Modelling Abiotic-Biotic Links in the Sabie River

GPW Jewitt • GL Heritage • DC Weeks • JA Mackenzie
A van Niekerk • AHM Görgens • J O'Keeffe • K Rogers
M Horn

Report to the Water Research Commission
by the
Institute for Water Research
Rhodes University

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KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

MODELLING ABIOTIC-BIOTIC LINKS IN THE SABIE RIVER

by

G.P.W. Jewitt[1], G.L. Heritage[2], D.C. Weeks[3], J.A. Mackenzie[2], A. van Niekerk[2], A.H.M. Görgens[1], J. O'Keeffe[3], K. Rogers[2] *and* M. *Horn*[4]

[1]Department of Civil Engineering
University of Stellenbosch
Stellenbosch
South Africa

[2]Centre for Water in the Environment
University of the Witwatersrand
Johannesburg
South Africa

[3]Institute for Water Research
Rhodes University
Grahamstown
South Africa

[4]Computing Centre for Water Research
University of Natal
Pietermaritzburg
South Africa

Report to the Water Research Commission on the project *Abiotic-Biotic Links in the Sabie River: The responses of riverine biota to changing hydrology and geomorphology*

PROJECT LEADERS: **J. O'Keeffe, A.H.M. Görgens, K. Rogers**

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DEDICATION

Andre van Niekerk
1960-1996

Whilst conducting fieldwork in 1996, a motor vehicle accident resulted in fatal injuries to our colleague, Andre van Niekerk. Andre made significant inputs to the research behind this project report. He contributed greatly to state of the art rivers research in South Africa, publishing significant work in the fields of fluvial hydraulics and geomorphology, and was one of the principal proponents of the concepts behind the linking of channel geomorphology to biotic assemblages, contained within these pages. His absence will be sorely felt by his colleagues, and the wider research community in South Africa and the rest of the World. We extend our sincere sympathies to his wife Simone and his children Benjie and Michael.

Members of the BLINK project team.

THE KRUGER NATIONAL PARK RIVERS RESEARCH PROGRAMME

The Kruger National Park Rivers Research Programme is a co-operative, interdisciplinary endeavour. It is directed at contributing to the conservation of the natural environment of rivers through developing skills and methodologies required to predict the response of the systems to natural and anthropogenic factors affecting water supply (quantity and quality); skills and methodologies required to establish the social acceptability of predicted changes; and through directed research, to develop the understanding of the ecological functioning of these systems required to improve the quality of prediction and advice to resource-use managers, researchers and stakeholders.

EXECUTIVE SUMMARY

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

ABIOTIC-BIOTIC LINKS IN THE SABIE RIVER: THE RESPONSES OF RIVERINE BIOTA TO CHANGING HYDROLOGY AND GEOMORPHOLOGY

The project arose as a result of a realisation by participants of the KNPRRP that links between the respective research components regarding the biotic and abiotic processes, were not clearly defined and were not being adequately addressed by the existing projects encompassed by the programme.

The stated project objectives were:

1. To draw together the abiotic and biotic information and knowledge collected by the KNPRRP into a suite of models which will improve the ability of researchers and resource managers to predict biotic response to geomorphological and hydrological changes in the Sabie River.
2. To use the above synthesised information to begin an implementation phase of the KNPRRP, in which environmental recommendations for the Sabie River can be supported by information and predictions from the Programme.
3. To contribute, by means of examples specific to the Sabie River, to the project of Dr. Jackie King, investigating abiotic/biotic links in other rivers.

The overall purpose of the project was to develop integrative modelling skills within the KNPRRP which could be transferred to the broader freshwater research community. Several innovative methods and techniques were explored in generating an integrated suite of models to estimate the responses of fish and riparian vegetation to changing hydrology and geomorphology of the Sabie River. These include:

1. The use of qualitative rule-based models (QRBMs) to simulate changes in geomorphology, fish and riparian vegetation,
2. The development of new techniques for relating fish habitat to river channel morphology,
3. The development of a geomorphology-based riparian vegetation model, and

4. The development of new tools and use of recent computing advances, such as graphical programming, hypertext documents and the internet, to aid in the transfer of data and information and the visualisation of model results.

As the project neared the end of its one-year lifespan, it became clear that many of the techniques developed, and methodologies applied, could not be rigorously tested before the final report was due. Consequently, the development and application of these methods is reported and it is accepted that their testing is incomplete. This document concentrates on the **processes** and **methodologies** developed in forging links between abiotic processes and abiotic responses, and in developing predictive potential, rather than on the application and testing of the resulting models.

The project was known as the KNPRRP Biotic Links project and is referred to in this document as the BLINKs project. A brief overview of the final report follows.

1. LINKING ABIOTIC PROCESSES AND BIOTIC RESPONSES IN THE RIVERS OF THE KRUGER NATIONAL PARK

The Kruger National Park (KNP) is South Africa's premier national park and a major drawcard to local and foreign tourists. The Park is dependent upon several rivers for its water supply, all of which rise outside of the Park's borders (Figure 1). Agricultural, forestry and industrial development as well as an urgent need to develop water supplies for a burgeoning human population increasingly affect these catchments. This increasing demand has affected water quality and quantity in the KNP rivers and is placing its riparian ecosystems under threat.

"The Kruger National Park Rivers Research Programme (KNPRRP) is a multi-disciplinary 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 flow of water forms the major connecting link between the various catchment components (Figure 2). Water, its quality and quantity, is the common concern in all the disciplines involved in KNPRRP. Thus, the development of an hydrology-based catchment modelling system in which "modules" from other disciplines may be incorporated will provide a particularly useful tool to bring together products from different KNPRRP projects, as well as providing an aid to managers and planners in identifying effective sustainable management options for the rivers of the KNP.

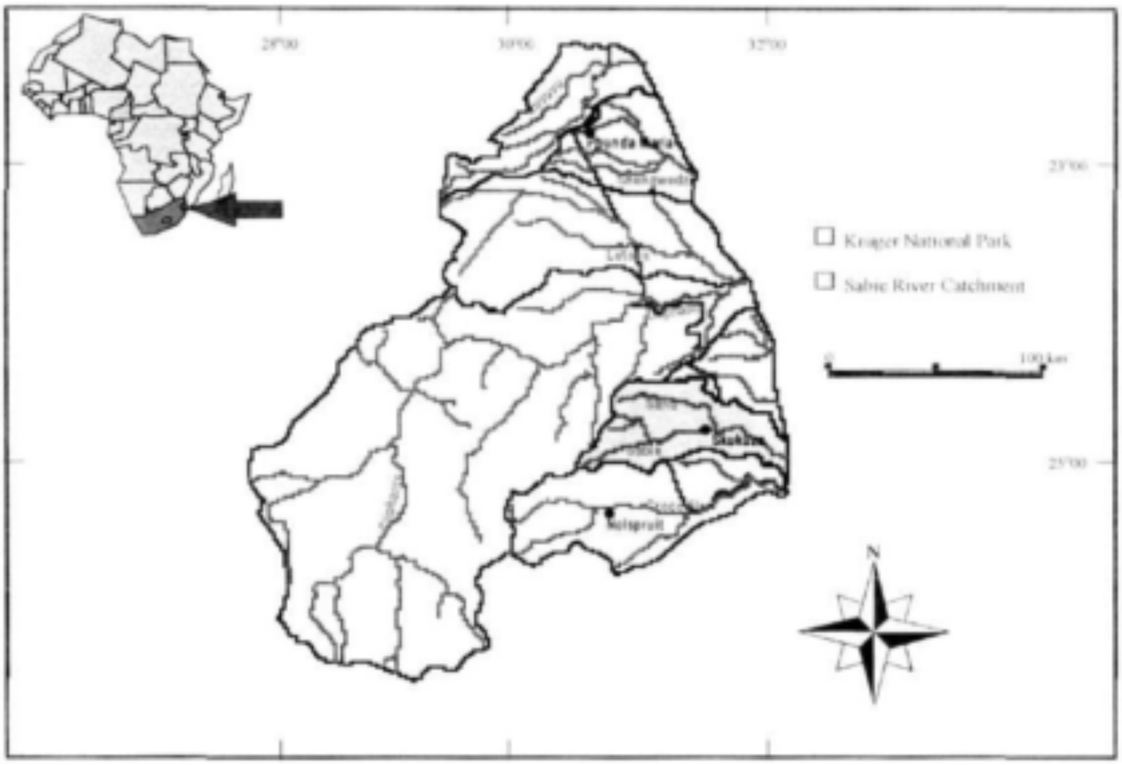

Figure 1. Location of the Kruger National Park and Sabie River Catchment.

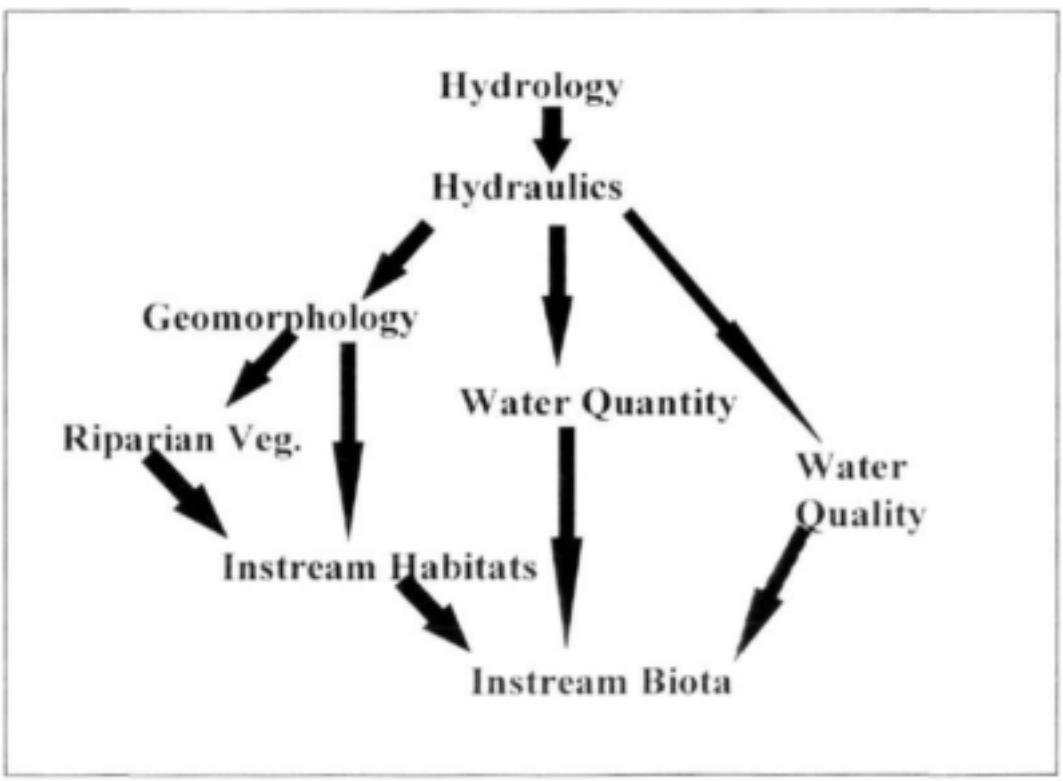

Figure 2. Conceptual flow of the linkages between abiotic and biotic components of a river system.

Since the inception of the KNPRRP, there has been an awareness of the need to relate aquatic biotic responses to abiotic channel and catchment conditions. The ultimate aim in forging these links is to establish the flow requirements of the aquatic ecosystems.

