water resources study : Subcatchment Information

Table A1 Subcatchment information

Catchment	Quaternary Catchment Number	Sub-catchment Number	Area (km²)	Mean Sub-catchment Altitude (m)	Mean Annual Precipitation (mm)
SAND	X32B	1	19.83	846.0	1290.0
		2	36.81	675.0	872.0
	X32A	3	76.90	906.0	1175.0
		4	32.53	624.0	767.0
	X32C	5	86.98	548.0	764.0
		6	141.52	466.0	656.0
	X32D	7	57.23	1745.0	1585.0
	X32D X32E X32F	8	170.70	594.0	785.0
	X32F	9	58.90	505.0	649.0
		10	52.66	472.0	680.0
	X32G	11	26.09	677.0	677.0
		12	311.72	380.0	612.0
	X32H	13	111.21	396.0	596.0
		14	76.80	387.0	619.0
		15	300.18	374.0	600.0
	X32J	16	209.54	304.0	599.0
		17	140.42	312.0	604.0
		Sub Total	1910.02		

Catchment		Quaternary Catchment Number	Sub-catchment Number	Area (km²)	Mean Sub-catchment Altitude (m)	Mean Annual Precipitation (mm)
SABIE	Upstream of Sand Confluence	X31A	18	173.18	1798.0	1217.0
			19	55.87	1466.0	1442.0
		X31B X31D	20	293.73	1380.0	1488.0
		X31C	21	46.11	1520.0	1276.0
			22	107.61	1300.0	1520.0
		X31D	23	35.45	869.0	1081.0
			24	57.42	704.0	926.0
		X31E	25	67.13	960.0	1542.0
			26	89.04	998.0	1326.0
			27	56.25	822.0	1073.0
		X31G	28	37.36	640.0	839.0
		X31F	29	83.58	1018.0	1451.0
		X31F X31G	30	138.20	670.0	885.0
		X31H	31	60.95	1080.0	1139.0
		X31J	32	36.19	753.0	905.0
			33	118.81	869.0	819.0
		X31K	34	38.62	579.0	732.0
		X31G X31K	35	33.14	509.0	651.0
		X31K	36	43.32	564.0	591.0
			37	55.60	533.0	641.0
			38	203.40	411.0	588.0
		X31L	39	136.59	533.0	757.0
			40	157.73	411.0	706.0
		X31K	41	123.94	485.0	592.0
		X31M	42	141.13	320.0	606.0
			43	266.52	350.0	491.0
			44	304.27	280.0	482.0
		X31M X33A	45	50.10	256.0	487.0
	Downstream of Sand Confluence	X33A	46	174.31	243.0	425.0
			47	91.71	182.0	603.0
			48	8.51	204.0	522.0
			49	256.93	204.0	435.0
		X33A X33B	50	259.64	316.0	500.0
		X33B	51	58.72	228.0	489.0
			52	12.66	250.0	500.0
		X33C X33D	53	254.76	220.0	500.0
		X33D	54	103.36	300.0	500.0
			55	93.49	300.0	450.0
			56	25.01	150.0	450.0
			Sub Total	4350.34		
			TOTAL	6260.36		

Appendix B

KNPRRP water resources study : Rainfall

"Rainfall is the fundamental driving force and pulsar input behind most hydrological processes" (Schulze, Dent, Lynch, Schäfer, Kienzle and Seed, 1995, pg AT3-1).
Rainfall - runoff models are particularly sensitive to the rainfall input and any error in rainfall estimates are amplified in streamflow simulations (Schulze *et al.*, 1995). Therefore, when selecting hydrological information to be used in modelling, the selection of the rainfall information should take the largest portion of the time spent on data acquisition.

All daily rainfall stations surrounding the Sabie and Sand river catchments were identified from the CCWR's database. The most representative rainfall station for each delimited subcatchment, as shown in Tables B1 and B2 for the Sand and Sabie catchments respectively, was then selected according to the following criteria:

* Altitude,
* Mean annual precipitation (MAP),
* Median monthly rainfall (from the 1'x1' gridded median monthly rainfall values for southern Africa developed by the Department of Agricultural Engineering), and
* At least 30 years of concurrent and recent observed daily data.

For stations with missing or suspect daily rainfall values, a technique had to be applied to provide an accurate estimate of the magnitude of rainfall occurring on a particular day. The missing records for the selected "driver" stations were infilled (i.e. patched) to be concurrent using a technique called RAPID (Rainfall Patching with Inverse Distance Weighting) developed by K.B. Meier, S.D. Lynch and R.E. Schulze of the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg. This technique ensures that synthesised values of the rainfall at the station representing a subcatchment fulfilled the following requirements:

* Rainfall values infilled using a particular method must be historically representative and not be stochastically generated. Hence they must represent as closely as possible the rainfall actually occurring at a specific station on a particular day (this being important when cascading simulated streamflows from one catchment to the next one downstream).
* A number of surrounding rainfall stations should be used in the synthesising process, so as to prevent directional bias.
* The technique must provide for fast computations, with computer time being of importance when considering the number of station records which have to be synthetically generated.

The 'RAPID' Inverse Distance Weighting (IDW) interpolation technique

The procedure of IDW involves the inverse weighting of the recorded rainfall from stations surrounding a driver station, depending on the distance of those stations from the driver station. This gives the closest station the highest and the furthest station selected the lowest weighting. In this study, the inverse of the distance squared was used, to give the closest station an even higher representation than other stations, as indicated in Equation B1. Because of the spatial variability of rainfall events in southern Africa it was necessary to account, as closely as possible, for the actual rainfall pattern surrounding the driver station. For this reason, the following sequence of computational steps, shown in Figure B1, was used:

* Identify a representative rainfall station, with this station termed the "driver" station, for each subcatchment.
* Identify all rainfall stations within one degree latitude and longitude of the driver station.
* Divide the area surrounding the driver station into four quadrants using the latitude and longitude of the driver station as the bisectors.
* Identify the closest 10 rainfall stations of each quadrant and retrieve the daily rainfall records for those stations from the CCWR rainfall database.
* Search the driver station record for the first missing or suspect day of rainfall.
* Identify the closest station in each quadrant with an actual value of rainfall occurring on that day (including zeros).
* Adjust these values by the ratio of the MAP at the grid point of the closest station and the MAP at the grid point of the driver station.
* Use these adjusted values to synthesise the rainfall of the driver station using IDW.

Mathematically the IDW procedure is expressed as

where

r_s = synthesised rainfall of the driver station (mm) for a specific day

$$r_s = \frac{\frac{R_d r_1}{R_1 d_1^2} + \frac{R_d r_2}{R_2 d_2^2} + \frac{R_d r_3}{R_3 d_3^2} + \frac{R_d r_4}{R_4 d_4^2}}{\frac{1}{d_1^2} + \frac{1}{d_2^2} + \frac{1}{d_3^2} + \frac{1}{d_4^2}} \qquad \textbf{(B1)}$$

$r_{1,2,3,4}$ = actual rainfalls (mm) which fell at the closest stations in Quadrants one to four respectively

$d_{1,2,3,4}$ = distance (in degrees and decimals) of each of the four representative closest stations from each quadrant to the driver station respectively

$R_{1,2,3,4}$ = MAP (mm) at the grid points of the stations chosen from quadrants one to four

R_d = MAP (mm) at the grid point of the driver station.

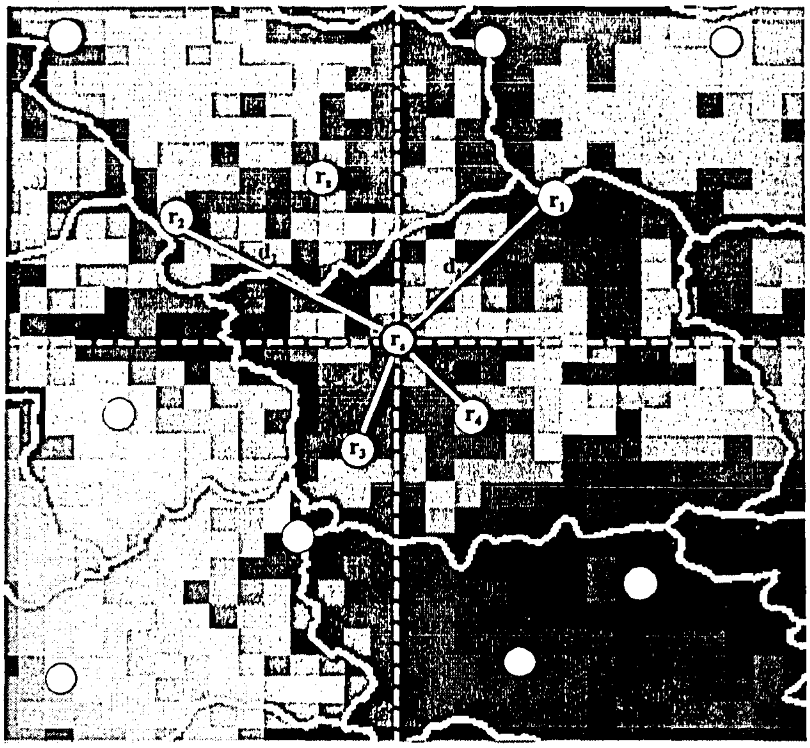

Figure B1 Synthesising missing rainfall records using Inverse Distance Weighting (IDW)

The reason for correcting the rainfall values using the MAP of the grid point and not the MAP of the station is that the length of record of the station may be too short to give an accurate value of the MAP at the site. The approach assumed:

* that the gridded values of MAP, which were determined by Dent *et al.* (1989), are correct
* the difference in distance between a degree latitude and a degree longitude is negligible at the local scale and
* that at a given driver station there is no need to use (say) monthly rainfall ratios in place of the MAP ratios.

In cases where a certain quadrant had no recorded rainfall values on the day required (e.g. where a quadrant fell over the ocean or outside South Africa, Lesotho and Swaziland), a single rainfall value was used from each of the remaining three quadrants. If two quadrants had no stations with representative rainfall for that day, two stations were selected from each of the remaining quadrants, so as to minimise the chance that the stations used for synthesising would be located too close to one another, thereby possibly biasing the synthesised rainfall value. If three quadrants had no stations with recorded rainfall on the day in question, then three rainfall stations were used in the final quadrant for the same reason indicated above.

The new median monthly rainfall amounts were then recalculated for the patched data sets and compared to the gridded median monthly rainfall amounts to give 12 precipitation correction factors for each subcatchment. The final "driver" stations, the subcatchments they represent and the total area represented by each gauge are shown in Table B3.

Table B1 South African weather bureau identification numbers of daily rainfall "driver" stations selected per subcatchment in the Sand catchment of the KNPRRP study area and the associated month-by-month factors used for the adjustment of daily precipitation values

Catchment	Quaternary Catchment Number	Sub-catchment Number	Rainfall Driver Station Number	Weir Identification Code	Daily Precipitation Adjustment											
					Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	X32B	1	A0594696		1.02	0.86	0.89	0.87	0.84	0.70	1.14	0.70	1.26	0.78	1.02	0.90
		2	A0595161		1.11	1.30	1.10	1.06	1.15	1.30	1.30	1.30	1.30	1.07	1.14	1.10
	X32A	3	A0594764		0.83	0.75	0.77	0.83	0.75	0.81	0.86	0.70	0.83	0.70	0.81	0.73
		4	A0595161		1.04	1.28	1.06	1.04	1.12	1.30	1.30	1.30	1.30	1.00	1.07	1.03
	X32C	5	A0595161		1.03	1.25	1.01	0.96	1.03	1.30	1.30	0.91	1.30	0.98	1.08	1.02
		6	A0595161		0.92	1.05	0.89	0.84	0.98	1.30	1.30	0.77	1.30	0.93	0.95	0.88
	X32D	7	A0594764		0.93	0.84	0.90	0.92	0.83	0.92	1.09	0.70	0.95	0.78	0.93	0.81
	X32D X32E X32F	8	A0595110		1.14	0.95	0.97	0.96	0.95	1.30	1.30	0.70	1.30	0.90	0.94	0.85
	X32F	9	A0595161		0.94	1.14	0.94	0.90	1.01	1.30	1.30	0.92	1.30	0.92	0.97	0.90
		10	A0595463		1.10	1.03	0.95	0.91	1.30	0.73	1.30	0.85	1.30	1.00	0.92	0.89
	X32G	11	A0595161		0.92	1.04	0.76	0.78	0.84	1.30	1.30	0.70	1.30	0.84	0.94	0.82
		12	A0595463	X3H008	1.10	1.00	0.89	0.86	<u>1.30</u>	0.86	<u>1.30</u>	0.80	<u>1.30</u>	1.01	0.92	0.87
	X32H	13	A0595816		1.08	1.15	1.12	1.29	1.01	0.88	0.70	0.70	1.30	0.98	1.07	0.95
		14	A0595463		1.07	1.00	0.82	0.81	1.18	1.22	1.30	0.70	1.30	0.88	0.89	0.86
		15	A0595463		1.03	0.94	0.83	0.78	1.08	0.70	1.30	0.70	1.30	0.81	0.85	0.83
	X32J	16	A0596179		1.11	1.30	1.16	1.02	1.23	0.70	0.78	0.70	1.13	0.88	0.94	0.95
		17	A0596179		1.10	1.30	1.13	0.99	1.18	0.70	0.77	0.70	1.09	0.86	0.90	0.95