Project Goals and Structure

Usually, 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. However, others have recognised that fluvial geomorphology is the logical integrating discipline to link river response to ecological functioning, as it is the geomorphology that forms the physical template for habitat development. This recognition was developed in this project and the habitat provided by the geomorphic template is a significant component of all the models developed.

The final product of this project is a suite of models which consists of an hydrology model and three qualitative rule-based models (QRBMs) to describe the geomorphic function (Chapter 3), fish response (Chapter 4) and riparian vegetation response (Chapter 5) of the Sabie River. The ACRU agro-hydrological modelling system is used to simulate catchment hydrological processes in order to provide input information to the QRBMs *viz.* daily streamflow and sediment yield. Planning of the models was guided by development of conceptual models of the fundamental components that influence the components themselves.

The KNPRRP BLINKs project consisted of three core working groups and a larger workshop group. The three core groups were small groups which corresponded regularly whilst developing QRBMs of geomorphology, fish and riparian vegetation. The larger workshop group met at approximately three-monthly intervals and provided guidance to the core groups.

The important role of models in various aspects of the project is recognised. Models which provide a quantifiable response to a given catchment development scenario are sought within many disciplines in order to aid objectivity in planning exercises. Also, models may be used as tools to assist in developing and nurturing communication between scientists of different disciplines. Amongst other benefits, models are known to identify shortfalls in understanding and data availability and thus stimulate further research and monitoring.

Coupled with powerful visualisation techniques, such predictive tools have been successfully incorporated in natural resource management information systems. An additional aim of this project has been to contribute to the development of an effective integrated predictive system for support of management and planning decisions in rivers and catchments where such decisions must be made. Such an Integrated Catchment Information System (ICIS) may then become a fundamental part of any decision support systems developed for the management of the rivers of the Kruger National Park and ultimately other rivers in South Africa.

Scale Issues

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" and application of scientific findings to it. The question of appropriate scales for integration of ecological, geomorphological and hydrological simulations is a complicated one. The question "How can one most efficiently link predictive models from various disciplines, when these may operate on differing and varying spatial and temporal dimensions?" is often asked. This question is especially important in the link between biotic and abiotic processes. In an effort to address problems associated with scale, all the models developed in this project utilise the concept of the representative reach and operate at asynchronous time steps. A representative reach is a stretch of river assumed to be representative of all similar stretches of the river. The use of asynchronous time-steps allows the model to simulate important processes at time-scales appropriate to those processes, and not at some predetermined and arbitrary time scale.

2. THE SABIE RIVER CATCHMENT

The Sabie River drains a catchment area of over 6000km^2 at the international border between South Africa and Mozambique on the eastern boundary of the Kruger National Park (Figure 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.

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 hydrometeorological information is generally of poor quality.

The Sabie River in the semi-arid Mpumulanga Lowveld 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, with varying degrees of bedrock influence (van Niekerk *et al.*, 1995) ranging from fully alluvial braided through to bedrock dominated anastomosing.

Forty-five indigenous species of freshwater fish are resident in the Sabie-Sand system, of which 39 are recorded in the Lowveld reaches. Using standard electro-fishing techniques and data spanning three and a half years, eleven species were found typically to make up more than 75% of the catch in shallow water habitats. These species have been defined as the Lowveld baseline assemblage for the system.

There are six vegetation types that include all the species within the riparian zone (riparian as well as terrestrial species), and each vegetation type is associated with certain hydrological and geomorphological characteristics of the river.

Some exotic invasives have become a concern along the Sabie River riparian zone, in particular *Lantana camara* and *Melia azedarach*. Higher up in the catchment, outside of the KNP, many *Pinus* and *Eucalypt* species occur as a result of forestry practices

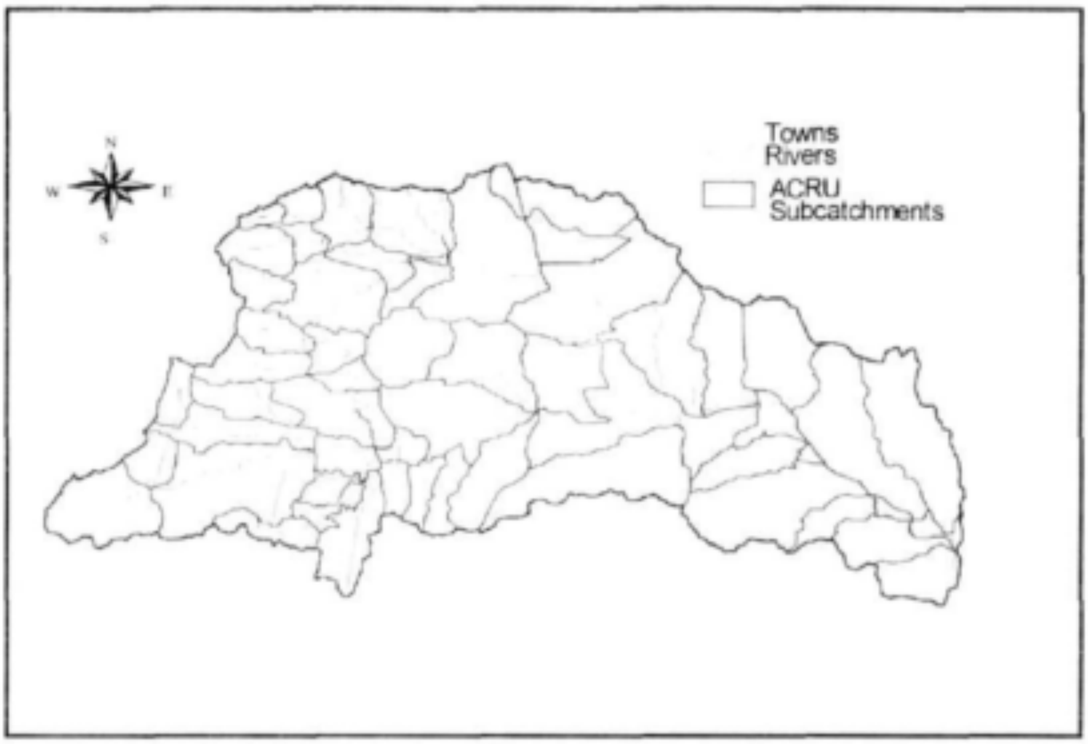

Figure 3. Subcatchment breakdown of the Sabie River catchment.

The Sabie catchment was further divided into 56 relatively homogenous sub-catchments for the purposes of simulating its hydrology and sediment production with the ACRU model (Figure 3).

3. 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.

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. 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 any point on the Sabie River. The rules are presented as a set of matrices defined by two simple indices, which were generated to define the relative levels of sedimentation, expected in each channel type segment along the river. These indices were then used to calculate the range of potential sedimentation values experienced over the last 40 years on the Sabie River.

Use of the geomorphological template to predict fish habitat takes place at three spatial scales (Figure 4). Initially, the channel type is recognised (as a representative reach), secondly, geomorphological units within it are identified. These units are in turn characterised by a sub-set of cover and substrate categories.

The model utilises a baseline geomorphological template consistent with the distribution of channel types along the Sabie River and this is used as the basis on which to route sediment inputs from the sub-catchments. Internally, the changing sediment balance within each channel type causes a change in the geomorphological composition at the scale of morphologic unit.

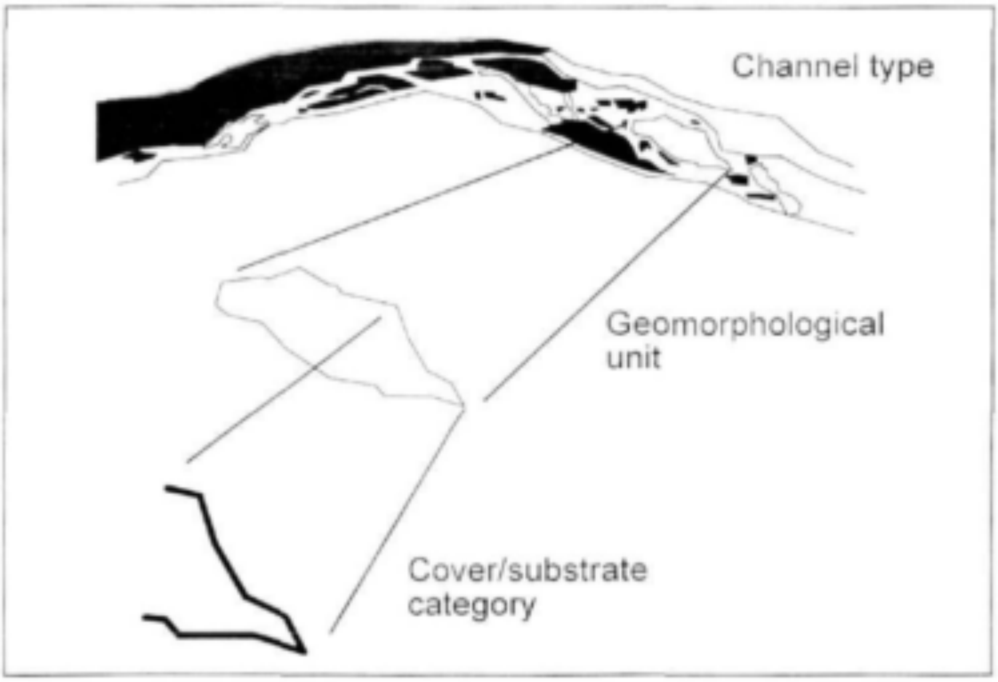

Figure 4. Utilisation of the geomorphological template to predict fish habitat operates at three scales.

At present the model suffers from several limitations as listed below:

- Inaccurate matrix rules due to limitations in available expert knowledge.
- Uncalibrated sediment input predictions.
- Untested geomorphological change hierarchies.
- Inadequate system of predicting the degree of local erosion and deposition at the channel-type scale.
- Model testing does not cover the full range of channel types recorded on the Sabie River in the Lowveld.

The geomorphological model could be improved in the following ways:

- Continued testing and refinement of the operating matrices based on simulations of each of the 40 channel type segments on the Sabie River.
- Improved correlation between the morphologic unit and fish habitat composition through field data collection.
- An investigation of the dynamics of sediment erosion and deposition at each of the channel type sections on the Sabie River utilising data already available.

4. THE KNPRRP FISH MODEL

The fish model is another version of a QRBM. It uses "rules" to predict the responses of specific fish groups characteristic of shallow Lowveld sections of the Sabie-Sand river system to varying flow conditions in the catchment and potential changes in the channel type of the representative reach.

It is the changing patterns of abundance established for these groups, both for normal and extreme seasonal conditions, which form the basis of the predictive model. To facilitate interpretation, the eleven shallow-water species important in the Lowveld are, where possible, grouped according to shared lifestyles largely based on their taxonomic and life history traits. Thus, six fish groups were identified, viz.;

1) Cichlids
2) Minnows
3) Yellowfish
4) Mudfish
5) Rock Catlets
6) Robbers

Methods were developed which allowed the translation of the channel geomorphic template into fish habitat suitability (Figure 5). Ultimately a Habitat Suitability Index to allow for the incorporation of information relating a change in fish habitat to geomorphic change was developed for inclusion in the model.

The model operates at a twice-annual time step, thus accounting for different fish responses for summer or winter seasons. Each season is assessed and classified as normal, wetter than normal, or drier than normal. Input to the model is a file describing the hydrological status of each season in which the fish response is to be estimated and a description of the habitat suitability of the river channel at the simulation site, by way of the Habitat Suitability Index. A conceptual view of this is shown in Figure 6. The rules developed relate the response of each fish group to these varying physical conditions.

Model output is presented in a graphical form consisting of an hypertext trace of the rules invoked at each time step, and an output file of the abundance of each fish group for 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 in the case of the fish state information.

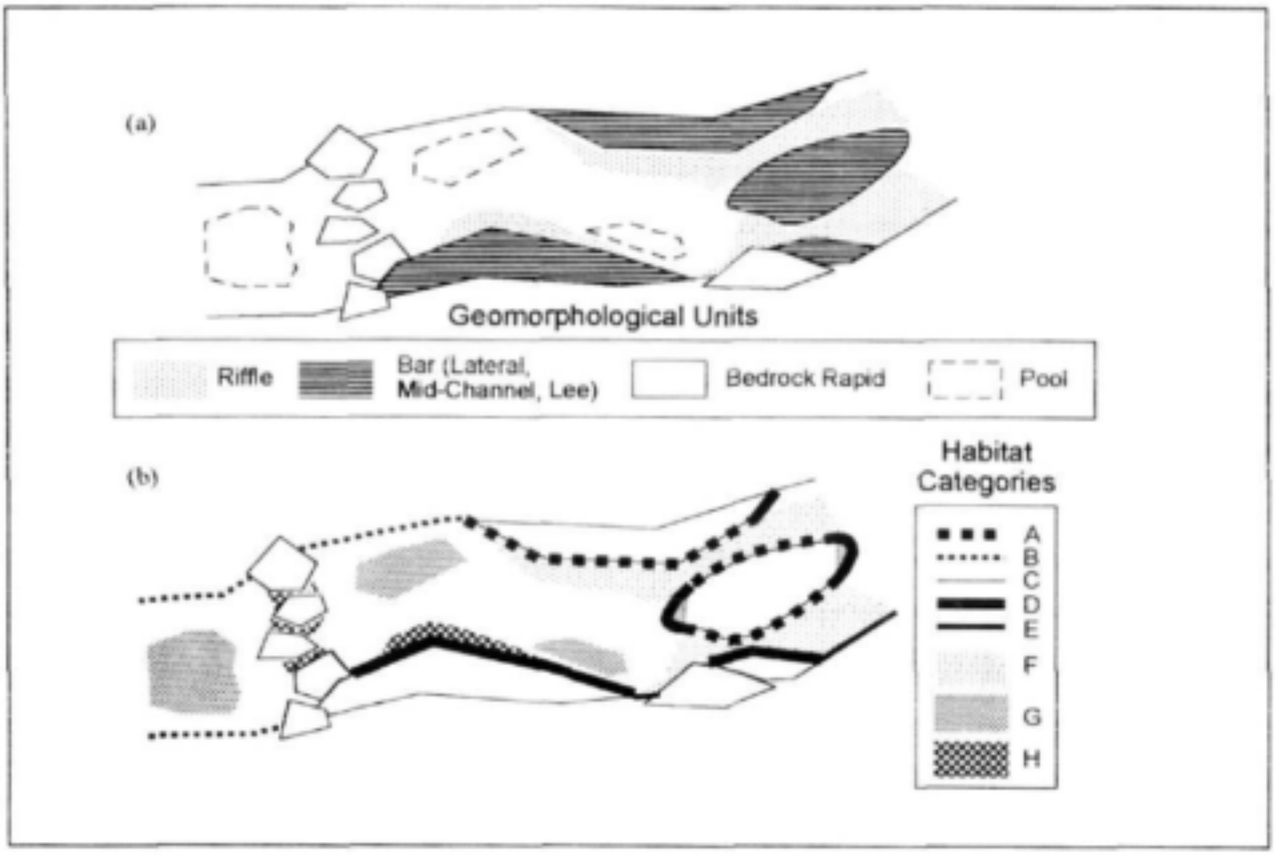

Figure 5. Geomorphological associations (a) translated into related fish habitat (b).

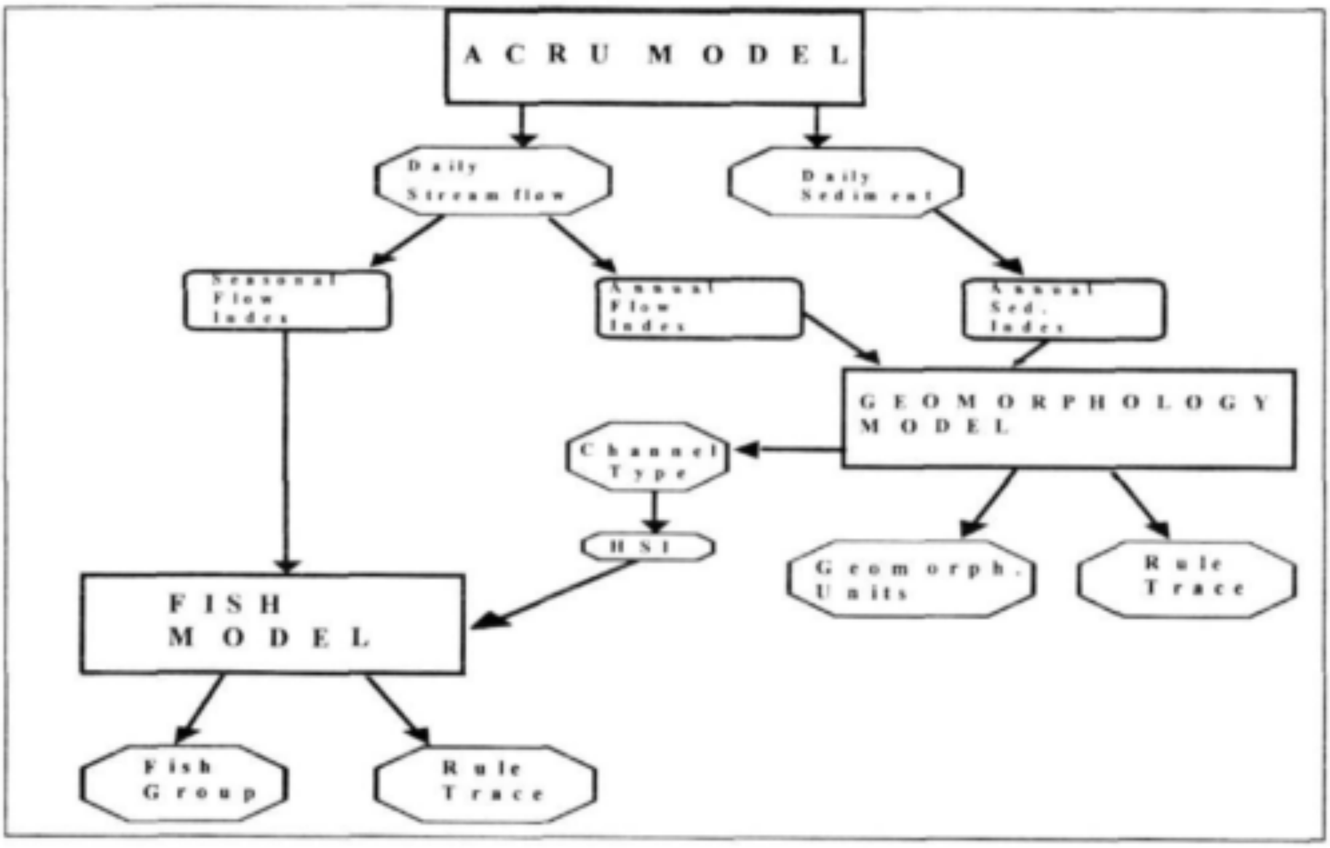

Figure 6. Overview of the links in the Fish Model.

It is important to note the following limitations of the model:

- The model is simulates fish response to seasonal hydrological variation in shallow reaches of the Lowveld section of the Sabie-Sand system only.
- The morphologic unit - fish habitat correlation figures developed are based on limited field data.
- The model has 3 possible input parameters for each time step i.e. dry, normal or wet, and these may result in one of 5 possible changes in "states" for each fish group, i.e. increase, increase a lot, decrease, decrease a lot, decrease a little. Consequently, the model output is highly sensitive to the input value

5. 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 (Figure 7) have played a major role in the definition of rules that govern vegetation response in the model.

Vegetation types were selected as response units for the model instead of species. There are six vegetation types that have been defined:

1) The *Breonadia salicina* vegetation type
2) The *Phragmites mauritianus* vegetation type
3) The Phyllanthus *reticulatus* vegetation type
4) The Combretum *erythrophyllum* vegetation type
5) The Diospyros *mespiliformis* vegetation type
6) The Spirostachys *africana* vegetation type.

Model inputs consist of five states of geomorphological features or units, which have been grouped according to their functionality and ability to support vegetation. These five functional groupings of geomorphological 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 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".

Responses of vegetation predicted by the model are generally in accordance with evident trends in available data, as well as current understanding of vegetation distribution patterns.

Several *a priori* model constraints were recognised at the conceptualisation stage of the model:

- The model only accounts for hydrological influence on the distribution of riparian vegetation in an indirect way.
- Although the model output is given on an annual basis, the vegetation change is independent of time and dependent on a geomorphological state change.
- The riparian vegetation model will not explicitly include finer-scale vegetation dynamics such as regeneration and mortality.
- Along the Sabie River there is a clear geological influence on the distribution patterns of vegetation types. This will not be included in the riparian vegetation model in this exercise, and it is suggested that a geological mediatory effect would be an improvement to the model.

Clearly a model with a high degree of simplicity such as the riparian vegetation model will have a number of fundamental assumptions and associated limitations. These include:

- A particular channel type or geomorphological unit will always be functionally the same in terms of a riparian vegetation response to that geomorphological feature, irrespective of its position in space. This assumption facilitates the functional grouping of geomorphological units.
- It is assumed in the model that the dispersal and presence of vegetation propagules is not limiting to a vegetation response.
- It is also assumed that once geomorphological change has occurred, site availability for recruitment will not limit a vegetation response. This means that as sites become available they are occupied by relevant vegetation types. The riparian vegetation model assumes therefore that these vegetation dynamics are taking place and predicts the expected outcome without modelling smaller-scale dynamics.