Note 1 Shaded cells indicate rainfall adjustment factors greater or equal to 10% in subcatchments which contain weirs
2 Underlined values indicate rainfall adjustment factors which exceeded 30% and were defaulted to 30% in subcatchments which contain weirs

Table B2 South African weather bureau identification numbers of daily rainfall "driver" stations selected per subcatchment in the Sabie catchment of the KNPRRP study area and the associated month-by-month factors used for the adjustment of daily precipitation values

Catchment		Quaternary Catchment Number	Sub-catchment Number	Rainfall Driver Station Number	Weir Identification Code	Daily Precipitation Adjustment											
						Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SABIE	Upstream of Sand Confluence	X31A	18	A0555461	X3H001	1.06	1.04	1.11	1.05	1.00	0.90	1.30	0.81	1.04	0.99	1.09	1.09
		X31A	19	A0555573	X3H002	0.83	0.80	0.95	0.83	0.89	0.70	0.82	0.70	0.75	0.75	0.84	0.76
		X31B X31D	20	A0555573		0.75	0.71	0.79	0.74	0.88	0.70	0.73	0.70	0.72	0.70	0.74	0.70
		X31C	21	A0594596	X3H003	0.94	0.87	0.98	0.95	0.85	0.70	1.14	0.70	0.89	0.80	1.00	0.87
		X31C	22	A0555631		0.81	0.74	0.85	0.71	0.93	0.70	0.99	0.70	0.70	0.70	0.81	0.82
		X31D	23	A0555878		0.87	0.82	0.95	0.88	0.87	0.70	1.30	0.70	0.85	0.71	0.83	0.84
		X31D	24	A0595210		0.99	0.92	1.04	0.91	0.95	1.05	1.30	0.70	1.10	0.80	0.99	0.98
		X31E	25	A0594802		1.04	0.96	1.00	1.00	0.87	0.88	1.13	0.70	0.97	0.79	0.93	0.95
		X31E	26	A0594806		1.19	1.01	1.10	1.00	0.98	0.70	1.30	0.70	1.03	0.94	1.05	0.88
		X31E	27	A0595110	X3H011	1.30	1.16	1.17	1.21	1.23	1.30	1.30	0.75	1.30	1.06	1.14	1.02
		X31G	28	A0595110		1.30	1.08	1.08	1.10	1.21	1.30	1.30	0.71	1.30	1.01	1.08	0.96
		X31F	29	A0594779		0.98	0.94	1.02	0.90	1.30	0.89	1.30	0.96	1.12	0.99	1.01	0.96
		X31F X31G	30	A0556183	X3H006	1.16	1.21	1.22	1.14	1.06	1.23	1.30	0.82	1.30	0.92	1.06	1.03
		X31H	31	A0555878	X3H007	1.04	1.02	1.09	1.04	1.00	0.78	1.30	0.70	1.04	0.92	1.03	1.03
		X31J	32	A0556127		1.09	1.03	1.16	0.95	0.99	0.70	1.30	0.72	1.30	0.95	1.05	1.08
		X31J	33	A0556460	X3H004	1.26	1.21	1.13	1.20	1.30	0.70	1.30	0.70	1.27	1.06	1.11	1.01
		X31K	34	A0556460		1.14	1.07	1.01	1.02	1.18	0.70	1.13	0.70	1.12	0.84	0.94	0.86
		X31G X31K	35	A0556460		1.20	1.14	1.03	1.02	1.11	0.70	1.30	0.70	1.15	0.84	0.94	0.85
		X31K	36	A0556460		1.09	1.01	0.95	0.96	1.03	0.70	1.03	0.70	1.04	0.79	0.88	0.80
		X31K	37	A0556460		0.95	0.88	0.82	0.82	0.82	0.70	1.00	0.70	0.91	0.70	0.78	0.70
		X31K	38	A0595443		1.14	0.84	1.11	0.97	1.30	0.72	1.30	0.70	1.27	0.83	0.92	0.84
		X31L	39	A0595443		1.29	1.02	1.30	1.14	1.30	1.09	1.30	0.70	1.30	1.00	1.03	0.93
		X31L	40	A0595443		1.10	0.84	1.06	0.92	1.12	0.70	1.30	0.70	1.21	0.81	0.90	0.80
		X31K	41	A0556460		0.97	0.92	0.82	0.82	0.75	0.70	0.99	0.70	0.92	0.70	0.79	0.70
		X31M	42	A0595443		1.03	0.78	1.00	0.89	1.08	0.70	1.30	0.70	1.18	0.74	0.84	0.75
		X31M	43	A0596179		1.06	1.28	1.15	1.02	1.26	0.70	0.93	0.70	1.15	0.88	0.93	0.89
		X31M	44	A0596179		1.03	1.26	1.11	0.97	1.22	0.70	0.85	0.70	1.08	0.83	0.88	0.85
		X31M X33A	45	A0596179		0.96	1.19	0.97	0.86	0.98	0.70	0.77	0.70	0.95	0.75	0.77	0.81
	Downstream of Sand Confluence	X33A	46	A0596179		1.06	1.27	1.07	0.92	1.05	0.72	0.77	0.70	1.02	0.82	0.84	0.93
		X33A	47	A0596179		0.99	1.26	1.03	0.93	1.09	0.70	0.77	0.70	0.99	0.80	0.81	0.84
		X33A	48	A0596179		1.04	1.30	1.01	0.95	1.04	0.74	0.77	0.70	1.05	0.82	0.81	0.86
		X33A	49	A0596179		0.99	1.27	0.99	0.94	1.03	0.70	0.76	0.70	1.00	0.81	0.81	0.83
		X33A X33B	50	A0557666		0.91	0.85	0.98	0.72	0.79	0.70	0.71	0.70	1.06	0.79	0.89	0.99
		X33B	51	A0557666		0.83	0.82	0.88	0.70	0.73	0.70	0.71	0.70	1.00	0.75	0.83	0.88
		X33B	52	A0557666	X3H015	1.03	1.07	0.93	0.83	0.88	0.83	0.71	0.81	1.18	0.88	0.92	0.98
		X33C X33D	53	A0557666		0.82	0.76	0.87	0.70	0.70	0.70	0.70	0.70	0.94	0.71	0.79	0.89
		X33D	54	A0557666		0.82	0.81	0.85	0.70	0.70	0.70	0.71	0.70	1.00	0.76	0.81	0.85
		X33D	55	A0557666		0.74	0.72	0.80	0.70	0.70	0.70	0.70	0.70	0.94	0.70	0.74	0.78
		X33D	56	A0557666		0.91	0.89	0.93	0.75	0.73	0.70	0.71	0.70	1.11	0.83	0.88	0.94

Note 1 Shaded cells indicate rainfall adjustment factors greater or equal to 10% in subcatchments which contain weirs
2 Underlined values indicate rainfall adjustment factors which exceeded 30% and were defaulted to 30% in subcatchments which contain weirs

Table B3 Subcatchments and total areas represented by each daily rainfall "driver" station used in the Sabie catchment of the KNPRRP study area

	Rainfall Driver Station Number	Subatchments Served By Rainfall Driver Station													Total Area Represented By Driver Station (km^2)
		Sand catchment						Sabie catchment							
1	A0555461							18							173.18
2	A0555573							19	20						349.60
3	A0555631							22							107.61
4	A0555878							23	31						96.40
5	A0556127							32							36.19
6	A0556183							30							138.20
7	A0556460							33	34	35	36	37	41		413.43
8	A0557666							50	51	52	53	54	55	56	807.64
9	A0594596							21							46.11
10	A0594696	1													19.83
11	A0594764	3	7												134.13
12	A0594779							29							83.58
13	A0594802							25							67.13
14	A0594806							26							89.04
15	A0595110	8						27	28						264.31
16	A0595161	2	4	5	6	9	11								382.83
17	A0595210							24							57.42
18	A0595443							38	39	40	42				638.85
19	A0595463	10	12	14	15										741.36
20	A0595816	13													111.21
21	A0596179	16	17					43	44	45	46	47	48	49	1502.31

Appendix C

KNPRRP water resources study : Determination of Potential Evaporation and Temperature

Monthly A-pan equivalent evaporation values were derived on a regional basis by multiple regression analysis from factors such as maximum temperature, daylength, distance from sea and altitude. These monthly values are then converted by Fourier Analysis to daily values internally within *the ACRU* model. The derived daily values of Potential Evaporation (E_r) are then adjusted down by 20% or up by 5% on a day-by-day basis, according to whether or not a threshold rainfall of 5mm was exceeded on that day.

The highest monthly means of daily maximum and minimum temperatures were in the Sabie catchments downstream of the Sand confluence (Subcatchments 51, 52, 54, 55, 56), while the lowest monthly means of daily maximum and minimum temperatures and the lowest mean monthly A-pan equivalent evaporations were in Subcatchment 18 of the Sabie catchment (Figures C1 and C2). The highest mean monthly A-pan equivalent evaporations, were in Subcatchment 12 of the Sand catchment (Figure C2). In winter months there is a smaller difference in E_r throughout the study area than in summer months. The figures illustrate that within the Sabie-Sand catchment significant differences in both temperature and E_r exist between subcatchments.

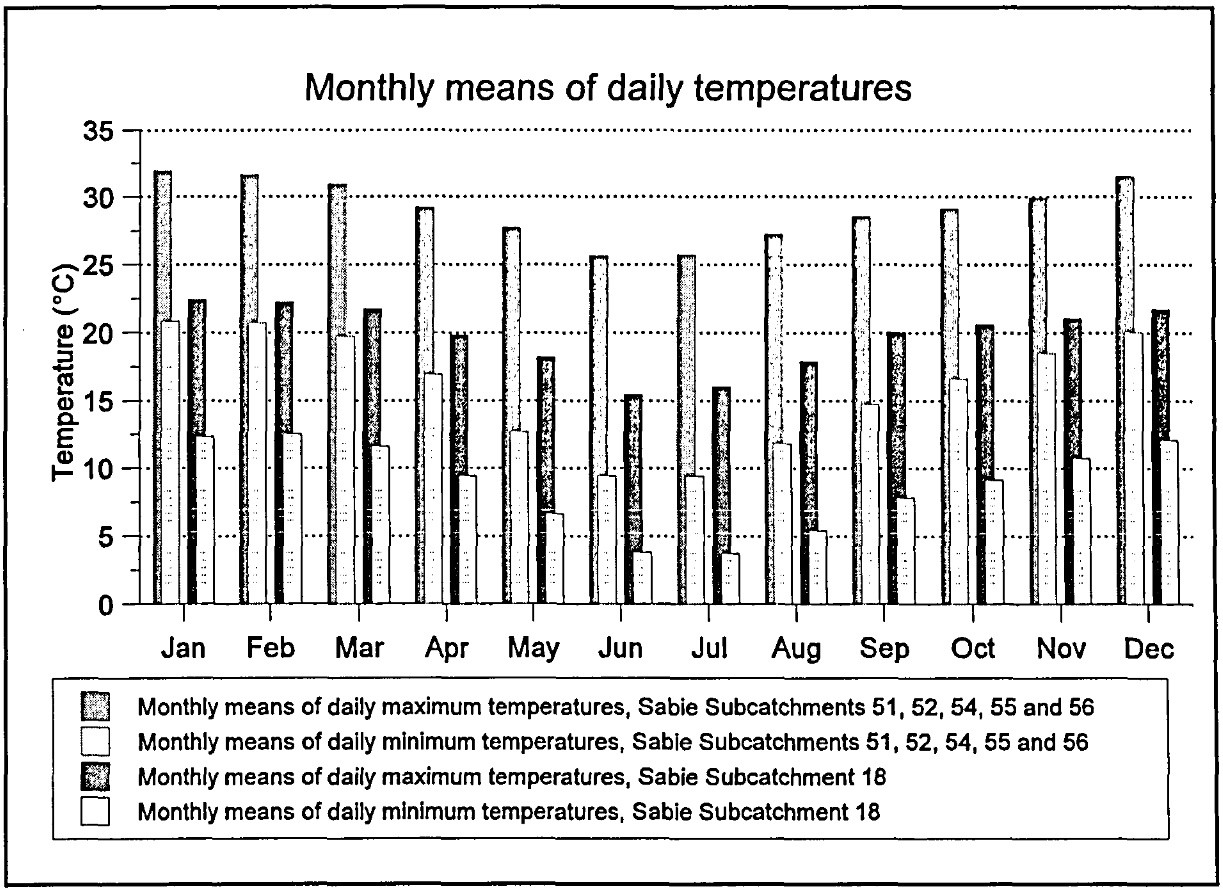

Figure C1 Ranges of monthly values of temperature in different subcatchments of the KNPRRP study area