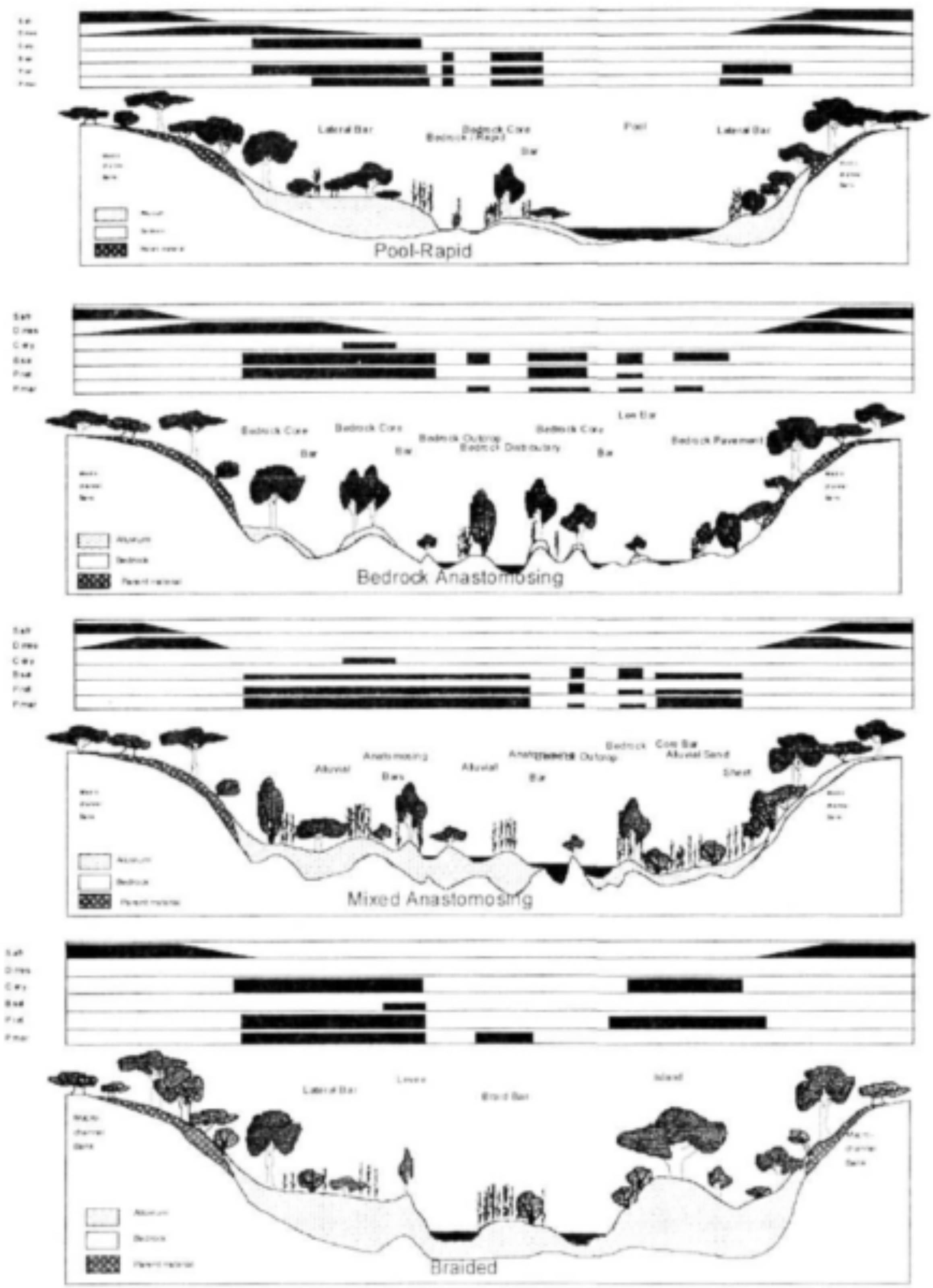

Figure 5.1 Diagrammatic profiles of the distribution of the six vegetation types on different morphological units at different channel types. The vegetation types are indicated by the shaded boxes which represent their distribution as a relative proportion.

6. SIMULATION OF RESPONSES TO POTENTIAL DEVELOPMENT SCENARIOS IN THE SABIE RIVER CATCHMENT

The eventual role of these models is to provide catchment managers and stakeholders with a tool that 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 fulfilling this requirement. In order to demonstrate the effectiveness of this suite of models, the modelling system developed was used to simulate the effects of various flow scenarios in the Sabie Catchment

The results from scenarios where the models were used to simulate the effects of the construction of a large dam on the Sabie River reflect the overriding response of the fish of the Sabie River to seasonal hydrological conditions. The geomorphic response is one of increasing sedimentation to most of these scenarios. Associated riparian vegetation response is a slow increase in the abundance of the *Phragmites* vegetation type. The riparian vegetation response is the least dynamic of all those simulated.

7. CONCLUSIONS, FUTURE MODEL REFINEMENTS AND FURTHER RESEARCH NEEDS

The project has been successful in achieving many of its aims and as well as the aims of the KNPRRP. It has been successful in forging links between catchment hydrology, geomorphology and fish and riparian vegetation of the Sabie River, in line with the aims identified by the project proposal. Furthermore, in terms of the KNPRRP goals, the modelling system provides a means of "predicting the response of systems to natural and anthropogenic factors affecting water supply".

The modelling system incorporates both "traditional" modelling techniques, in the form of the ACRU model, as well as knowledge-based systems. These have been integrated into a single modelling system, forming part of the KNPRRP ICIS.

Some of the rules developed and used may be applicable to areas outside of the Lowveld regions of the KNP, however much testing would be necessary to establish this. Far more transferable than the rules and models developed, is the **modelling methodology** and **expertise**. The development of qualitative models using rules to represent the assumptions made by experts in their fields, seems to hold great promise in other areas where a link between biotic responses to abiotic components of a catchment is a requirement.

In addition to model development, a higher level goal of the BLINK project, was the development of an effective interdisciplinary project. The facilitation of successful interdisciplinary research is in effect, a form of resolution of a scale problem. It has been noted that higher levels of systems such as a river are characterised by broad perspective and broad detail, while the lower levels have fine detail and narrow perspective. The focus of individual disciplines tends towards high detail levels of a system. ***The BLINK project builds on the belief that effective interdisciplinary research requires that participating individuals expand their vantage points toward levels which have broad perspective and relatively lower detail.*** In the BLINK project, the links between abiotic and biotic components required the movement of ecological, and to a lessor extent, geomorphological information to broader levels, where detail is obscured, but broad patterns were identifiable and comparable.

A major and significant product of this project has been the development of expertise in integrative modelling of biotic and abiotic responses to changing catchment conditions in South Africa.

The following recommendations are considered the most important future research needs pertaining to further refinement and development of the Sabie models.

1. Intensive mapping of geomorphological units in the field in order to further explore the relationship between geomorphological units and fish habitat.
2. Incorporation of direct hydrological input into the riparian vegetation model.
3. Improved resolution of geomorphology output and subsequent improved input to the riparian vegetation model.
4. Further refinement and testing of the matrices which form the basis of the geomorphology model.
5. Linking of upstream and downstream reaches to provide for movement of sediment through the reach under consideration in the geomorphology model.
6. Refinement of hydrological input parameters to the fish model.
7. Inclusion of biotic responses to critical water quality parameters.

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ACKNOWLEDGEMENTS

The financial support of this project by the Water Research Commission is gratefully acknowledged. The Department of Water Affairs and Forestry, the National Parks Board and staff at the Kruger National Park, provided logistical support. The assistance of Ms. Gayle Rolando in organising workshop facilities and providing sustenance is greatly appreciated.

Computing equipment, software and networking support was supplied by the Computing Centre for Water Research. The staff of the Computing Centre for Water Research, in particular Mr. Karl Wortmann and Mr. Mike Horn, played a major role in the development of utilities to provide graphical output for the fish and geomorphology models and incorporating these into the KNPRRP Integrated Catchment Information System. The CCWR also assisted by providing a WWW and FTP site for participants.

Mr Andy Pike of the Department of Agricultural Engineering, University of Natal performed the ACRU modelling tasks required for the Sabie Catchment.

This has been a truly multi-disciplinary project. We would like to thank all project participants for giving up their time to attend various workshops; for the enthusiastic way in which they have approached this project and for their thoughts and suggestions regarding the model development and this report. The project participants were;

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Dr	George	Heritage	University of Newcastle
Mr	Mike	Horn	Computing Centre for Water Research
Prof	Chris	James	University of the Witwatersrand
Mr	Graham	Jewitt	University of Stellenbosch
Dr	Jackie	King	University of Cape Town
Mr	James	Mackenzie	University of the Witwatersrand
Prof	Jay	O'Keeffe	Rhodes University
Ms	Sharon	Pollard	Wits Rural
Prof	Kevin	Rogers	University of the Witwatersrand
Ms	Denise	Schael	University of Cape Town
Ms	Rebecca	Tharme	University of Cape Town
Mr	Andre	Van Niekerk	University of the Witwatersrand
Mr	Dez	Weeks	Rhodes University

GLOSSARY OF TERMS

1:100 Yr Storm	Rainfall event that occurs only once every 100 years on average (similarly for 1:25 yr storm, flood etc.)
ACRU	Agricultural Catchments Research Unit
Backwater Rating Curve	Water surface profile generated using a hydraulic modelling procedure.
Base Flow	The flows that exist in a river all year. Base flows are generally the flow that exists in a river when there is no rainfall or runoff. Base flow is primarily provided by the groundwater system.
Biodiversity	The variety of life found in an area. It includes variety in genetic strains in populations, the richness of different species, the distribution and abundance of plant and animal communities and the processes through which all living things interact with one another and with the environment.
Biotope	An homogeneous environment that satisfies the habitat requirements of a biological community
Catchment	The region drained by or contributing water to a stream, lake or other body of water.
Catchment Variable	Parameter that may act to influence conditions in the riparian zone, (land use).
Channel Change Matrix	Rules relating flow and sediment regimes to geomorphologic unit change states .
Channel Type	'Reach' of channel containing a characteristic assemblage of geomorphological units
Competence	Ability of a river 'reach' to transport unconsolidated material downstream.
Confluence	Junction of two river channels where the discharges merge.
Cover/Substrate Category	Sub-division of geomorphologic units based on their cover and sediment character.
DSS	Decision Support System, a set of tools (usually computer based) to aid ..

	and for short periods.
Erosion	The process by which the ground surface is worn away by the action of wind and water; also the process by which the bed and banks of a stream are worn away by the action of water.
Fauna	Animal life of a locality or region, or, animals taken collectively as distinguished from plants (flora).
FIN	Fish Index of Niceness, a habitat suitability index reflecting the suitability of a particular reach to support various fish groups.
Flood Plain	The area of ground along a stream course that is covered by water during flood events.
Flora	Plant life of a locality or region, or, plants taken collectively as distinguished from animals (fauna)
Flow Index	Ratio of annual flow normalised against the 40 year average.
FORTRAN	Formula translation, programming language used for the models in the KNPRRP
Freshet	Minor flood event required to stimulate breeding in many fish species
Generic Channel Type	Baseline set of channel types that can define all of the channel types recorded on the Sabie.
Geology	Existing soil conditions either close to the ground surface or deep in the earth. Generally determines the type of material (ie. Sand, clay, rock, etc.).
Geomorphological Template	Assemblage of geomorphic units measured for a particular site.
GIS	Geographical Information System
Groundwater Table	The free surface level of groundwater, subject to atmospheric pressure under the ground, generally rising and falling with the season, the rate of withdrawal, the rate of recharge and other conditions.
GUI	Graphical User Interface
Holistic	Overall 'catchment wide' approach to determining process interaction.
Hydraulic Conditions	Local flow conditions as defined by parameters such as velocity, flow depth and water surface slope.

	velocity, flow depth and water surface slope.
Hydraulics	The movement of water through a stream, creek or river is defined by hydraulics. The study of hydraulics looks at the speed of the water depth and forces that it exerts on the river.
Hydrogeology	The physical process of groundwater including factors that influence the amount of water available, the flow of water into and through the ground and the flow of water to the surface through springs or to rivers.
Hydrograph	A flow versus time graph derived from direct measurement or prediction of runoff or stream flow.
Hydrologic Conditions	Relates to the flow conditions in a stream or river system including the response to rainfall and snowmelt. Interest includes how flow varies with time.
Hydrological Cycle	The movement of water from the atmosphere to the earth and its return to the atmosphere through condensation, precipitation, evaporation and transpiration
Hydrology	The process that controls surface flow conditions. When rainfall hits the ground surface or snowmelt occurs part of the water goes into the soil, part of it evaporates and the rest moves along the ground surface to streams. The movement of surface water over the ground surface is the area of interest in hydrology.
ICIS	Integrated Catchment Information Sytem
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
Infiltration	The passage of water into the soil. The term is also used to refer to water entering a sewer system from the ground through such means as, but not limited to, defective pipes, pipe joints, connections and manhole walls and including that from sewer service connections. It includes all extraneous water during wet weather, such as groundwater and surface water, but does not include inflow.
Geomorphologic Unit	Sedimentary or bedrock structure such as a lateral bar or bedrock pavement (Table 3.*).
Perennial	A stream that flows all year.
Reach	Arbitrary length of study river.
Riparian	Pertaining to the bank or shore of a river, lake or stream.