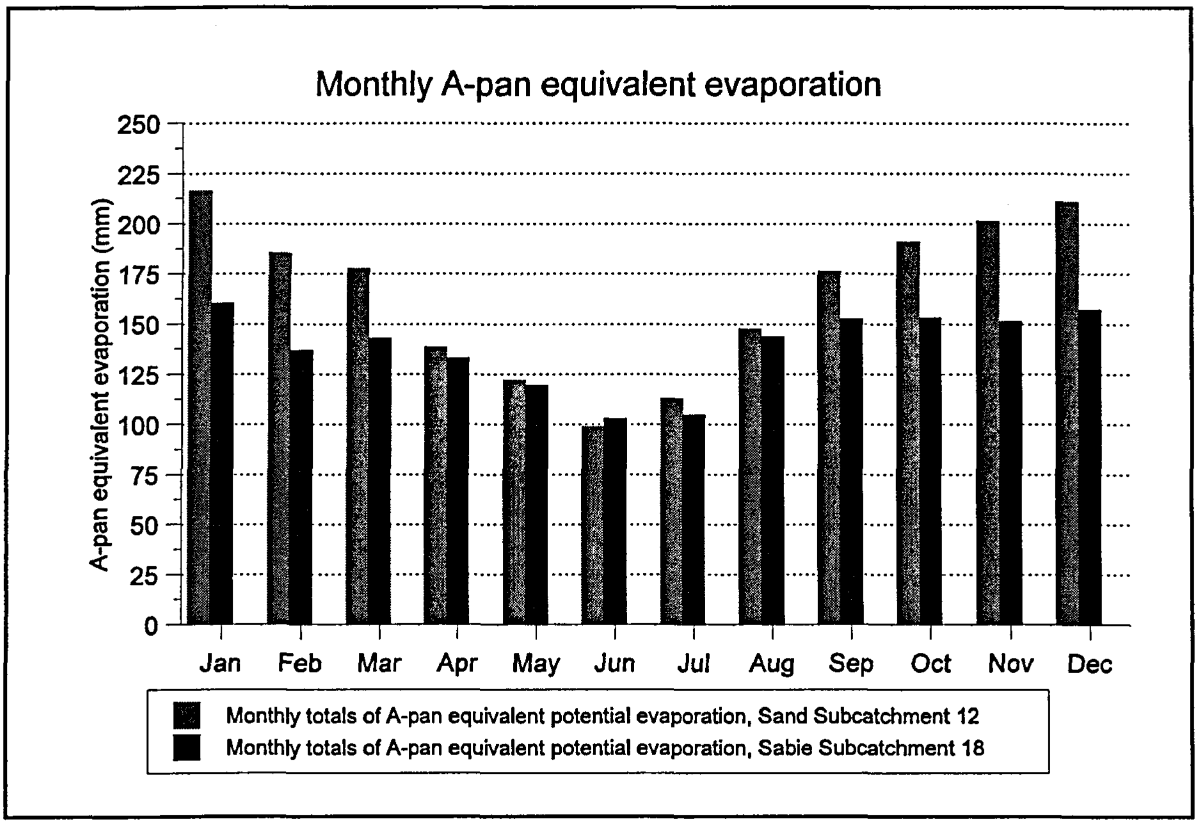

Figure C2 Ranges of mean monthly A-pan equivalent reference potential evaporations in different subcatchments of the KNPRRP study area

Appendix D

KNPRRP water resources study : Land Types and Derived Soils Properties

Table D1 Soil Land Types identified in the KNPRRP study area

A Red-yellow apedal, freely drained soils	Ab	Red dystrophic / mesotrophic soils	Ab10, Ab32 Ab33, Ab34 Ab35, Ab36 Ab37, Ab38 Ab40, Ab41 Ab42, Ab43 Ab59
	Ac	Red and yellow dystrophic / mesotrophic soils	Ac81, Ac83 Ac84, Ac85 Ac86, Ac87 Ac88, Ac89
	Ae	Red, high base status, >300mm deep, no dunes	Ae132
D Prismacutanic and / or pedocutanic soils	Dc	Duplex soils with non-red B horizons >50% of the area covered by duplex soils	Dc34
E One or more of vertic, melanic or red structured soils	Ea	Vertic, melanic or red structured soils cover > 50% area	Ea78 Ea92
F Glenrosa and / or Mispah soils	Fa	Lime not encountered frequently in soil profile	Fa330 Fa345 Fa346
	Fb	Lime occurs regularly in one or more valley bottom soils	Fb66 Fb166 Fb167 Fb168 Fb169 Fb184 Fb185
H Grey regic sands	Hb	20% of area > Constantia (Ct); Shepstone (Sp) and Vilafontes (Vf) soil forms < 80% of area	Hb1
I Other land classes	Ib	Exposed rock covers 60-80% of the area	Ib161 Ib193 Ib194

Appendix E

KNPRRP water resources study : Translation of Land Type Soils Information by the AUTOSOIL Program

AUTOSOIL output includes the thicknesses of the topsoil and subsoil horizons, values of the soil water content at permanent wilting point, drained upper limit and saturation (porosity) for both soil layers, as well as saturated drainage redistribution rates. Values of the above variables were determined for each soil series making up a Land Type and then area-weighted according to the proportions of each soil series in a Land Type and then the proportions of each Land Type found in a subcatchment. The final subcatchment values of the variables which were used in simulations of hydrological responses from present land uses are summarised in Table E1. An average dominant texture class of sandy clay loam was assumed for all subcatchments. The table also contains runoff related values, derived from Land Type information, of two further variables, *viz.* fractions of adjunct impervious areas within a subcatchment, constituting the areas around channel zones assumed to be permanently wet and from which direct overland flow is hypothesised to occur after a rainfall event, and disjunct impervious areas such as rock outcrops, from which rainfall running off infiltrates into surrounding areas and influences their water budgets.

Table E1 Subcatchment soils related information for model input in the KNPRRP study area : Sand catchment

Catchment	Sub-catchment	Thickness of A Horizon (m)	Thickness of B Horizon (m) (Area Weighted for Forestry)	Permanent Wilting Point ($m.m^{-1}$)		Drained Upper Limit ($m.m^{-1}$)		Porosity ($m.m^{-1}$)		Saturated Redistribution ($Fraction.day^{-1}$)		Adjunct Impervious Area (fraction)	Disjunct Impervious Area (fraction)
				A	B	A	B	A	B	A	B		
Sand	1	0.28	0.72	0.163	0.197	0.271	0.320	0.411	0.430	0.38	0.38	0.007	0.053
	2	0.26	0.55	0.151	0.180	0.257	0.301	0.415	0.427	0.40	0.40	0.007	0.000
	3	0.27	0.65	0.161	0.192	0.268	0.314	0.412	0.428	0.38	0.38	0.007	0.103
	4	0.26	0.51	0.146	0.174	0.251	0.293	0.418	0.429	0.42	0.42	0.007	0.000
	5	0.29	0.67	0.095	0.109	0.190	0.212	0.450	0.446	0.59	0.59	0.005	0.000
	6	0.30	0.70	0.083	0.094	0.176	0.193	0.458	0.450	0.62	0.62	0.005	0.000
	7	0.29	0.72	0.165	0.198	0.273	0.322	0.405	0.427	0.38	0.38	0.006	0.150
	8	0.28	0.63	0.125	0.147	0.225	0.259	0.431	0.437	0.50	0.50	0.005	0.016
	9	0.29	0.64	0.084	0.095	0.177	0.194	0.457	0.449	0.62	0.62	0.005	0.000
	10	0.30	0.62	0.083	0.094	0.176	0.193	0.458	0.450	0.62	0.62	0.005	0.000
	11	0.23	0.31	0.106	0.111	0.199	0.206	0.439	0.434	0.52	0.52	0.007	0.031
	12	0.28	0.55	0.086	0.097	0.179	0.195	0.456	0.448	0.60	0.60	0.006	0.004
	13	0.22	0.44	0.110	0.114	0.203	0.208	0.436	0.432	0.49	0.49	0.008	0.037
	14	0.22	0.47	0.094	0.101	0.188	0.196	0.448	0.443	0.48	0.48	0.013	0.031
	15	0.21	0.45	0.101	0.111	0.194	0.204	0.446	0.442	0.46	0.46	0.012	0.027
	16	0.21	0.46	0.121	0.132	0.210	0.222	0.446	0.441	0.44	0.44	0.009	0.016
	17	0.21	0.45	0.098	0.108	0.192	0.201	0.447	0.442	0.46	0.46	0.013	0.029

Table E2 Subcatchment soils related information for model input in the KNPRRP study area : Sabie catchment

Catchment	Sub-catchment	Thickness of A Horizon (m)	Thickness of B Horizon (m) (Area Weighted for Forestry)	Permanent Wilting Point (m.m⁻¹)		Drained Upper Limit (m.m⁻¹)		Porosity (m.m⁻¹)		Saturated Redistribution (Fraction.day⁻¹)		Adjunct Impervious Area (fraction)	Disjunct Impervious Area (fraction)
				A	B	A	B	A	B	A	B		
SABIE	18	0.31	0.75	0.169	0.198	0.277	0.321	0.400	0.424	0.38	0.38	0.002	0.070
	19	0.31	0.81	0.165	0.196	0.272	0.319	0.404	0.424	0.40	0.40	0.000	0.090
	20	0.33	0.83	0.173	0.214	0.281	0.341	0.396	0.427	0.39	0.39	0.000	0.074
	21	0.28	0.71	0.150	0.182	0.252	0.296	0.417	0.417	0.41	0.41	0.000	0.061
	22	0.31	0.79	0.166	0.205	0.274	0.330	0.401	0.425	0.40	0.40	0.002	0.108
	23	0.31	0.62	0.182	0.224	0.292	0.353	0.411	0.437	0.35	0.35	0.005	0.003
	24	0.25	0.58	0.160	0.187	0.267	0.310	0.409	0.424	0.38	0.38	0.005	0.054
	25	0.32	0.82	0.174	0.214	0.282	0.341	0.396	0.428	0.38	0.38	0.003	0.122
	26	0.32	0.81	0.168	0.208	0.276	0.334	0.401	0.426	0.39	0.39	0.004	0.112
	27	0.30	0.71	0.182	0.226	0.293	0.354	0.410	0.437	0.35	0.35	0.005	0.000
	28	0.28	0.76	0.175	0.211	0.284	0.338	0.409	0.432	0.36	0.36	0.004	0.030
	29	0.33	0.84	0.163	0.204	0.269	0.329	0.403	0.424	0.41	0.41	0.004	0.131
	30	0.28	0.72	0.165	0.200	0.273	0.324	0.407	0.428	0.38	0.38	0.004	0.037
	31	0.33	0.90	0.172	0.212	0.281	0.339	0.407	0.430	0.37	0.37	0.002	0.052
	32	0.29	0.70	0.169	0.202	0.278	0.327	0.413	0.431	0.36	0.36	0.005	0.028
	33	0.26	0.61	0.156	0.185	0.263	0.307	0.413	0.427	0.39	0.39	0.006	0.021
	34	0.28	0.60	0.124	0.147	0.226	0.260	0.442	0.442	0.47	0.47	0.004	0.001
	35	0.28	0.57	0.125	0.148	0.227	0.261	0.441	0.441	0.47	0.47	0.004	0.000
	36	0.30	0.66	0.098	0.113	0.196	0.219	0.469	0.456	0.55	0.55	0.001	0.000
	37	0.29	0.79	0.094	0.104	0.191	0.208	0.475	0.459	0.56	0.56	0.000	0.007
	38	0.23	0.45	0.130	0.136	0.230	0.244	0.440	0.439	0.44	0.44	0.002	0.034
	39	0.29	0.80	0.093	0.106	0.188	0.208	0.451	0.447	0.59	0.59	0.005	0.007
	40	0.26	0.45	0.092	0.104	0.185	0.202	0.453	0.446	0.57	0.57	0.006	0.005
	41	0.26	0.69	0.109	0.115	0.206	0.218	0.462	0.452	0.50	0.50	0.000	0.020
	42	0.22	0.35	0.107	0.114	0.198	0.206	0.449	0.444	0.46	0.46	0.013	0.026
	43	0.21	0.49	0.105	0.117	0.200	0.212	0.452	0.442	0.49	0.49	0.000	0.030
	44	0.20	0.45	0.123	0.141	0.214	0.231	0.444	0.438	0.45	0.45	0.003	0.007
	45	0.20	0.44	0.119	0.141	0.212	0.232	0.442	0.436	0.47	0.47	0.001	0.002
	46	0.21	0.46	0.097	0.105	0.190	0.198	0.447	0.443	0.45	0.45	0.015	0.034
	47	0.20	0.47	0.108	0.124	0.202	0.217	0.449	0.440	0.49	0.49	0.000	0.022
	48	0.20	0.44	0.121	0.143	0.213	0.234	0.442	0.435	0.47	0.47	0.000	0.000
	49	0.21	0.49	0.109	0.124	0.202	0.217	0.450	0.441	0.49	0.49	0.000	0.025
	50	0.26	0.65	0.160	0.196	0.245	0.282	0.428	0.438	0.44	0.44	0.007	0.009
	51	0.24	0.58	0.140	0.172	0.226	0.255	0.438	0.437	0.47	0.47	0.003	0.006
	52	0.29	0.79	0.196	0.247	0.274	0.327	0.417	0.436	0.43	0.43	0.006	0.000
	53	0.24	0.57	0.155	0.186	0.245	0.283	0.436	0.435	0.41	0.41	0.003	0.114
	54	0.26	0.68	0.177	0.219	0.261	0.306	0.423	0.436	0.43	0.43	0.003	0.011
	55	0.24	0.62	0.171	0.205	0.261	0.304	0.426	0.435	0.40	0.40	0.002	0.073
	56	0.24	0.59	0.160	0.191	0.249	0.289	0.433	0.435	0.41	0.41	0.002	0.102

Appendix F

KNPRRP water resources study : Land Cover under Assumed Present Conditions

Land cover/use input into *ACRU* includes

* an interception loss value, which can change from month to month during a plant's annual growth cycle, to account for the estimated interception of rainfall by the plant's canopy on a rainday,
* a monthly consumptive water use (or "crop") coefficient (converted internally in the model to daily values by Fourier Analysis), which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference potential evaporation (e.g. A-pan or equivalent), and
* the fraction of plant roots that are active in extracting soil moisture from the topsoil horizon in a given month, this fraction being linked to root growth patterns during a year and periods of senescence brought on, for example, by a lack of soil moisture or by frost.