River Morphology	In terms of a river this refers to its physical characteristics (ie. Depth, width, slope and the way in which it meanders through the landscape).
Sediment	Soils or other surface materials transported by wind or water as a result of erosion.
Sediment Index	Ratio of annual sediment inputs normalised against the 40 year average.
Streamflow	That portion of the precipitation on a drainage area that is discharged from the area into stream channels.
Sub-Catchment	Areas of the main catchment that drain into individual tributaries.
Transect	Linear section across a channel.
Unsteady Flow	Flow that varies in magnitude over the time period of monitoring.
Water Table	The upper level of the free groundwater in a zone of saturation, except when separated from an underlying groundwater by unsaturated material.

1. LINKING ABIOTIC PROCESSES AND BIOTIC RESPONSES IN THE RIVERS OF THE KRUGER NATIONAL PARK

G.P.W. Jewitt, A.H.M. Görgens and G.L. Heritage

The Kruger National Park (KNP) is South Africa's premier national park and a major drawcard to local and foreign tourists. The park is dependent upon several rivers for its water supply, all of which rise outside of the Park's borders (Figure 1.1). Agricultural, forestry and industrial development as well as an urgent need to develop water supplies for a burgeoning human population increasingly affect these catchments. This increasing demand has affected water quality and quantity in the KNP rivers and is placing its riverine ecosystems under threat.

"The Kruger National Park Rivers Research Programme (KNPRRP) is a multi-disciplinary 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 physical landscapes, river channels and streamflow, and biotic components such as wildlife and the people that occupy it. Degradation of any of these components may affect the entire ecosystem.

The flow of water forms the major connecting link between the various catchment components as illustrated in Figure 1.2. Water, its quality and quantity, is the common concern in all the disciplines involved in the KNPRRP. Thus the development of an hydrology-based catchment modelling system, in which "modules" from other disciplines may be incorporated, will provide a particularly useful tool to bring together products from different KNPRRP projects. It will also provide an aid to managers and planners in identifying effective sustainable management options for the rivers of the KNP. This programme continues to the background of great political change within South Africa, a large poverty-ridden population within the river systems upstream of the KNPRRP, 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 (DWAF, 1995).

A large area of the KNP river catchments is situated in the former self-governing states. Many of the communities in these areas live in impoverished conditions. Supply of water to these communities is a priority.

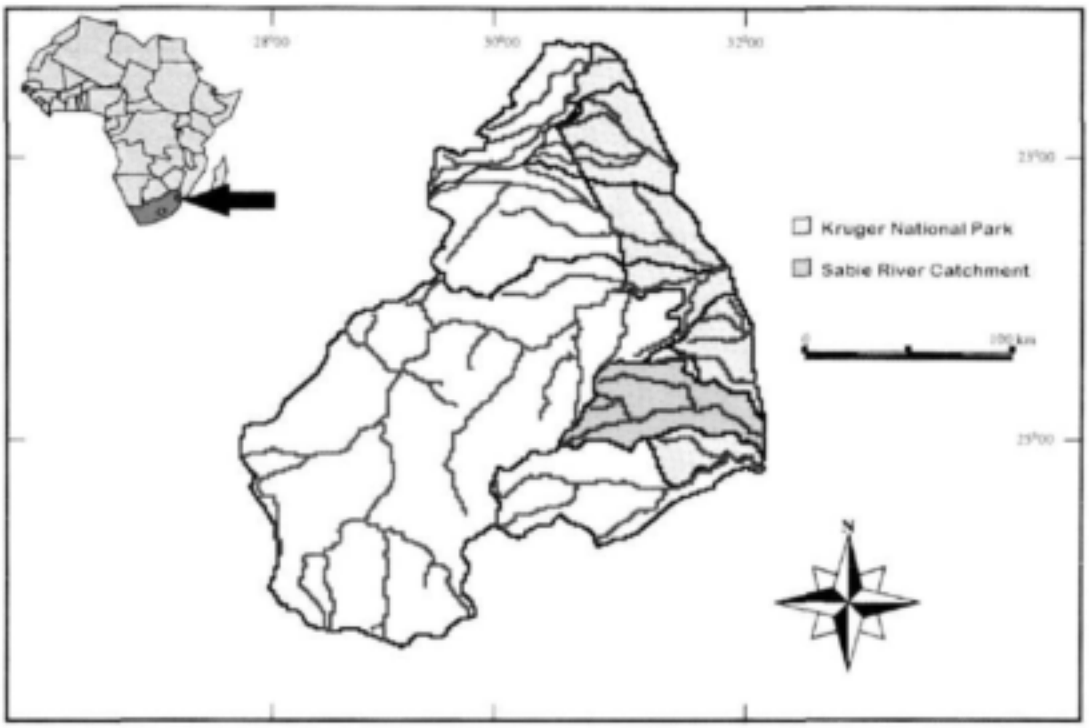


Figure 1.1 Location of the Kruger National Park and Sabie River Catchment.

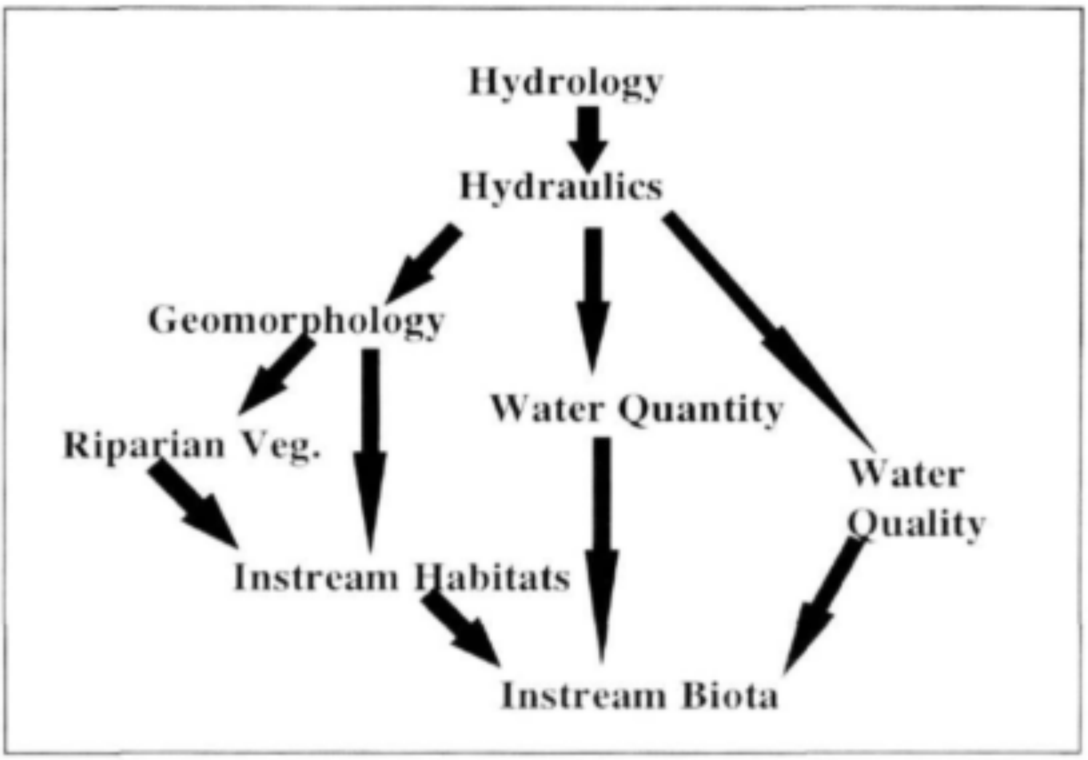


Figure 1.2 Conceptual diagram showing links between catchment abiotic and biotic components.

1.1 LINKING CATCHMENT ABIOTIC AND BIOTIC COMPONENTS

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 1.3). The ultimate aim of forging these links would be to establish the flow requirements for the aquatic ecosystems. In terms of this project, it is the flow requirements of the aquatic ecosystem which are highlighted, though the important influences of other abiotic components are recognised (Figures 1.2 and 1.3).

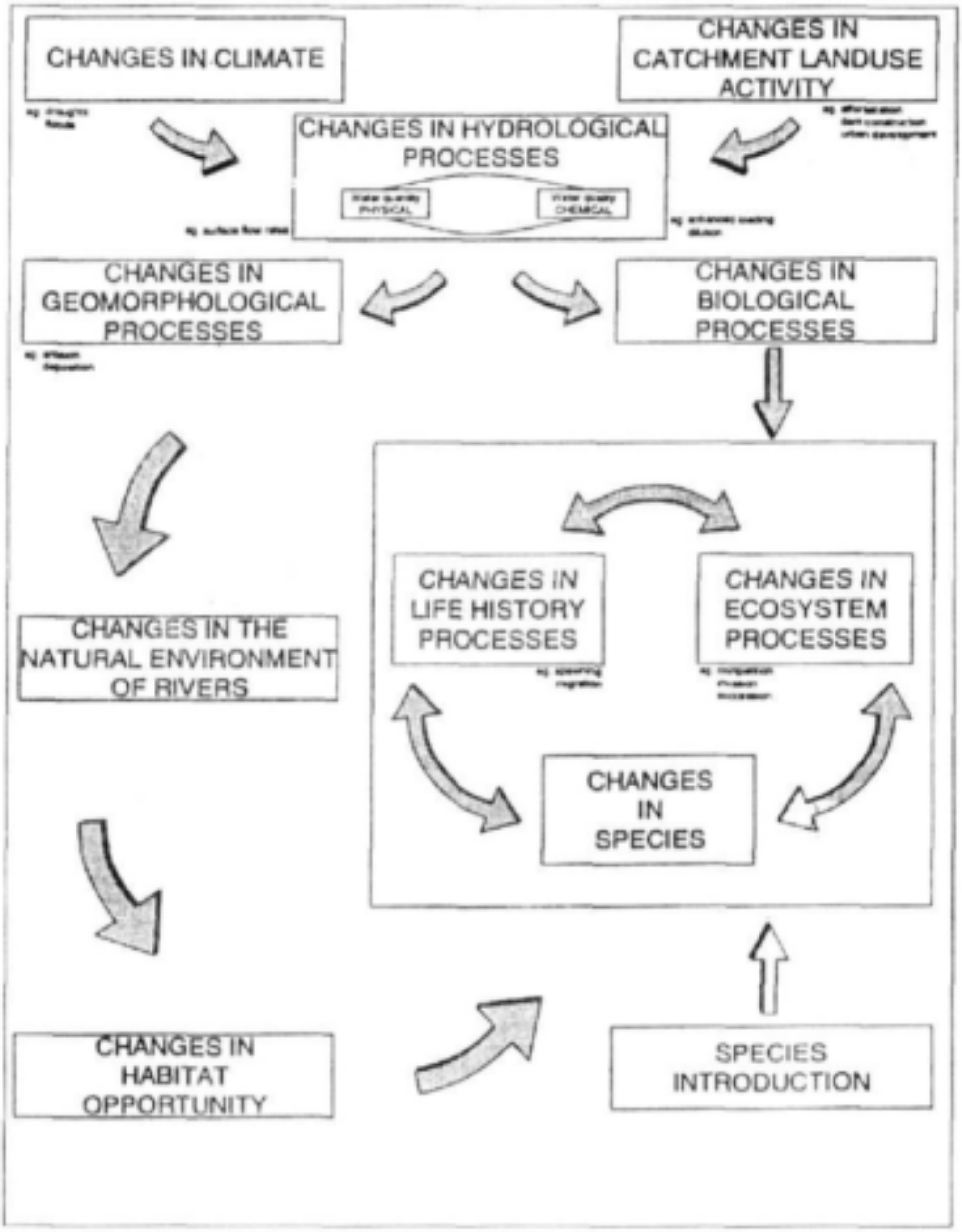


Figure 1.3 Understanding and predicting change in the natural environment of rivers (Breen *et al*, 1994).

For many years, attempts to predict the environmental flow requirements for riparian biota have concentrated on establishing the discharge regime which will maintain or enhance the habitat for riverine flora and fauna. Flow regimes were established using historical data to set flow minima (Tennant 1976) or periods of increased flows to correspond with fish migration and spawning (Hoppe 1975). Transect methods were developed which used cross-sections and the flow record to simulate values of ecologically important variables, such as flow depth and velocity across the discharge range (Cochnauer 1976, White 1976). A further refinement of this approach was achieved by the development of the suite of models collectively known as the Instream Flow Incremental Methodology (IFIM) which linked the changing physical conditions to specific habitat preferences of one or more target species present in the river (Bovee 1982).

The IFIM approach has gained widespread acceptance and has been used in many river systems across the globe with computer packages being developed such as PHABSIM (Milhous *et al.* 1981), RHYHABSIM (Jowett 1989) and RIMOS (Vaskinn 1985). Despite this, there have been criticisms of the method (Gore and Nestler 1988; King and Tharme, 1994). Simulation of the physical hydraulic environment has been shown to be inaccurate under unsteady flow conditions, due to the difficulty in calibrating backwater rating curves, particularly under low flow conditions (Osborne *et al.* 1988). Biological interactions are also ignored.

Fundamentally these approaches assume 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 and the usable area for resident species. 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. Also, river response may be predicted at geomorphological scales that can be directly related to biotic habitat.

The geomorphological 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 common 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).

In a dynamic system, if the geomorphological template is altered this directly affects the habitat availability. Also, geomorphological change is likely to be longer term and less reversible than altered hydraulic conditions (for example, flow depth or wetted perimeter) in response to a modified flow regime (Figure 1.4). Although local hydraulics remains an important factor affecting ecological response, it is no longer static because of this geomorphic change, which in turn necessitates dynamic geomorphic description.

Immediately following a geomorphologically significant flood event a residual fish assemblage will be present at a site (a, Figure 1.5). This represents a short-term change in the species tolerant of the flood conditions, the others having moved into refugia. Subsequent to the flood, there is a longer term response with other fish species returning in response to the available habitat as defined by the new geomorphological template (b, Figure 1.5). Subtle changes to the geomorphology during intermediate flows will lead to slight alterations in fish species composition as the substrate and cover, and therefore, habitat distribution alters. There is thus a need to integrate geomorphic studies with hydrological and ecological studies in assessing the ecological implications of flow regime modification, as such studies generate a more holistic picture of the functioning of the system (Russell and Rogers 1989) (Figure 1.4).

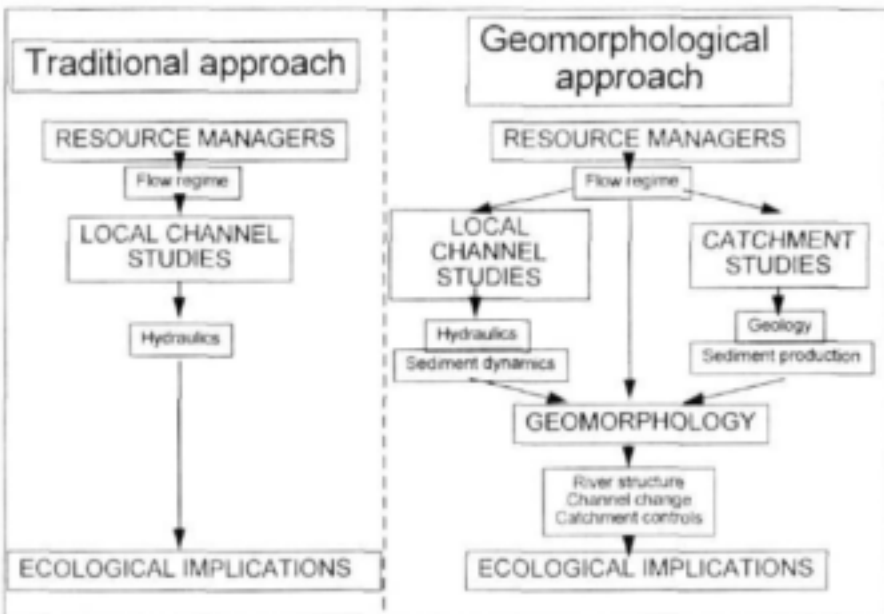


Figure 1.4 Conceptual diagram showing the difference between a "Traditional " and a Geomorphological approach to a study of river system functioning

Vegetative response patterns to altered geomorphology are somewhat different (Figure 1.6). Floods initially adversely impact on many riparian species (a, Figure 1.6), recovery is then gradual (b, Figure 1.6) with the new community being a function of the seed species present and their germination. The first flood shown in Figure 1.6, results in an overall increase in sediment, resulting in a vegetative assemblage more characteristic of alluvial reaches. The second flood, in contrast, leads to considerable erosion probably exposing bedrock across areas of the channel. The resultant assemblage here is likely to be dominated by species more tolerant of low sediment conditions

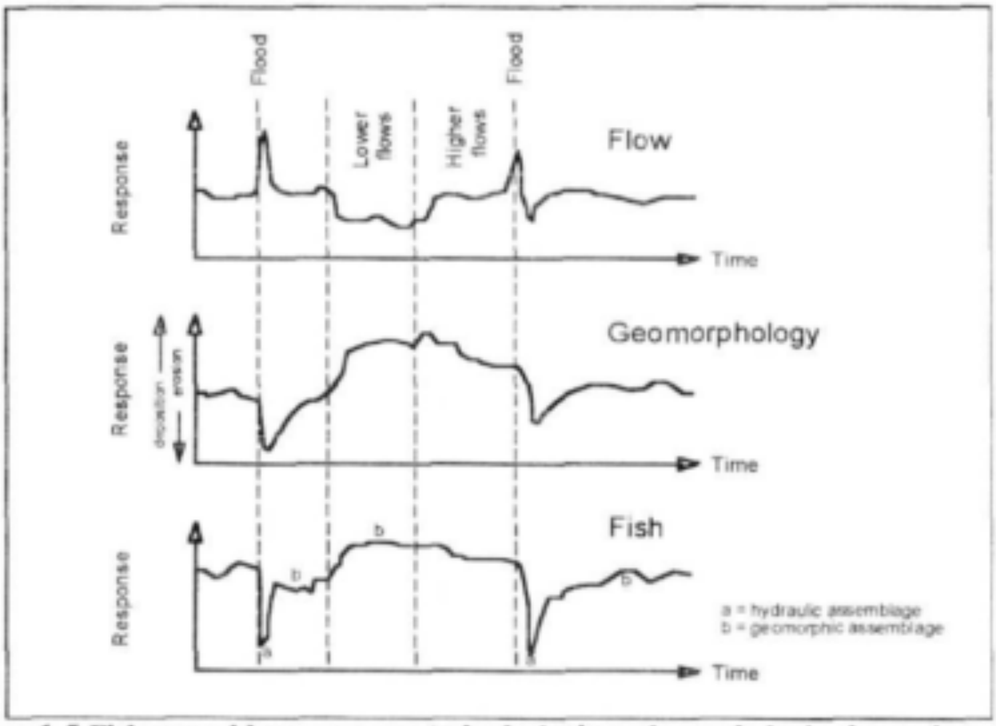


Figure 1.5 Fish assemblage response to hydrologic and morphologic change in a river system.

The interaction of the topography with hydrological processes also gives rise to a highly complex physical environment of different fluvial geomorphic units with different sediment and cross-section characteristics, which play an equally important role in influencing species distribution. A highly unpredictable extreme seasonal flow regime, combined with a relatively high sediment load, gives rise to a patchy mosaic of numerous fluvial geomorphic units with different sediment characteristics. This patchiness is further enhanced in a mixed bedrock/alluvial system which displays characteristics of both bedrock and alluvial channels (van Niekerk *et al.* 1995). The high degree of patchiness of different geomorphic units provides a highly intricate physical 'template' of different substrata and hydrological characteristics for the vegetation to become established on. It has been shown that a good relationship exists between riparian vegetation and different geomorphic units along the Sabie River (van Coller *et al.*, 1997), as well as in rivers of other more temperate regions (Hupp & Osterkamp 1985).

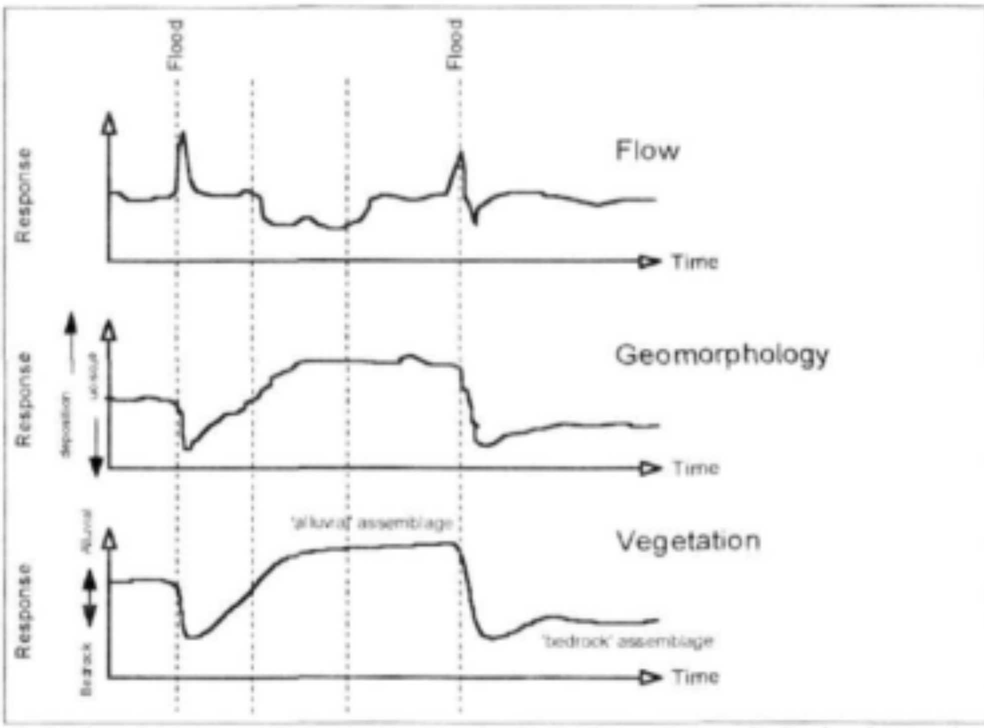


Figure 1.6 Riparian vegetation response to hydrologic and morphologic change in a river system.