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

The percentages of the areas of respective land covers for the Sand and Sabie catchments are given in Tables F1 and F2 respectively. For each of these assumed present condition land covers the *ACRU* input variables are presented in Table F3.

A number of factors should be noted:

* Areas classified "Plantations and Woodlots" were assumed, for runoff generation purposes, to respond like an equal mixture of Pine and Eucalypt of intermediate maturity and with pitting assumed to be the site preparation for both species.
* Areas classified "Grassland and Unclassified" were assumed, for runoff generation purposes, to respond like veld in fair hydrological condition.
* Areas classified "Degraded" were assumed, for runoff generation purposes, to respond like veld in poor hydrological condition.
* Areas classified "Settlements and Urban Areas" were assumed, for runoff generation purposes, to respond like urban formal residential areas of medium density.
* Areas classified "Cultivated Commercial (Mixed)" were assumed, for runoff generation purposes, to respond like maize (planting date : 1 November; growing season : 140 days).

* Areas classified "Cultivated Commercial (Irrigated)" were assumed, for runoff generation purposes, to respond like a double crop of maize and wheat.
* Areas classified "Cultivated Subsistence and Semi Commercial" were assumed, for runoff generation purposes, to respond like the *ACRU* classification of subsistence crops (lower levels of fertilizer; planting date : 1 November).

Table F1 Subcatchment distribution (%) of present land cover and land use : Sand catchment (according to CSIR LANDSAT TM, 1993)

Landsat TM classification		Plantations & Woodlots	Plantations & Woodlots	Indigenous Forest	Woodland	Grassland & Unclassified	Degraded	Settlements & Urban Areas	Cultivated Commercial (Mixed)	Cultivated Commercial (Irrigated)	Cultivated Subsistence & Semi Commercial
ACRU Classification		**Pine** (Intermediate Age; *Pitted*)	**Eucalypt** (Intermediate Age; *Pitted*)	**Indigenous Forest** (Zululand)	**Woodland** (Indigenous Tree/ *bush savannah*)	**Grassland** (Veld in *Fair Condition; All Areas*)	**Grassland** (Veld in *Poor Condition; All Areas*)	**Urban** (Formal Residential; *Medium Density*)	**Maize** (Nov. 1; *140 days; All areas*)	**Double-cropping** (*Maize & Wheat*)	**Subsistence Crops** (Scattered Plants; *Nov. 1*)
ACRU Land Cover code		9010303	9010304	8010106	7010203	9010301	7010208	7010209	3120102	3120301	7010207
Catchment	Sub-catchment										
SAND	1	14.19	14.21	10.17	51.74	0.90	8.79	0.00	0.00	0.00	0.00
	2	1.15	1.16	0.00	29.70	0.00	58.23	9.76	0.00	0.00	0.00
	3	6.28	6.30	12.36	47.71	4.49	22.04	0.82	0.00	0.00	0.00
	4	1.04	1.05	0.00	8.62	1.16	77.02	11.11	0.00	0.00	0.00
	5	0.00	0.00	0.00	48.43	0.53	41.68	5.68	2.27	0.00	1.41
	6	0.00	0.01	0.00	49.93	0.78	42.84	1.59	0.03	0.00	4.82
	7	4.33	4.34	29.45	54.95	3.99	0.11	1.15	1.68	0.00	0.00
	8	4.47	4.48	0.00	31.24	1.13	48.69	6.34	1.93	0.00	1.72
	9	0.00	0.00	0.00	28.52	0.88	56.15	0.64	0.42	0.00	13.39
	10	0.00	0.00	0.00	20.88	0.12	66.29	1.98	0.14	0.00	10.59
	11	0.00	0.00	0.00	0.39	0.00	95.17	4.44	0.00	0.00	0.00
	12	0.09	0.10	0.00	16.57	0.06	64.37	0.38	0.49	0.00	17.94
	13	0.00	0.00	0.00	77.11	0.32	20.69	0.64	0.00	0.00	1.24
	14	0.00	0.00	0.00	87.25	0.12	9.71	0.00	0.00	0.00	2.92
	15	0.00	0.00	0.00	99.09	0.00	0.88	0.00	0.03	0.00	0.00
	16	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	17	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F2 Subcatchment distribution (%) of present land cover and land use : Sabie catchment (according to CSIR LANDSAT TM, 1993)

Landsat TM classification		Plantations & Woodlots	Plantations & Woodlots	Indigenous Forest	Woodland	Grassland & Unclassified	Degraded	Settlements & Urban Areas	Cultivated Commercial (Mixed)	Cultivated Commercial (Irrigated)	Cultivated Subsistence & Semi Commercial
ACRU Classification		**Pine** (Intermediate Age; Pitted)	**Eucalypt** (Intermediate Age; Pitted)	**Indigenous Forest** (Zululand)	**Woodland** (Indigenous Tree/ bush Savannah)	**Grassland** (Veld in Fair Condition; All Areas)	**Grassland** (Veld in Poor Condition; All Areas)	**Urban** (Formal Residential; Medium Density)	**Maize** (Nov. 1; 140 days; All areas)	**Double-cropping** (Maize & Wheat)	**Subsistence Crops** (Scattered Plants; Nov. 1)
ACRU Land Cover code		9010303	9010304	8010106	7010203	9010301	7010208	7010209	3120102	3120301	7010207
Catchment	Sub-catchment										
SABIE	18	28.04	28.05	16.07	0.00	25.74	0.00	2.10	0.00	0.00	0.00
	19	34.88	34.90	13.88	0.00	14.92	0.00	1.42	0.00	0.00	0.00
	20	29.01	29.02	2.60	14.47	16.59	0.00	0.39	0.06	7.86	0.00
	21	37.06	37.06	1.18	0.00	23.16	0.00	1.54	0.00	0.00	0.00
	22	32.87	32.88	13.14	0.06	21.05	0.00	0.00	0.00	0.00	0.00
	23	3.39	3.39	0.00	5.25	3.25	0.00	0.00	0.00	84.72	0.00
	24	3.49	3.50	0.00	50.24	0.15	0.00	0.00	34.96	7.66	0.00
	25	38.37	38.38	9.04	0.38	13.83	0.00	0.00	0.00	0.00	0.00
	26	34.88	34.88	14.53	0.00	15.71	0.00	0.00	0.00	0.00	0.00
	27	21.02	21.02	0.00	6.12	46.88	0.00	4.96	0.00	0.00	0.00
	28	13.82	13.84	0.00	63.66	2.00	2.65	0.00	4.03	0.00	0.00
	29	39.36	39.37	3.16	0.00	16.47	0.00	1.64	0.00	0.00	0.00
	30	20.55	20.56	0.00	36.40	1.31	17.60	0.62	2.72	0.00	0.24
	31	43.95	43.96	0.00	5.92	6.17	0.00	0.00	0.00	0.00	0.00
	32	16.95	16.96	0.00	31.72	0.85	0.00	0.00	0.00	33.52	0.00
	33	7.30	7.31	0.00	41.24	0.61	22.85	5.17	12.01	3.51	0.00
	34	0.00	0.00	0.00	33.52	0.00	42.93	8.66	14.89	0.00	0.00
	35	0.00	0.00	0.00	21.40	0.00	52.02	3.46	23.12	0.00	0.00
	36	0.00	0.00	0.00	37.05	0.00	59.78	3.17	0.00	0.00	0.00
	37	0.00	0.00	0.00	95.28	0.00	4.63	0.00	0.00	0.00	0.09
	38	0.00	0.00	0.00	35.84	0.00	45.90	8.77	0.00	0.00	9.49
	39	0.29	0.30	0.00	93.23	0.09	1.00	0.34	1.15	0.00	3.60
	40	0.00	0.00	0.00	2.43	0.00	78.57	3.96	1.46	0.00	13.58
	41	0.00	0.00	0.00	99.98	0.00	0.02	0.00	0.00	0.00	0.00
	42	0.00	0.00	0.00	38.74	0.15	40.01	4.33	9.97	0.00	6.80
	43	0.00	0.00	0.00	99.89	0.00	0.00	0.11	0.00	0.00	0.00
	44	0.00	0.00	0.00	99.41	0.00	0.04	0.51	0.01	0.00	0.03
	45	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	46	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	47	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	48	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	49	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	50	0.00	0.00	0.00	99.97	0.03	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	52	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	53	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	54	0.00	0.00	0.00	99.95	0.05	0.00	0.00	0.00	0.00	0.00
	55	0.00	0.00	0.00	99.87	0.06	0.00	0.07	0.00	0.00	0.00
	56	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F3 Month-by-month input variables for *ACRU* for present land covers and land uses (Note: Units of interception loss : mm.rainday^{-1}; other variables are dimensionless)

MAIZE -ALL AREAS Planting Date : 1 November Growing Season : 140 days	*ACRU* Land Cover code	3120102											
	Water Use Coefficient	1.10	0.95	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.98
	Interception Loss	1.50	1.40	1.30	1.20	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.90
	Roots in Topsoil	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
DOUBLE CROPPING Maize and Wheat	*ACRU* Land Cover code	3120301											
	Water Use Coefficient	1.10	0.95	0.46	0.00	0.20	0.30	0.60	0.97	0.94	0.20	0.49	0.98
	Interception Loss	1.50	1.40	1.30	0.00	0.50	1.00	1.30	1.50	1.00	0.00	0.50	1.00
	Roots in Topsoil	0.74	0.78	0.91	0.96	1.00	0.92	0.75	0.65	0.55	1.00	0.92	0.79
WOODLAND (Indigenous Tree/ bush savannah)	*ACRU* Land Cover code	7010203											
	Water Use Coefficient	0.75	0.75	0.75	0.65	0.55	0.40	0.40	0.50	0.65	0.75	0.75	0.75
	Interception Loss	2.00	2.00	2.00	1.80	1.60	1.60	1.60	1.60	1.60	1.80	1.90	2.00
	Roots in Topsoil	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.90	0.85	0.80	0.80
SUBSISTENCE CROPS Scattered Plants Planting Date : 1 November	*ACRU* Land Cover code	7010207											
	Water Use Coefficient	0.80	0.70	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.20	0.35	0.60
	Interception Loss	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50
	Roots in Topsoil	0.79	0.79	0.78	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90
VELD, POOR HYDROLOGICAL CONDITION - ALL AREAS no frost	*ACRU* Land Cover code	7010208											
	Water Use Coefficient	0.55	0.55	0.55	0.45	0.20	0.20	0.20	0.20	0.40	0.45	0.55	0.55
	Interception Loss	0.80	0.80	0.80	0.70	0.60	0.60	0.60	0.60	0.65	0.75	0.80	0.80
	Roots in Topsoil	0.90	0.90	0.90	0.94	1.00	1.00	1.00	1.00	0.95	0.92	0.90	0.90
FORMAL RESIDENTIAL, MEDIUM DENSITY (Pervious portion) no frost	*ACRU* Land Cover code	7010209											
	Water Use Coefficient	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.70	0.80	0.80	0.80
	Interception Loss	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.20	1.30	1.40	1.40
	Roots in Topsoil	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.90	0.90	0.90	0.90
INDIGENOUS FOREST - ZULULAND	*ACRU* Land Cover code	7010106											
	Water Use Coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Interception Loss	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	Roots in Topsoil	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
VELD, FAIR HYDROLOGICAL CONDITION - ALL AREAS no frost	*ACRU* Land Cover code	9010301											
	Water Use Coefficient	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	Interception Loss	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.20
	Roots in Topsoil	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
PINE, INTERMEDIATE AGE Site preparation: pitting	*ACRU* Land Cover code	9010303											
	Water Use Coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Interception Loss	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	Roots in Topsoil	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
EUCALYPT, INTERMEDIATE AGE Site preparation: pitting	*ACRU* Land Cover code	9010304											
	Water Use Coefficient	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Interception Loss	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	Roots in Topsoil	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Appendix G

KNPRRP water resources study : Irrigation

The following information on irrigation practices in the KNPRRP catchments was assumed for the *ACRU* model runs:

* the water use by ginger was assumed to be the same as that of summer tomatoes,
* the coefficient of initial abstraction (*COAIRR*) for all irrigated crops in all months was assumed to be 0.25,
* the soil texture for irrigated soils (*ITEXTI*) was assumed to be Sandy Clay Loam with soil moisture contents at permanent wilting point (*WPIR*) of 0.159 $m.m^{-1}$, at drained upper limit (*FCIR*) of 0.254 $m.m^{-1}$ and at porosity (*POIR*) of 0.402 $m.m^{-1}$,
* the interception loss (*DINTIR*) for all irrigated crops was assumed to be 1.1 $mm.rainday^{-1}$,
* the potential maximum rooting depths of all irrigated crops under prevailing conditions (*RDMAX*) were assumed to be 1.0 m while the soil depth to which the majority of soil water extraction takes place for all fully grown irrigated crops (*RDUP*) was assumed to be 0.8 m,
* Table G1 contains the crop coefficients of the irrigated crops at maximum rooting depths (*CCOV*) and at maximum ground cover (*CCMAX*), the amount of water applied per 7 day irrigation cycle (*IRAMT*) and the sources of the irrigation water (*IRRAPL*),
* the maximum ground cover (PGRDM) for all irrigated crops was assumed to be 100 per cent while the critical leaf water potential (*CRLW*) for all irrigated crops was assumed to be -1200.0 kPa,
* the irrigation schedule (*ISCHED*) was halted (according to the operating rules explained in the *ACRU* Manual) once a threshold rainfall (*RLIM*) of 20 mm had been exceeded,
* conveyance losses (*CONLOS*) were taken to be 11%, while wind drift and spray evaporation losses (*EVWIN*) were assumed to be 10%. Balancing farm dam losses (*FAMLOS*) were not considered in this study,
* all irrigation abstractions were assumed to occur from water sources within the subcatchment in which irrigation was practised (*INCELL*), and all irrigation return flows (from stormflows and deep percolation) were thus returned initially to their own subcatchment outlets (*UPSTIR*),
* the total area (ha) irrigated per subcatchment for each month is given in Table G2 and the month-by-month water use coefficients for the perennial, summer and winter irrigated crops are given in Tables G3, G4 and G5 respectively (it is assumed that transpiration ceases for water use coefficients of less than 0.3), and
* the subcatchment distribution (%) of irrigated crops is shown in Table G6 while Table G7 contains the final area weighted water use coefficients for all subcatchments containing irrigation.

Table G1 Input information on irrigation for the KNPRRP study area

Catchment	Sub-catchment	Application Amount (mm)	Source of Irrigation Water	Water Use Coefficient at Maximum Rooting Depth	Water Use Coefficient at Maximum Ground Cover
SAND	5	15	Reservoir	0.53	0.53
	6	25	Reservoir	0.41	0.51
	8	18	River	0.57	0.57
	9	25	Reservoir	0.49	0.51
	12	22	River	0.46	0.51
SABIE	20	17	River	0.61	0.61
	23	17	Reservoir	0.61	0.61
	24	17	Reservoir	0.58	0.58
	28	25	River	0.70	0.70
	30	21	River	0.63	0.63
	31	17	Reservoir	0.61	0.61
	32	17	Reservoir	0.61	0.61
	33	17	Reservoir	0.61	0.61
	34	17	Reservoir	0.61	0.61
	35	20	River	0.57	0.57
	38	25	River	0.46	0.51
	42	15	River	0.53	0.53

Table G2 Total area irrigated (ha) per subcatchment for each month in the KNPRRP study area

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	5	585	585	585	585	585	585	585	585	585	585	585	585
	6	1000	1000	1000	970	970	970	970	970	970	1000	1000	1000
	8	425	425	425	385	385	385	385	385	385	425	425	425
	9	680	680	680	580	580	580	580	580	580	680	680	680
	12	405	405	405	405	405	405	405	405	405	405	405	405
SABIE	20	1482	1482	1482	1275	1275	1275	1275	1275	1275	1482	1482	1482
	23	1235	1235	1235	1063	1063	1063	1063	1063	1063	1235	1235	1235
	24	1365	1365	1365	899	899	899	899	899	899	1365	1365	1365
	28	100	100	100	5	5	5	5	5	5	100	100	100
	30	625	625	625	275	275	275	275	275	275	625	625	625
	31	148	148	148	128	128	128	128	128	128	148	148	148
	32	840	840	840	723	723	723	723	723	723	840	840	840
	33	741	741	741	638	638	638	638	638	638	741	741	741
	34	247	247	247	213	213	213	213	213	213	247	247	247
	35	373	373	373	229	229	229	229	229	229	373	373	373
	38	400	400	400	180	180	180	180	180	180	400	400	400
	42	765	765	765	765	765	765	765	765	765	765	765	765

Table G3 Monthly water use coefficients for irrigated perennial crops in the KNPRRP study area

Land Cover	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avocados	*ACRU* Land Cover code	3010101											
	Water Use Coefficient	0.71	0.67	0.65	0.60	0.57	0.55	0.52	0.62	0.72	0.75	0.76	0.72
Pastures	*ACRU* Land Cover code	3021001											
	Water Use Coefficient	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
Citrus	*ACRU* Land Cover code	3021101											
	Water Use Coefficient	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Bananas	*ACRU* Land Cover code	3021201											
	Water Use Coefficient	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Tea	*ACRU* Land Cover code	7770101											
	Water Use Coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Pecan Nuts	*ACRU* Land Cover code	7770102											
	Water Use Coefficient	0.65	0.65	0.65	0.65	0.35	0.35	0.35	0.65	0.65	0.65	0.65	0.65
Mangos	*ACRU* Land Cover code	7770103											
	Water Use Coefficient	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Macadamias	*ACRU* Land Cover code	7770104											
	Water Use Coefficient	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Litchis	*ACRU* Land Cover code	7770105											
	Water Use Coefficient	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Coffee	*ACRU* Land Cover code	7770106											
	Water Use Coefficient	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Deciduous Fruit	*ACRU* Land Cover code	7770107											
	Water Use Coefficient	0.50	0.59	0.42	0.20	0.20	0.20	0.20	0.20	0.23	0.27	0.31	0.40

Table G4 Monthly water use coefficients for irrigated summer crops in the KNPRRP study area

Land Cover	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ground Nuts	*ACRU* Land Cover code	3020401											
	Water Use Coefficient	0.62	0.50	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.63
Tobacco	*ACRU* Land Cover code	3020801											
	Water Use Coefficient	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.36	0.74	0.90
Cotton	*ACRU* Land Cover code	3020901											
	Water Use Coefficient	0.84	0.88	0.75	0.43	0.31	0.20	0.20	0.20	0.20	0.20	0.28	0.53
Maize	*ACRU* Land Cover code	3120102											
	Water Use Coefficient	1.10	0.95	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.98
Beans	*ACRU* Land Cover code	7770108											
	Water Use Coefficient	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.40	0.70	0.70	0.20
Tomatoes	*ACRU* Land Cover code	7770111											
	Water Use Coefficient	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.40	0.70	0.70
Onions	*ACRU* Land Cover code	7770113											
	Water Use Coefficient	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.60	0.70	0.70	0.20
Cucurbits	*ACRU* Land Cover code	7770115											
	Water Use Coefficient	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.40	0.60	0.70	0.70
Brassicas	*ACRU* Land Cover code	7770117											
	Water Use Coefficient	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.50	0.70	0.70	0.20
Soya	*ACRU* Land Cover code	7770120											
	Water Use Coefficient	0.70	0.90	0.95	0.80	0.50	0.20	0.20	0.20	0.20	0.20	0.20	0.50

Note : Water Use Coefficients for Ginger assumed to be same as for summer Tomato

Table G5 Monthly water use coefficients for irrigated winter crops in the KNPRRP study area

Land Cover	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Potatoes	*ACRU* Land Cover code	3020604											
	Water Use Coefficient	0.20	0.20	0.40	0.71	0.99	1.00	0.20	0.20	0.20	0.20	0.20	0.20
Beans	*ACRU* Land Cover code	7770109											
	Water Use Coefficient	0.20	0.20	0.20	0.40	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20
Peas	*ACRU* Land Cover code	7770110											
	Water Use Coefficient	0.20	0.20	0.30	0.40	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20
Tomatoes	*ACRU* Land Cover code	7770112											
	Water Use Coefficient	0.20	0.20	0.30	0.40	0.70	0.70	0.70	0.20	0.20	0.20	0.20	0.20
Onions	*ACRU* Land Cover code	7770114											
	Water Use Coefficient	0.20	0.30	0.60	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Cucurbits	*ACRU* Land Cover code	7770116											
	Water Use Coefficient	0.20	0.20	0.40	0.60	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20
Brassicas	*ACRU* Land Cover code	7770118											
	Water Use Coefficient	0.20	0.20	0.50	0.70	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Maize	*ACRU* Land Cover code	7770119											
	Water Use Coefficient	0.20	0.20	0.20	0.20	0.49	0.98	1.10	0.95	0.46	0.20	0.20	0.20

Table G6 Subcatchment distribution (%) of irrigated crops for the KNPRRP study area (according to Chunnett, Fourie and Partners, 1990)

		Catchment	Sand					Sabie											
	Crop	*ACRU* Land Cover code	5	6	8	9	12	20	23	24	28	30	31	32	33	34	35	38	42
Perennial Crops	Avocados	3010101						12.00	12.00	6.37		7.20	12.00	12.00	12.00	12.00	5.16		
	Pastures	3021001			9.30														
	Citrus	3021101	65.81				25.60	2.00	2.00	29.03		22.40	2.00	2.00	2.00	2.00	34.84		64.94
	Banana	3021201			2.33			66.00	66.00	15.93		8.00	66.00	66.00	66.00	66.00	5.16		
	Tea	7770101						2.00	2.00	0.35			2.00	2.00	2.00	2.00			
	Pecan Nuts	7770102										3.20							
	Mangos	7770103	34.19				4.00			3.19							3.87		32.47
	Macadamia Nuts	7770104						1.00	1.00	0.18			1.00	1.00	1.00	1.00			
	Litchis	7770105										0.80							1.30
	Coffee	7770106			60.47					0.80							0.97		
	Deciduous Fruit	7770107						0.80	0.80	4.39		2.40	0.80	0.80	0.80	0.80	5.16		
Summer Crops	Ground Nuts	3020401		2.54		5.56	3.20											6.90	
	Tobacco	3020801						14.00	14.00	26.90	95.24	51.20	14.00	14.00	14.00	14.00	29.68		
	Cotton	3020901																6.90	
	Maize	3120102		30.46		42.86	25.60											34.48	
	Beans	7770108		5.08			3.20			0.27							0.32	6.90	
	Tomatoes	7770111		2.54						0.27							0.32		0.65
	Ginger	7770111			18.60			1.00	1.00	8.14		4.80	1.00	1.00	1.00	1.00	9.68		
	Onions	7770113		2.54						0.27							0.32	6.90	
	Cucurbits	7770115		5.08		5.56	3.20			0.27							0.32	6.90	
	Brassicas	7770117								0.27							0.32		
	Soya Beans	7770120		2.54	4.65														
Winter Crops	Potatoes	3020604																5.17	
	Beans	7770109					5.60	0.20	0.20	0.57			0.20	0.20	0.20	0.20	0.65		
	Peas	7770110						0.20	0.20	0.57			0.20	0.20	0.20	0.20	0.65		
	Tomatoes	7770112		25.38	2.33	23.81	7.20	0.20	0.20	0.57			0.20	0.20	0.20	0.20	0.65	5.17	0.65
	Onions	7770114		2.54		11.11	5.60	0.20	0.20	0.57			0.20	0.20	0.20	0.20	0.65	5.17	
	Cucurbits	7770116			2.33		5.60	0.20	0.20	0.57	4.76		0.20	0.20	0.20	0.20	0.65	5.17	
	Brassicas	7770118		6.09		11.11	5.60	0.20	0.20	0.57			0.20	0.20	0.20	0.20	0.65	5.17	
	Maize	7770119		15.23			5.60											5.17	

Table G7 Final area weighted water use coefficients for all subcatchments containing irrigation

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	5	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	6	0.51	0.47	0.36	0.31	0.42	0.45	0.46	0.32	0.27	0.26	0.37	0.49
	8	0.66	0.67	0.58	0.57	0.56	0.54	0.52	0.51	0.54	0.57	0.63	0.65
	9	0.61	0.55	0.43	0.36	0.43	0.32	0.32	0.20	0.21	0.22	0.36	0.59
	12	0.58	0.55	0.47	0.44	0.50	0.47	0.42	0.38	0.37	0.37	0.45	0.57
SABIE	20	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	23	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	24	0.53	0.48	0.47	0.47	0.47	0.46	0.45	0.46	0.47	0.52	0.62	0.66
	28	0.39	0.20	0.21	0.22	0.22	0.22	0.20	0.20	0.20	0.35	0.71	0.87
	30	0.54	0.44	0.41	0.40	0.39	0.38	0.38	0.40	0.41	0.50	0.71	0.79
	31	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	32	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	33	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	34	0.69	0.65	0.65	0.64	0.64	0.64	0.63	0.64	0.65	0.68	0.74	0.76
	35	0.50	0.44	0.44	0.43	0.43	0.43	0.41	0.42	0.43	0.48	0.60	0.64
	38	0.58	0.53	0.41	0.32	0.37	0.33	0.27	0.25	0.27	0.30	0.42	0.56
	42	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66

Appendix H

KNPRRP water resources study : Runoff

Stormflow from a rainfall event depends on

* the *magnitude* of the rainfall (hence daily rainfall input),
* the *initial abstractions* (I_a) before runoff commences (i.e. interception, surface depression storage and initial infiltration - hence inputs on soil properties and seasonally varying evaporative demand, plus a coefficient of initial abstraction, cI_a, which also accounts for seasonal rainfall intensity patterns),
* the *wetness of the catchment* (hence the daily multi-soil layer water budget), and
* a *critical soil depth* (D_{sc}) which is considered to "control" stormflow generation (and which is dependent on vegetation, soil and rainfall characteristics).
* The stormflow generated from the catchment's hillslopes after a given rainfall event does not all reach the stream on the same day as the rain fell, because part of it is a delayed lateral flow. A delay factor (F_{sr}) has therefore been incorporated in *ACRU* (dependent on catchment slope, area, soil and vegetation characteristics).
* The rain that falls on the permanently wet riparian zone (i.e. adjunct impervious areas) is considered to contribute to same-day and direct stormflow.