1.2 THE KNPRRP BIOTIC-ABIOTIC LINKS PROJECT

This project arose as a result of a realisation by KNPRRP participants that the link between the respective research outputs regarding the biotic and abiotic processes was not clearly defined in the KNPRRP charter, and was not being adequately addressed by the existing projects encompassed by the KNPRRP.

One of the aims of the Decision Support System (DSS) sub-programme of the KNPRRP was to develop a hydrologically driven computer based modelling system which could enable the integration of the predictive methods used by different water related disciplines. This system would be used for the assessment of impacts due to changes in an upstream catchment area on river morphology, ecology and other factors which may affect the status of the rivers of the KNP. In the KNPRRP programme documentation project 2.1, the "Simulation Model for Water Quality and Quantity Project", was given the task of developing methodologies for the "integration with existing predictive capabilities for other processes" (Breen *et al*, 1994). However, it was unclear how this integration would be achieved. It was clear, however, that the ultimate focus of the KNPRRP was the ecological functioning of the aquatic ecosystems - this was the medium through which prediction results would be passed on to managers, planners and stakeholders.

KNPRRP participants realised only too well that predictions of changes in flow regime are often meaningless. To many people, 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". Thus, it was not clear from the programme documentation how the biotic responses would be linked with abiotic processes. Extensive discussions amongst KNPRRP scientists, culminated in a "Biotic Links" workshop held at Pretoria during October 1995, the success of which resulted in the formulation of this project.

The overall goal of the workshop was to investigate means of linking predictions of changes in fish communities in the Sabie-Sand River System to predictions of geomorphological change. A brief report of the workshop appears in Appendix 1. The workshop was deemed a success, as a "skeleton" of a model which formed a link between catchment abiotic and biotic responses could be formulated. It was agreed that the idea of using qualitative or knowledge-based predictions was useful and that attempts should be made to extend this approach beyond fish predictions to other catchment biotic components based on a conceptual model discussed in the workshop (Figure 1.2). Consequently, a one-year research proposal to this effect, was submitted to and accepted by the Water Research Commission (WRC). The ensuing project became known as the "BLINK Project".

The final product of this project is a suite of models which consists of a hydrology model and three Qualitative Rule Based Models (QRBMs) to describe the geomorphic function (Chapter 3), fish response (Chapter 4) and riparian vegetation response (Chapter 5) of the Sabie River. The QRBMs operate at the spatial scale of a representative reach, typically several hundred metres in length and at asynchronous temporal scales. The ACRU agro-hydrological modelling system (Schulze, 1995) is used to simulate catchment hydrological processes in order to provide input information to the QRBMs *viz.* daily streamflow and sediment yield. Figure 1.7 provides an overview of the interaction and linkages between the models and may be compared to the conceptual overview illustrated in Figure 1.2. Detailed explanations of these links are provided in the following chapters. The HSPF model (Bicknel *et al.*, 1996) is included in Figure 1.7 as a proposed tool in order to simulate water quality components in further stages of development.

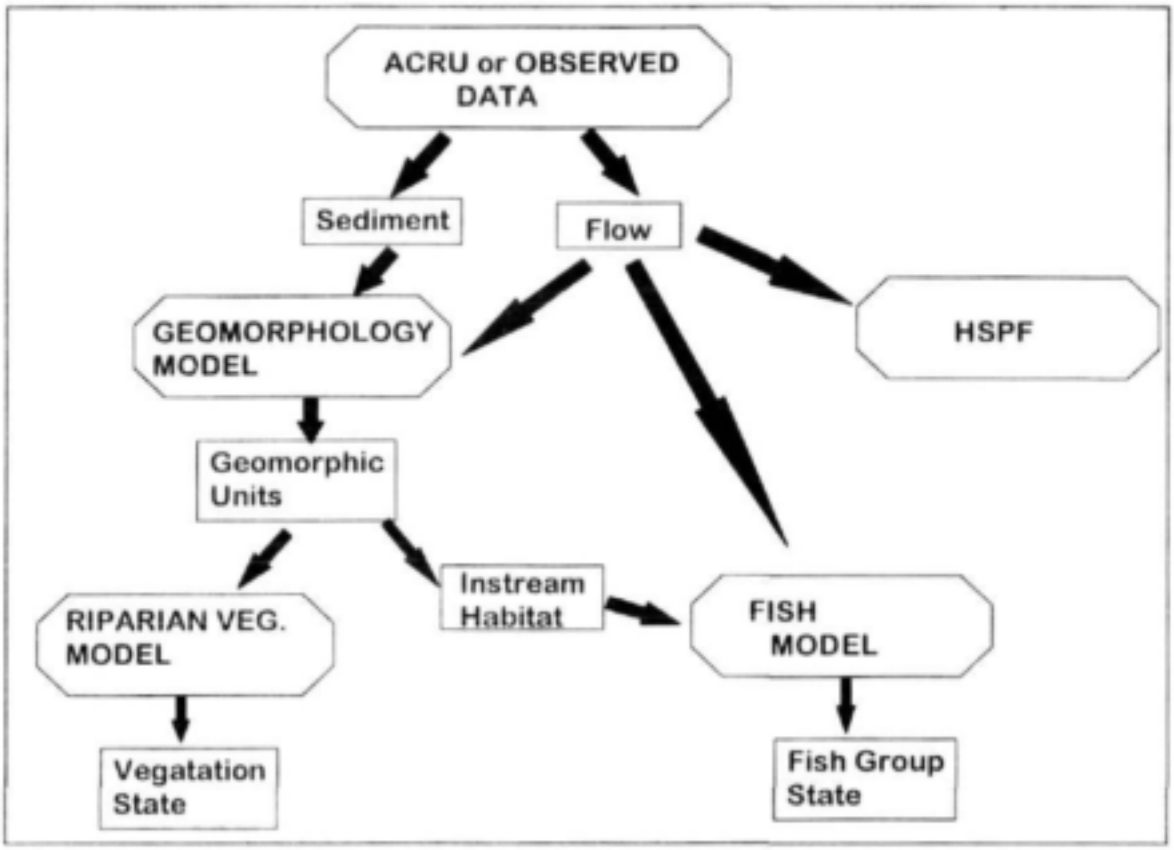


Figure 1.7 The Components of the BLINK Sabie River Modelling System.

1.3 MODELS AND MODELLING FOR INTEGRATION OF CATCHMENT ABIOTIC AND BIOTIC COMPONENTS

Models which provide a quantifiable response to a given catchment development scenario are sought within many disciplines in order to aid objectivity in planning exercises. A second, 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.

In terms of an Integrated Modelling System, a major problem with forging links between the abiotic and biotic responses to flow changes is that research in the abiotic and biotic fields experienced, until recently, little contact (King and Tharme, 1993). It has been said, "multidisciplinary communication is one of the missing links in science" (Pattern, 1994). Modelling, especially that involving the development 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 such an Integrated Modelling System may act as a living repository for the knowledge which the collective scientific community has about the catchment involved (Maaren and Dent, 1995).

1.3.1 What is a Model?

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 a model of that system. A model can be either a mathematical or a statistical description of specific aspects of a process. It can also 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 finances of a firm, a spreadsheet to calculate population growth or the diagram, formula and rules in software to allow the 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, or expert system shells where the rules are made of logical text statements. In the context of this document, it is important to distinguish between QRBMs and the better known quantitative models.

Qualitative Models

In numeric models, relationships between constituents are generally mathematical; in a rule-based system, they are based on heuristic logic (Davis *et al.*, 1989). There are instances where the intricate and complex nature of a 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. 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 rules or logical inference and makes use of 'IF-THEN-ELSE' constructs to describe process behaviour, rather than algorithms such as partial differential equations, which are typically constructed to describe the physics and chemistry of time varying processes. This concept is explained further using ideas formulated by Nicolson and James (1995). Most commonly, model components are described using numerical variables, with equations to assign values to these variables. For example, if the flood levels of a river need to be simulated, then flow depth is an important component to capture. 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 Manning equation), which relates the flow depth to the discharge for a given channel, could be used. Hydrology and hydraulics models make use of several equations such as these (e.g. flow resistance, sediment transport, continuity of water mass, soil moisture balance), either in the form of partial differential equations (PDEs) or empirical regression equations. The resolution of these equations generally requires numerical methods, and is computationally intensive. Many hydraulic models such as HEC-6 (Hydraulic Engineering Centre, 1977)and MOBED (Krishnappan, 1981) 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.

Nicolson and James (1995) note that important model components may be described with lower resolution than is done by these models. It may be unnecessary for a model to predict depth of streamflow to the accuracy of a millimetre, and it could be sufficient to 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 (again, with the name *depth*), 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 cumec) THEN (*depth = overtopped*). This way of managing variables has become known as qualitative, rule-based modelling (Starfield, 1990). The rules forming the model are usually elicited from human experts in the field of interest, but may also be elicited by other means such as experimentation or hypothetical application of more detailed models.

In the remainder of this document models, which are constructed using detailed numerical equations, are referred to as quantitative models and are seen to form the "traditional" modelling approach.

1.3.2 Models as Integrative Communication Tools

The integrative power of model development has been noted by several authors (Holling, 1976, Starfield et al, 1993; Pattern, 1994; Grayson and Doolan, 1995). Modelling has the ability to bring intuition to the fore, and make it 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 between different aspects of a problem (Pattern, 1994). Amongst other benefits, models are known to identify shortfalls in understanding and data availability and thus stimulate 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, 1976; Pattern, 1994; Grayson and Doolan, 1995). The use of models and model building in this project, both to stimulate communication, and as potential management tools,represents a fundamental break with the manner in which water resources modelling exercises have been undertaken in the past. Typically, in catchment management and associated modelling exercises, one or two large multi-purpose models have been applied (Donigian *et al*., 1991; Fedra, 1995). These models are typically user "unfriendly", difficult to engage, not transparent, require extensive training to use and require powerful computing facilities and complex databases to operate. The function of these multi-purpose models has been specifically of a water resources engineering nature. However, with projects involving multi-disciplinary groups and the recognition that effective natural resource management requires effective communication, comes a recognition that such models are often 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). Consequently, 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, is preferred. Starfield (1996) believes 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 multidisciplinary teams of specialists working on separate components of the model. This enables them to focus on the section of the model where they can contribute their expertise, whilst retaining the multi-disciplinary nature of ecosystem modelling.

The work presented in this project is based on the recognition that, in order to adequately represent the level of scientific understanding of the different disciplines involved in the development of the computer based models, the models need to be easy to use, and should be engageable by participants with limited modelling experience. The functioning and technical details of these models are described in detail in the following chapters of this document.

The use of models and their development has become an accepted practice in many natural science disciplines, including hydrology, geomorphology and ecology. However, it is in the ecological field where resistance to modelling is strongest. This is a result of many complex interactions, most of which have their source in differences between the mode of observation, analysis methods and aims amongst sciences dealing with abiotic and biotic components.

The relationships between abiotic and biotic components of an ecological system, as well as between cause and effect, are usually understood in an approximate and qualitative manner, rather than in a detailed and quantitative sense. The development of quantitative numerical ecological modelling systems has rarely been successful. The limitations of these types of ecological models have often been highlighted and the necessity of ecological scientists producing such models queried (Fryer, 1987; Harris, 1994; Schrader-Frechette and McCoy, 1994). However, a recognition that models need not be complicated computer programs involving complicated mathematics is leading to a change of these perceptions. Schrader-Frechette and McCoy (1994) suggest that in the ecological fields, it will be more useful to apply practical and precise knowledge of particular species (taxa) and low-level theories to predict what will happen to them, rather than trying to predict complex interactions among many species, to make explicit the ecological insights necessary to provide predictive power for environmental management. This approach has resulted in even such sceptics as Harris (1994) changing their views and admitting that "I have reassessed the prospects for ecosystem modelling and prediction and have concluded that there are indeed predictable and "modellable" features of aquatic ecosystems" (Harris, 1996).