The baseflow contribution

* derives from soil water which has *percolated* out of the base of the subsoil horizon (hence the importance of soil depth and the saturated redistribution fraction) into a baseflow store, from which
* baseflow amounts are released into the stream at an exponential decay rate (F_{bfi}).

Tables H1 and H2 contain values of coefficients of initial abstraction (cI_a) for the Sand and Sabie catchments respectively while critical soil depths (D_{sc}) were input as the thickness of the topsoil horizons for all land covers/uses except in the case of afforestation, where from previous verification studies (Schulze, 1995) an area-weighted value was used (with the maximum value for D_{sc} of 0.40m resulting from a subcatchment containing 100% afforestation).

Values for saturated redistribution rates and adjunct and disjunct impervious areas are given for the Sand and Sabie catchments in Table E1 and E2. Finally, stormflow delay factors (F_{sr}) and baseflow decay rates (F_{bfi}) were assigned regional default values of 0.30 (3.0% per day) and 0.009 (0.9% per day) respectively.

In order to model the runoff hydrograph generated from a particular rainfall event more realistically, the hydrograph routine option within the *ACRU* model was invoked. This option requires information on subcatchment slope and channel slope, channel width and the side slope of the main channel for the downstream channel. This information is given in Tables H3 and H4.

Table H1 Coefficients of initial abstraction (cI_a) for the KNPRRP study area : Sand catchment

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	1	0.25	0.25	0.25	0.25	0.31	0.31	0.31	0.31	0.31	0.31	0.25	0.25
	2	0.17	0.17	0.17	0.17	0.21	0.21	0.21	0.21	0.21	0.21	0.17	0.17
	3	0.23	0.23	0.23	0.23	0.28	0.28	0.28	0.28	0.28	0.28	0.23	0.23
	4	0.16	0.16	0.16	0.16	0.19	0.19	0.19	0.19	0.19	0.19	0.16	0.16
	5	0.18	0.18	0.18	0.18	0.24	0.24	0.24	0.24	0.24	0.24	0.18	0.18
	6	0.18	0.18	0.18	0.18	0.24	0.24	0.24	0.24	0.24	0.24	0.19	0.18
	7	0.26	0.26	0.26	0.26	0.32	0.32	0.32	0.32	0.32	0.32	0.26	0.26
	8	0.19	0.19	0.19	0.19	0.23	0.23	0.23	0.23	0.23	0.23	0.19	0.19
	9	0.17	0.17	0.17	0.17	0.22	0.22	0.22	0.22	0.22	0.22	0.19	0.18
	10	0.17	0.17	0.17	0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.18	0.17
	11	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15
	12	0.17	0.17	0.17	0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.18
	13	0.19	0.19	0.19	0.19	0.27	0.27	0.27	0.27	0.27	0.27	0.19	0.19
	14	0.20	0.20	0.20	0.20	0.29	0.29	0.29	0.29	0.29	0.29	0.20	0.20
	15	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	16	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	17	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20

Table H2 Coefficients of initial abstraction (cI_a) for the KNPRRP study area : Sabie catchment

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SABIE	18	0.31	0.31	0.31	0.31	0.34	0.34	0.34	0.34	0.34	0.34	0.31	0.31
	19	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.33
	20	0.29	0.29	0.29	0.29	0.33	0.33	0.32	0.32	0.32	0.32	0.30	0.29
	21	0.31	0.31	0.31	0.31	0.34	0.34	0.34	0.34	0.34	0.34	0.31	0.31
	22	0.32	0.32	0.32	0.32	0.34	0.34	0.34	0.34	0.34	0.34	0.32	0.32
	23	0.21	0.21	0.21	0.21	0.30	0.26	0.22	0.22	0.22	0.22	0.34	0.25
	24	0.21	0.21	0.21	0.21	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.23
	25	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.33
	26	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.33
	27	0.26	0.26	0.26	0.26	0.32	0.32	0.32	0.32	0.32	0.32	0.26	0.26
	28	0.24	0.24	0.24	0.24	0.31	0.31	0.31	0.31	0.31	0.31	0.24	0.24
	29	0.32	0.32	0.32	0.32	0.34	0.34	0.34	0.34	0.34	0.34	0.32	0.32
	30	0.25	0.25	0.25	0.25	0.29	0.29	0.29	0.29	0.29	0.29	0.26	0.25
	31	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.33
	32	0.25	0.25	0.25	0.25	0.32	0.30	0.28	0.28	0.28	0.28	0.30	0.27
	33	0.21	0.21	0.21	0.21	0.26	0.26	0.26	0.26	0.26	0.26	0.23	0.22
	34	0.18	0.18	0.18	0.18	0.22	0.22	0.22	0.22	0.22	0.22	0.19	0.19
	35	0.17	0.17	0.17	0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19
	36	0.17	0.17	0.17	0.17	0.21	0.21	0.21	0.21	0.21	0.21	0.17	0.17
	37	0.20	0.20	0.20	0.20	0.29	0.29	0.29	0.29	0.29	0.29	0.20	0.20
	38	0.18	0.18	0.18	0.18	0.23	0.23	0.23	0.23	0.23	0.23	0.19	0.18
	39	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.21	0.20
	40	0.16	0.16	0.16	0.16	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17
	41	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	42	0.18	0.18	0.18	0.18	0.23	0.23	0.23	0.23	0.23	0.23	0.20	0.19
	43	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	44	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	45	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	46	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	47	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	48	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	49	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	50	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	51	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	52	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	53	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	54	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	55	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
	56	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20

Table H3 Inputs to flow routing for the KNPRRP study area : Sand catchment

Catchment	Sub-catchment	Sub-catchment Slope (%) *SLOPE*	Slope of Downstream Channel (%) *CSLOPE*	Length of Downstream Channel (m) *CHLEN*	Bottom Width of Downstream Channel (m) *BWIDTH*	Side Slope of Main Channel (Horizontal units per vertical unit) *ZSIDE*
SAND	1	110.3	110.54	68000.0	40.0	10.0
	2	30.6	30.59	102000.0	40.0	10.0
	3	120.3	120.38	64000.0	40.0	10.0
	4	30.2	30.23	93000.0	40.0	10.0
	5	20.8	20.78	151000.0	40.0	10.0
	6	20.6	20.61	190000.0	40.0	10.0
	7	170.0	170.25	165000.0	40.0	10.0
	8	40.8	40.80	62000.0	40.0	10.0
	9	20.5	20.54	85000.0	40.0	10.0
	10	20.8	20.85	190000.0	40.0	10.0
	11	20.0	20.03	195000.0	40.0	10.0
	12	20.4	20.39	183000.0	40.0	10.0
	13	10.5	10.55	60000.0	40.0	10.0
	14	10.7	10.69	160000.0	40.0	10.0
	15	20.1	20.10	276000.0	80.0	10.0
	16	20.3	20.35	104000.0	80.0	10.0
	17	20.1	20.13	50000.0	80.0	10.0

Table H4 Inputs to flow routing for the KNPRRP study area : Sabie catchment

Catchment	Sub-catchment	Sub-catchment Slope (%) *SLOPE*	Slope of Downstream Channel (%) *CSLOPE*	Length of Downstream Channel (m) *CHLEN*	Bottom Width of Downstream Channel (m) *BWIDTH*	Side Slope of Main Channel (Horizontal units per vertical unit) *ZSIDE*
SABIE	18	160.0	20.13	50000.0	40.0	10.0
	19	110.6	160.04	299000.0	40.0	10.0
	20	100.1	110.75	299000.0	40.0	10.0
	21	70.3	100.18	100000.0	40.0	10.0
	22	120.0	70.47	258000.0	40.0	10.0
	23	40.7	110.94	100000.0	40.0	10.0
	24	90.0	40.72	62300.0	40.0	10.0
	25	90.5	90.00	86000.0	40.0	10.0
	26	110.3	90.65	107000.0	40.0	10.0
	27	40.5	110.32	79000.0	40.0	10.0
	28	50.3	40.54	95000.0	40.0	10.0
	29	70.2	50.32	158000.0	40.0	10.0
	30	60.5	70.19	148000.0	40.0	10.0
	31	70.8	60.57	86000.0	40.0	10.0
	32	80.4	70.77	45000.0	40.0	10.0
	33	70.8	80.37	114000.0	40.0	10.0
	34	50.1	70.81	48000.0	40.0	10.0
	35	40.9	50.11	70000.0	40.0	10.0
	36	50.2	40.92	244000.0	40.0	10.0
	37	30.0	50.22	100000.0	40.0	10.0
	38	30.1	20.95	196000.0	80.0	10.0
	39	40.9	30.10	402000.0	80.0	10.0
	40	20.4	40.90	265000.0	80.0	10.0
	41	20.3	20.60	402000.0	40.0	10.0
	42	20.1	20.34	402000.0	80.0	10.0
	43	20.1	20.05	396000.0	80.0	10.0
	44	10.9	20.10	134000.0	150.0	10.0
	45	10.9	10.87	50000.0	150.0	10.0
	46	20.0	10.86	285500.0	150.0	10.0
	47	20.0	20.04	285500.0	150.0	10.0
	48	10.9	10.98	43000.0	250.0	10.0
	49	20.1	10.89	180000.0	250.0	10.0
	50	10.7	20.08	180000.0	300.0	10.0
	51	10.9	10.75	15900.0	250.0	10.0
	52	10.7	10.89	80000.0	300.0	10.0
	53	20.5	10.71	115000.0	300.0	10.0
	54	10.7	20.52	37000.0	300.0	10.0
	55	20.3	10.72	91000.0	300.0	10.0
	56	20.2	20.27	100.0	300.0	10.0

Appendix I

KNPRRP water resources study: Afforestation

* In the simulation of 'afforestation' the *ACRU* model takes cognisance of tree genera (i.e. it distinguishes between water use characteristics of eucalypts and pines, but not between species within a genera), tree age, site preparation technique and some of the other attributes which change with afforestation, including changes in LAI, canopy interception, wet canopy evaporation rates, initial infiltration, rooting characteristics and plant water stress thresholds. The plant water stress for the three genera is assumed to commence at different fractions of plant available water, *viz.* 0.9 for pines and 0.1 for eucalypts (Schulze, 1995). This indicates that pines are a more conservative water consumer than the other genera, by already partially closing stomata at high plant available water.
* Assuming established rotations to be in place, with some trees young and others of intermediate age or mature or just harvested, a mean tree age of 8 years for pines and 3 to 5 years for eucalypts, was input for simulations.
* From previous verification studies on afforested catchments (Schulze, 1995), the thicknesses of the subsoil horizons were increased by an area-weighted percentage of a maximum of 0.25 m (for a subcatchment containing 100% afforestation).

Appendix J

KNPRRP water resources study : Dams

The dam/reservoir water budget in *ACRU* consists of daily *gains* through streamflows, rainfall onto the water surface areas and (where applicable) inter-basin water transfers, and *losses* through surface water evaporation, abstractions by irrigation and for other purposes, overflow, normal flow releases for downstream riparian users and seepage. To effect a dam water budget the individual dams' capacities at full supply, shapes of the dams and surface areas at full supply need to be known. Furthermore, estimates of seepage (assumed to be 1/1 500 of full supply capacity per day for earth walled dams) and normal flow releases (also assumed to be 1/1500 of full supply capacity per day), obtained from Chuunett and Fourie (1990) or WRSM90) need to be made.

In *ACRU* model runs, dead storage was input as 10% and month-by-month reservoir evaporation rates were obtained for this area from the *ACRU* User Manual, with values varying from 0.62 of A-pan evaporation in winter to 0.72 in autumn (see Figure J1). No information on abstractions or water transfers from any reservoirs was available at the time of this study. Information on reservoirs and their associated operating rules, as required for the *ACRU* model, are summarised in Table J1.

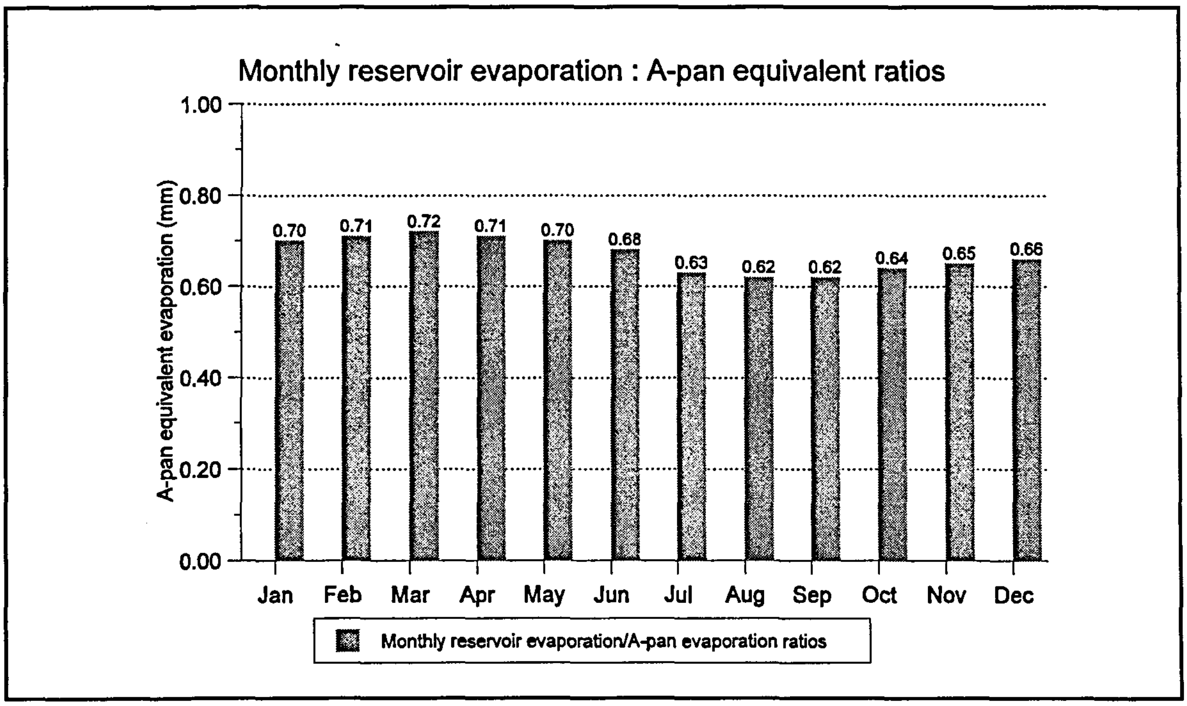

Figure J1 Monthly reservoir : A-pan equivalent evaporation ratios for the KNPRRP study area

Table J1 Input (and other) information of dams in the KNPRRP study area

Catchment	Quaternary Catchment Number	Subcatchment	Reservoir Name	Reservoir Capacity at Full Supply (m^3) *DAMCAP*	Source	Reservoir Surface Area at Full Supply (ha) *SURFAC*	Source	Reservoir Shape *ARCAP*	Normal Flow ($m^3.day^{-1}$) *QNORM*	Seepage ($m^3.day^{-1}$) *SEEP*	Initial Reservoir Storage (%) *PERDAM*	Dead Storage (%) *DEDSTO*	Wall Length (m) *WIDTH*	Source	Assumed Spillway Width (m) *SWIDTH*	Coefficient of Discharge *CDISCH*	Remarks
SAND	X32A	4	Casteel	1600000.	Chunnett, Fourie & Partners	17.66	GIS	Default	7295.3	1066.0	80.0	10.0	230.0	GIS	5.0+	3.0	
	X32C	5	Acorn's Hoek	1100000.	Chunnett, Fourie & Partners	33.66	GIS	Default	84.4	733.0	80.0	10.0	307.0	GIS	5.0+	3.0	
		6	Edinburgh	3300000.	Chunnett, Fourie & Partners	25.72	GIS	Default	131.5	2200.0	80.0	10.0	275.0	GIS	5.0+	3.0	
	X32F	9	Orinoco	1900000.	Chunnett, Fourie & Partners	17.01	GIS	Default	92.5	1266.0	80.0	10.0	275.0	GIS	5.0+	3.0	
SABIE	X31A	19		50000.	WRSM90	2.00	WRSM90	Default	720.9	33.0	80.0	10.0	18.0**	Calc	2.0+	3.0	Individual dams lumped together
	X31D	23		3008000.	WRSM90	128.00	WRSM90	Default	11.8	2005.0	80.0	10.0	37.0**	Calc	5.0+	3.0	Individual dams lumped together
		24		600000.	WRSM90	13.00	WRSM90	Default	23645.7	400.0	80.0	10.0	24.0**	Calc	3.0+	3.0	Individual dams lumped together
	X31J	31	Da Gama	13600000.	Chunnett, Fourie & Partners	123.54	GIS	Default	19.7	9066.0	80.0	10.0	400.0	GIS	50.0+	3.0	
		32		14803000.	WRSM90	165.00	WRSM90	Default	31.3	9868.0	80.0	10.0	150.0**	Calc	50.0+	3.0	Individual dams lumped together
		33		376000.	WRSM90	12.00	WRSM90	Default	69.7	250.0	80.0	10.0	79.0**	Calc	3.0+	3.0	Individual dams lumped together
	X31K	34		110000.	WRSM90	1.00	WRSM90	Default	84.9	73.0	80.0	10.0	11.0**	Calc	2.0+	3.0	Individual dams lumped together
	X33B	52	Lower Sabie	800000.	Chunnett, Fourie & Partners	25.28*	Calc	Default	4.1	533.0	80.0	10.0	116.0**	Calc	5.0+	3.0	

* denotes surface areas calculated using area:volume relationship on pg AT14-9 (Schulze, 1995)

** denotes wall lengths calculated using average area:length and volume:length relationships

Note : all spillway widths have been estimated

Appendix K

KNPRRP water resources study : Sediment Yield

The following assumptions were made in the estimation of the event-by-event catchment sediment yield by the Modified Universal Soil Loss Equation (MUSLE):

* The slope length and steepness factor (*LS*) was calculated from the average catchment slope within the *ACRU* model.
* No conservation practices were supported within the Sand or Sabie catchments (*P*).
* 30% of the event based sediment yield from the catchment reaches the outlet on the day of the event.
* No information was available for the estimation of the runoff erosivity constants (α_{sy} and β_{sy}). Defaults of 8.934 and 9.560 were assumed for these constants respectively.

The maximum and minimum soil erodibility factors (K_{max} and K_{min})and the monthly cover factors (*C*) are given in Table K1 for each subcatchment. These were derived from land use and soils information, using information supplied in the *ACRU* User Manual

Table K1 Maximum and minimum soil erodibility factors (K_{max} and K_{min}) and monthly cover factors (*C*) for the Sand catchment

Catchment	Sub-catchment	Maximum Soil Erodibility Factor (K_{max})	Minimum Soil Erodibility Factor (K_{min})	Monthly Cover Factors (*C*)											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	1	0.26	0.06	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.04	0.04	0.03	0.03	0.02
	2	0.33	0.07	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02
	3	0.28	0.06	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
	4	0.38	0.08	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02
	5	0.80	0.19	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	6	0.80	0.22	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
	7	0.23	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	8	0.59	0.13	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02
	9	0.80	0.22	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02
	10	0.80	0.22	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02
	11	0.70	0.16	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	12	0.80	0.21	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	13	0.65	0.14	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	14	0.78	0.17	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	15	0.77	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	16	0.75	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	17	0.77	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01

Table K2 Maximum and minimum soil erodibility factors (K_{max} and K_{min}) and monthly cover factors (C) for the Sabie catchment

Catchment	Sub-catchment	Maximum Soil Erodibility Factor (K_{max})	Minimum Soil Erodibility Factor (K_{min})	Monthly Cover Factors (C)											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SABIE	18	0.21	0.05	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.07	0.06	0.05	0.05	0.04
	19	0.24	0.05	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.08	0.07	0.06	0.05	0.05
	20	0.18	0.05	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.07	0.06	0.06	0.05	0.04
	21	0.32	0.07	0.04	0.05	0.06	0.07	0.08	0.09	0.09	0.09	0.08	0.07	0.06	0.05
	22	0.21	0.05	0.04	0.04	0.05	0.06	0.07	0.08	0.08	0.08	0.07	0.06	0.05	0.04
	23	0.17	0.05	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.04	0.04
	24	0.24	0.05	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.01
	25	0.17	0.05	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.09	0.08	0.07	0.06	0.05
	26	0.20	0.05	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.08	0.07	0.06	0.05	0.05
	27	0.17	0.05	0.03	0.03	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.05	0.04	0.03
	28	0.19	0.05	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.04	0.04	0.03	0.03	0.02
	29	0.22	0.05	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.09	0.08	0.07	0.06	0.05
	30	0.23	0.05	0.03	0.03	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.05	0.04	0.03
	31	0.20	0.05	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.10	0.09	0.08	0.07	0.06
	32	0.22	0.05	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.05	0.04	0.04
	33	0.29	0.06	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.02
	34	0.54	0.12	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
	35	0.53	0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	36	0.75	0.17	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
	37	0.79	0.18	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
	38	0.55	0.12	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02
	39	0.80	0.20	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	40	0.80	0.20	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	41	0.71	0.16	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	42	0.77	0.17	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
	43	0.78	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	44	0.77	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	45	0.78	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	46	0.76	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	47	0.80	0.18	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	48	0.78	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	49	0.79	0.18	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	50	0.63	0.14	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	51	0.74	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	52	0.54	0.12	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	53	0.63	0.14	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	54	0.58	0.13	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	55	0.55	0.12	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	56	0.60	0.13	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01

Appendix L

KNPRRP water resources study : Domestic Abstractions and Inter-Basin Transfers from Rivers

Abstractions from rivers for purposes other than irrigation included domestic water consumption and water supply to game and livestock as well as two water transfer schemes from Subcatchment 35, viz. Water supply to Pretoriouskop and KaNgwane (see Executive Summary). These annual volumes were either obtained from Chunnett, Fourie and Partners (1990) and from WRSM90 or were derived from livestock and human population census figures. These annual total consumptions were apportioned between each month while still conserving the total volume. Tables L1 and L2 contain estimated livestock and human populations, the associated effective water consumption and the water transfer scheme in Subcatchment 35 for the Sand and Sabie catchments respectively. The final estimated monthly river abstractions are given in Table K3 and K4 for the Sand and Sabie catchments respectively.

Table L1 Estimated livestock and human populations, the associated effective water consumption and water transfers for the Sand catchments

Catchment	Sub-catchment	Equivalent head of livestock	Estimated water consumption by livestock and game (at 45 $l.head^{-1}.day^{-1}$) (1000 $m^3.day^{-1}$)	Projected Population for 1996 (5% growth compounded annually)	Estimated human consumption (at 10 $l.person^{-1}.day^{-1}$) (1000 $m^3.day^{-1}$)	Inter-Basin Transfers (1000 $m^3.day^{-1}$)	Total Estimated Water Use (Cols 4+6+7) (1000 $m^3.day^{-1}$)
SAND	1	2130	0.096	9869	0.099		0.195
	2	2130	0.096	10587	0.106		0.202
	3	2130	0.096	20135	0.201		0.297
	4	2130	0.096	6209	0.062		0.158
	5	2130	0.096	31732	0.317		0.413
	6	3333	0.150	9580	0.096		0.246
	7	2130	0.096	21128	0.211		0.307
	8	3032	0.136	32017	0.320		0.457
	9	1664	0.075	5685	0.057		0.132
	10	3634	0.164	7830	0.078		0.242
	11	3634	0.164	2296	0.023		0.186
	12	3367	0.152	29741	0.297		0.449
	13	3100	0.140	4821	0.048		0.188
	14	3367	0.152	2039	0.020		0.172
	15	1500	0.067	516	0.005		0.073
	16	966	0.043	225	0.002		0.046
	17	966	0.043	225	0.002		0.046

Table L2 Estimated livestock and human populations, the associated effective water consumption and water transfers for the Sabie catchments

Catchment	Sub-catchment	Equivalent head of livestock	Estimated water consumption by livestock and game (at 45 l.head⁻¹.day⁻¹) (1000 m³.day⁻¹)	Projected Population for 1996 (5% growth compounded annually)	Estimated human consumption (at 10 l.person⁻¹.day⁻¹) (1000 m³.day⁻¹)	Inter-Basin Transfers (1000 m³.day⁻¹)	Total Estimated Water Use (Cols 4+6+7) (1000 m³.day⁻¹)
SABIE	18	966	0.043	11560	0.116		0.159
	19	966	0.043	3415	0.034		0.078
	20	1083	0.049	3415	0.034		0.083
	21	966	0.043	5044	0.050		0.094
	22	1199	0.054	3415	0.034		0.088
	23	1548	0.070	1737	0.017		0.087
	24	2205	0.099	32661	0.327		0.426
	25	2130	0.096	7417	0.074		0.170
	26	1432	0.064	2061	0.021		0.085
	27	2731	0.123	20458	0.205		0.327
	28	2431	0.109	0	0.000		0.109
	29	1141	0.051	3415	0.034		0.085
	30	2072	0.093	11270	0.113		0.206
	31	966	0.043	3415	0.034		0.078
	32	1432	0.064	1737	0.017		0.082
	33	1419	0.064	29666	0.297		0.361
	34	3647	0.164	12084	0.121		0.285
	35	2506	0.113	14991	0.150	2.09	2.348
	36	3984	0.179	3545	0.035		0.215
	37	3142	0.141	10923	0.109		0.251
	38	3032	0.136	29519	0.295		0.432
	39	3558	0.160	11393	0.114		0.274
	40	3634	0.164	14967	0.150		0.313
	41	1766	0.079	4748	0.047		0.127
	42	2567	0.115	10475	0.105		0.220
	43	1366	0.061	112	0.001		0.063
	44	2033	0.091	3545	0.035		0.127
	45	966	0.043	225	0.002		0.046
	46	966	0.043	225	0.002		0.046
	47	966	0.043	225	0.002		0.046
	48	966	0.043	225	0.002		0.046
	49	966	0.043	225	0.002		0.046
	50	966	0.043	225	0.002		0.046
	51	966	0.043	225	0.002		0.046
	52	966	0.043	225	0.002		0.046
	53	966	0.043	225	0.002		0.046
	54	966	0.043	225	0.002		0.046
	55	966	0.043	225	0.002		0.046
	56	966	0.043	225	0.002		0.046

Table L3 Monthly abstractions (m^3) from rivers in the Sand catchment for purposes other than irrigation

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SAND	1	200	200	200	200	200	200	200	200	200	200	200	200
	2	200	200	200	200	200	200	200	200	200	200	200	200
	3	300	300	300	300	300	300	300	300	300	300	300	300
	4	200	200	200	200	200	200	200	200	200	200	200	200
	5	400	400	400	400	400	400	400	400	400	400	400	400
	6	200	200	200	200	200	200	200	200	200	200	200	200
	7	300	300	300	300	300	300	300	300	300	300	300	300
	8	500	500	500	500	500	500	500	500	500	500	500	500
	9	100	100	100	100	100	100	100	100	100	100	100	100
	10	200	200	200	200	200	200	200	200	200	200	200	200
	11	200	200	200	200	200	200	200	200	200	200	200	200
	12	400	400	400	400	400	400	400	400	400	400	400	400
	13	200	200	200	200	200	200	200	200	200	200	200	200
	14	200	200	200	200	200	200	200	200	200	200	200	200
	15	100	000	100	000	100	000	100	000	100	000	100	000
	16	100	000	100	000	100	000	100	000	100	000	100	000
	17	100	000	100	000	100	000	100	000	100	000	100	000

Table L4 Monthly abstractions (m^3) from rivers in the Sabie catchment for purposes other than irrigation

Catchment	Sub-catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
SABIE	18	200	200	200	200	200	200	200	200	200	200	200	200	2400
	19	200	000	200	000	200	000	200	000	200	000	200	000	1200
	20	200	000	200	000	200	000	200	000	200	000	200	000	1200
	21	200	000	200	000	200	000	200	000	200	000	200	000	1200
	22	200	000	200	000	200	000	200	000	200	000	200	000	1200
	23	200	000	200	000	200	000	200	000	200	000	200	000	1200
	24	400	400	400	400	400	400	400	400	400	400	400	400	4800
	25	200	200	200	200	200	200	200	200	200	200	200	200	2400
	26	200	000	200	000	200	000	200	000	200	000	200	000	1200
	27	300	300	300	300	300	300	300	300	300	300	300	300	3600
	28	100	100	100	100	100	100	100	100	100	100	100	100	1200
	29	200	000	200	000	200	000	200	000	200	000	200	000	1200
	30	200	200	200	200	200	200	200	200	200	200	200	200	2400
	31	200	000	200	000	200	000	200	000	200	000	200	000	1200
	32	200	000	200	000	200	000	200	000	200	000	200	000	1200
	33	400	400	400	400	400	400	400	400	400	400	400	400	4800
	34	300	300	300	300	300	300	300	300	300	300	300	300	3600
	35	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	27600
	36	200	200	200	200	200	200	200	200	200	200	200	200	2400
	37	300	300	300	300	300	300	300	300	300	300	300	300	3600
	38	400	400	400	400	400	400	400	400	400	400	400	400	4800
	39	300	300	300	300	300	300	300	300	300	300	300	300	3600
	40	300	300	300	300	300	300	300	300	300	300	300	300	3600
	41	100	100	100	100	100	100	100	100	100	100	100	100	1200
	42	200	200	200	200	200	200	200	200	200	200	200	200	2400
	43	100	000	100	000	100	000	100	000	100	000	100	000	600
	44	100	100	100	100	100	100	100	100	100	100	100	100	1200
	45	100	000	100	000	100	000	100	000	100	000	100	000	600
	46	100	000	100	000	100	000	100	000	100	000	100	000	600
	47	100	000	100	000	100	000	100	000	100	000	100	000	600
	48	100	000	100	000	100	000	100	000	100	000	100	000	600
	49	100	000	100	000	100	000	100	000	100	000	100	000	600
	50	100	000	100	000	100	000	100	000	100	000	100	000	600
	51	100	000	100	000	100	000	100	000	100	000	100	000	600
	52	100	000	100	000	100	000	100	000	100	000	100	000	600
	53	100	000	100	000	100	000	100	000	100	000	100	000	600
	54	100	000	100	000	100	000	100	000	100	000	100	000	600
	55	100	000	100	000	100	000	100	000	100	000	100	000	600
	56	100	000	100	000	100	000	100	000	100	000	100	000	600

Appendix M

KNPRRP water resources study : Verification

Daily observed streamflow data were available from the DWAF gauging stations X3H008 on the Sand River and X3H001, X3H002, X3H003, X3H004, X3H007, X3H011 and X3H015 on the Sabie River. Data were not available for weir X3H006 at the time of this study. The data from the all stations except for X3H001 and X3H004 were found to be unsuitable for a verification study, since many periods of missing data were found in the record and it was apparent that the some of the structures were being overtopped during periods of high streamflows. Since the runoff generating area upstream of weir X3H004 is made up of three subcatchments containing many hundreds of hectares of irrigation, and given the uncertainties related to the irrigation regimes of these subcatchments, it was decided to exclude this weir from the verification study. Consequently, a streamflow verification was carried out at DWAF gauging station X3H001, located at the outlet of Subcatchment 18 on the Sabie River.

For the purpose of this study, the *ACRU* model was run with flow routing invoked (see Smithers and Caldecott's chapter in Schulze, *1995* for a description of flood routing in the *ACRU* model). This option "routes" the runoff which is generated for each subcatchment, attenuating the streamflow through the stream channels and dams (according to their physical characteristics), thereby circumventing the problem of an entire days' runoff "arriving" at the outlet of a subcatchment at one time. The resulting lagged simulated streamflow at X3H001 was then compared with the observed streamflow record. Table M1 contains the monthly statistical results from the verification run of the *ACRU* model.

Table M1 Results from the verification of monthly totals of daily streamflows at X3H001 in Subcatchment 18 of the Sabie river system for the full simulation period (1940 to 1995)

Statistic	Monthly Verification
Sum of observed data (mm)	13174.10
Sum of simulated data (mm)	13289.32
Percentage difference between total observed and simulated flows	-0.87
Median annual observed flow (mm)	293.60
Median annual simulated flow (mm)	262.50
Percentage difference between coefficients of variation of observed and simulated flows	-39.30
Percentage difference between the skewness coefficients of observed and simulated flows	-5.60
Gradient of a scatter plot of observed vs estimated flows	1.12
Y-intercept of the regression line (mm)	-2.83
Correlation coefficient	0.80
Coefficient of agreement of observed vs simulated flows	0.88

Monthly totals of daily simulated and observed streamflows as well as accumulated totals of streamflows from the verification study for weirs X3H003, X3H011 and X3H007 are shown in Figures M1, M2 and M3 respectively. X3H007 are shown in Figures M1, M2 and M3 respectively.

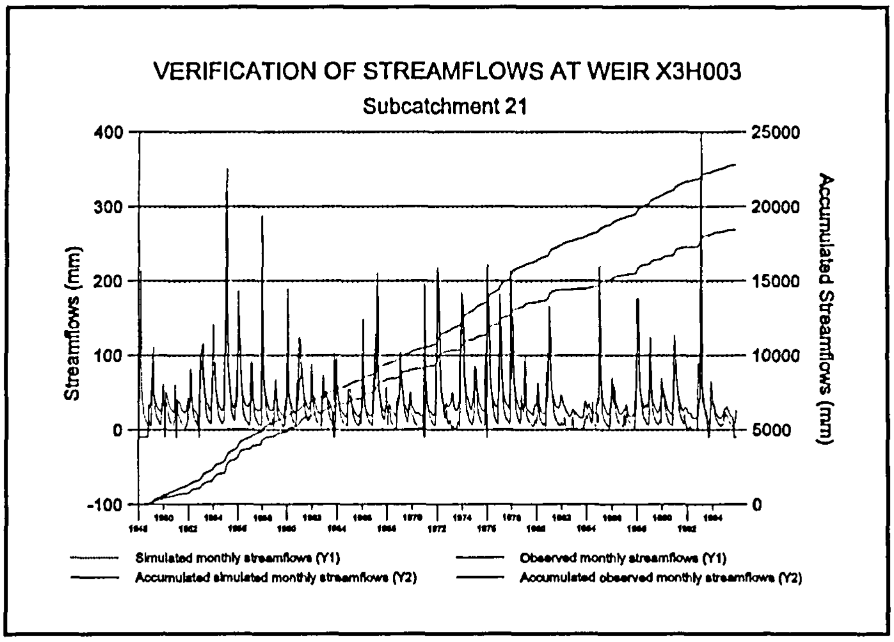

Figure M1 Accumulated and monthly simulated and observed streamflows at weir X3H003 for the period 1953 to 1995

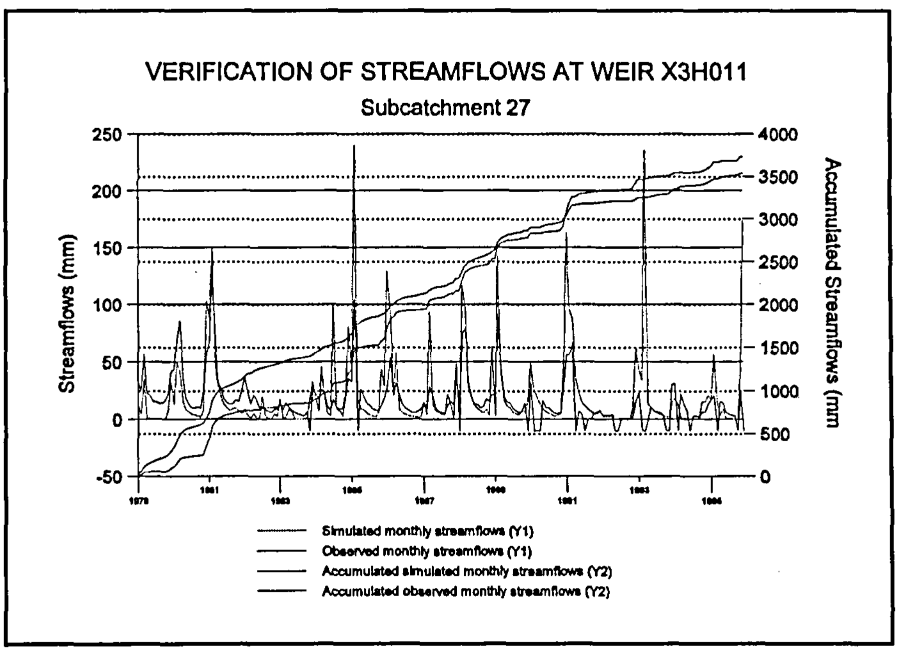

Figure M2 Accumulated and monthly simulated and observed streamflows at weir X3H011 for the period 1979 to 1995

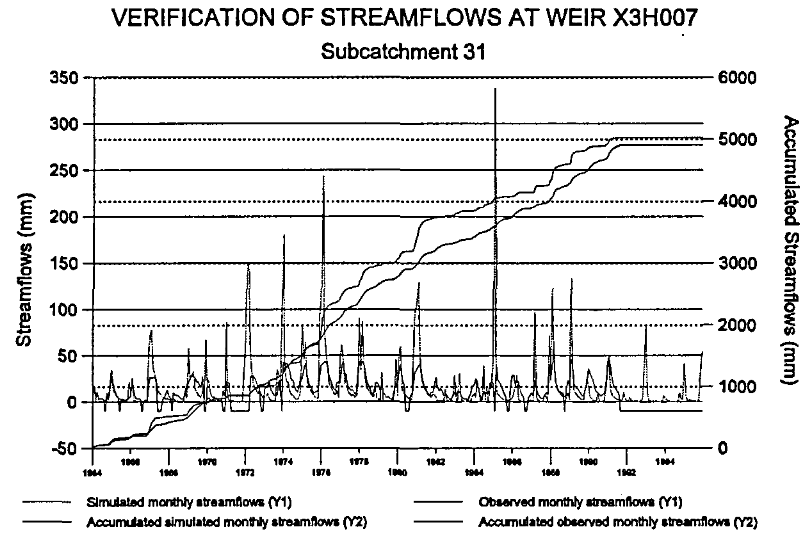

Figure M3 Accumulated and monthly simulated and observed streamflows at weir X3H007 for the period 1964 to 1995