It is both difficult to build quantitative ecological models, and even more difficult to justify them. It would appear that the development of "knowledge-based" models, in the form of QRBMs, for predictive purposes is a feasible option.

Some KNPRRP participants have, in the past, expressed concern that there was insufficient information available to even attempt the development of such predictive tools. However, it has been noted that knowledge-based models reflect the current state of knowledge and are by no means static (Starfield, 1996). In 1991, referring to management of the rivers of the KNP, O'Keeffe and Davies (1991) wrote, "We believe that an insistence on rigorous scientific methods, and the use of complete biological information, would only result in the environmental aspects of the rivers being ignored in favour of the urgent need to develop water supplies for the burgeoning human populations on the borders of the KNP".

This does not imply that quality control in QRBMs and their supporting data are not important. As with any modelling exercise, verification of the model is essential, as are some form of sensitivity analyses, and there has been no intention of compromising on these issues by using knowledge-based models. Such models must be subject to appropriate validation, verification and testing as with any other predictive system.

1.3.3 Knowledge-based Systems in Natural Resources Management

Typically knowledge-based systems have been applied to problems where (Hayes-Roth et al., 1983):

i) much of the information needed to solve a problem is heuristic (i.e. based on rules of thumb), rather than mechanistic;

ii) this information is likely to change, either because of a need to explore alternative possibilities, or because fresh information becomes available;

iii) the information is incomplete and uncertain;

iv) explanation of results/advice are required, thus developing trust in the results, i.e. the system is not a "black box";

v) a "natural language" (such as English) dialogue with the user is required.

These points seem to provide solutions to the dilemma facing the ecologist from whom predictions of impacts on ecological systems arising from, for example, various development scenarios in a catchment, are required. It has been shown that ecologists have responded positively to the knowledge-based approach to prediction (Holling, 1976; Starfield *et al.*, 1989; Starfield, 1993; Starfield, 1996). Managers have also responded positively to this approach (Holling, 1978; Davies *et al.*, 1989; Starfield, 1993).

As implied earlier, there is a real and a perceived gulf between natural resource managers and scientists. Frequently, the former have to make rapid decisions and are willing to accept risks, whilst the latter are cautious in making predictions based on incomplete research (Starfield *et al.*, 1989; Doolan and Fairweather, 1995). Knowledge-based predictive systems may bridge this gap for, as suggested previously, they incorporate the current, but updateable, state of knowledge - which often may be incomplete and inconsistent. Furthermore, Starfield *et al.*, (1989) argue that making the available knowledge explicit and dynamic provides a basis for consistent arguments and thus ensures that both "sides", i.e. researcher and manager, have the same mental picture or model.

Recently, knowledge-based systems have moved out of the realm of the purely theoretical and have been used with some success in predicting ecological responses to changes in prevailing conditions (Loehle, 1987; Wilde, 1994; Starfield, 1996). Coupled with powerful visualisation techniques, these predictive tools have consequently been successfully incorporated in natural resource- management information systems.

The available literature shows a progression of such knowledge-based systems in environmental management from "good ideas" in the early 1980s to complex working systems in the mid 1990s (e.g., Starfield, 1989; Loh and Reykiel, 1992; Starfield, 1993; Warwick *et al.* 1993). Many of these researchers have recognised that knowledge-based simulation systems do have some significant advantages over quantitative numeric type simulation systems. Simulation methods which use PDEs 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 between a range of values, or an optimal versus several sub-optimal solutions. The demands of precision in a quantitative numeric simulation system may result in solutions being highly sensitive to some critical input parameter (Warwick *et al.*, 1993). The use of knowledge-based systems may circumvent many of these problems.

Rule based systems are more flexible and easier to update than simulation systems based on complicated equations as, according to Starfield *et al.*, 1989;

i) the rules which constitute the model may be structured as a data file rather than a computer program,

ii) their syntax is user friendly,

iii) a trace feature can make the internal workings of the model easy to follow.

These tools and techniques, once developed, may be incorporated into an integrated system focusing on the problem areas under consideration.

1.3.4 An Integrated Catchment Information System for the Rivers of the Kruger National Park

It is axiomatic to the objectives that any models developed in this project should be easy to use and understand, simple to operate and produce easily interpreted output. One way to achieve this is to provide access to them via a graphical, user friendly environment.

The aim of this project, and that of the KNPRRP DSS sub-programme, is to produce an effective integrated predictive system for support of management and planning decisions in rivers and catchments where such decisions must be made. Such an Integrated Catchment Information System (ICIS) may then become a fundamental part of any decision support systems developed for the management of the rivers of the Kruger National Park. 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.

The KNPRRP ICIS will provide a tool to assess impacts of change and thus to compare predicted future river states with a desired river state. Furthermore, the ICIS should provide a management tool which can be used to compare different catchment development scenarios, i.e. the "what-if" situation, as described in Chapter 6. An idealised ICIS is shown in Figure 1.8. The various components in the system interact by exchanging data and information, the control of which is the task of the ICIS manager.

- a Graphical User Interface (GUI),
- a system manager to interpret commands from the GUI and communicate with other components of the system,
- GIS for display and interrogation of spatial data,
- tools for display of metadata and time series data,
- various predictive tools, including numeric simulation models and QRBMs,
- a database for storage of spatial data, metadata and time series data, and
- tools for linking to remote databases and information sources, such as the WWW.

A full description of the ICIS developed for the KNPRRP is given in other KNPRRP reports (van Rensberg and Dent, 1995; Jewitt and Görgens, 1995).

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 (Thiessen and Loucks, 1992; Palmer *et al*., 1993; Punnet and Stiles, 1993; IMLAB , 1996). With the use of an effective GUI, the differing views of managers and researchers may be represented. The manager's view is represented by the GUI and the researcher's view by the data, algorithms and rules in the models embedded in the system (Davis *et al*. 1989). 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 for modelling or analysis.

The integrated catchment information system developed for the KNPRRP uses the ARCVIEW GIS display system to provide the GUI. The ARCVIEW script language AVENUE, has been used to modify the GUI to show functions which are useful to the typical system user (Figure 1.8). 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 spatial data display and management systems both locally and internationally (e.g. da Costa *et al*., 1995; Walker and Johnson, 1995). Local examples are DWAF's Watermarque system (Cobban *et al*., 1995) and the CCWR's WDMGuide (Van Rensburg and Dent, 1995), as well as systems developed by civil engineering consultants to the DWAF as part of the Community Water Supply and Sanitation System (Greyling, 1996).

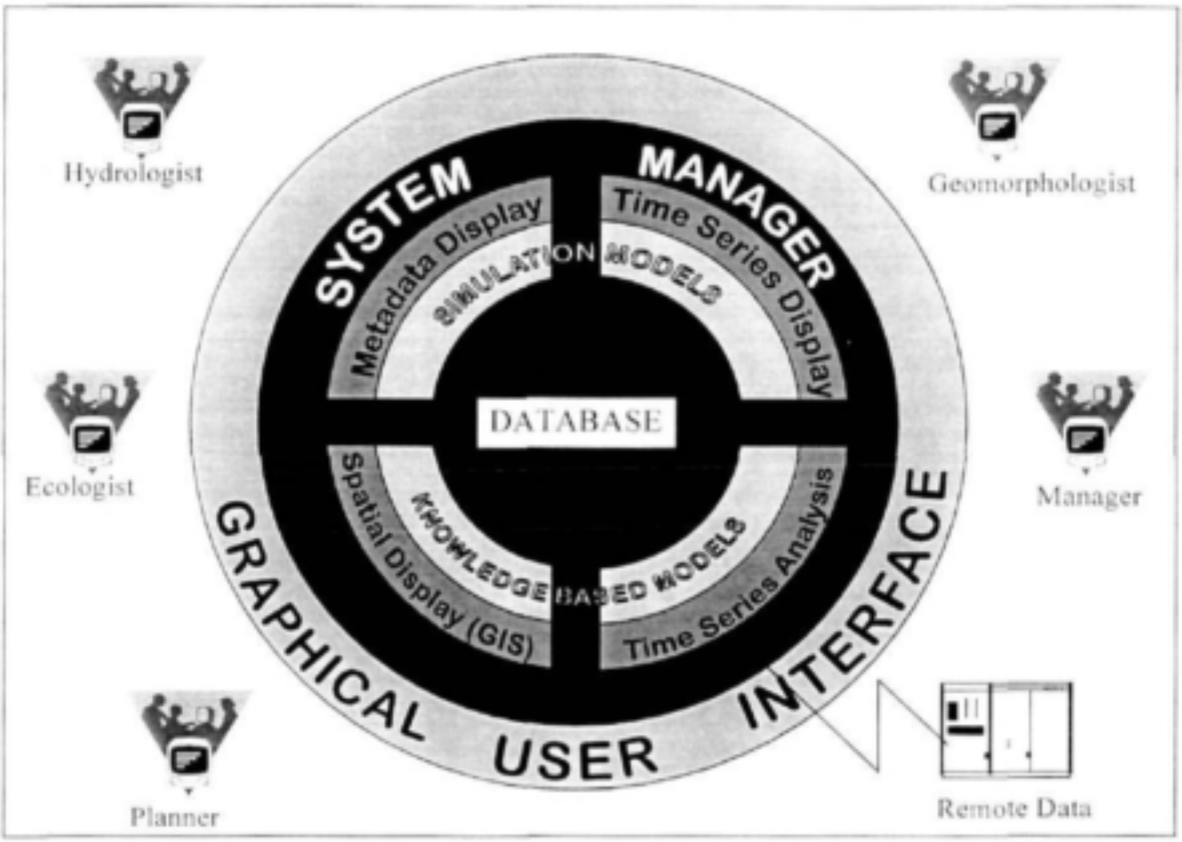


Figure 1.8 A Conceptualised Integrated Catchment Information System for the KNP (Jewitt and Görgens, 1995).

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, 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.

Various tools are needed for the display of model output. Many of these are being produced by the CCWR as part of the Technology Information Training and Transfer Sub-Programme of the KNPRRP. 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).

This 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 created, continue in this vein.

1.4 PROJECT PARTICIPANTS AND MODELLING METHODOLOGY

The KNPRRP BLINK project consisted of three core working groups and a larger workshop group. The three core groups were small groups which corresponded regularly whilst developing QRBMs of geomorphology, fish and riparian vegetation. The larger workshop group met at approximately three monthly intervals and provided guidance to the core groups. Participants of both the core and workshop group are listed in Appendix II.

The fish model was the first model developed. Links between fish response and channel geomorphology had been the focus of the workshop described in Appendix I, and data for this model appeared to be more readily available at the preliminary stages of the project. The best way of establishing a link between the abiotic and biotic catchment components seemed to be to develop a prototype model. Further refinement, testing or rejection could then follow. Consequently, the first model developed by this project was a prototype fish model.

Typically model development follows four broad stages;

i) identification of entities relevant to the problem,

ii) definition of relationships between entities,

iii) development of rules or formulae that define these relationships, and

iv) refinement and eventual acceptance or rejection of the model.

This was the approach followed in the development of the suite of models included in this report. In the case of the biotic models, i.e. the fish and riparian vegetation models, it was necessary to identify the abiotic criteria to which biotic components react and then to identify which of these were significant and which scales were important and manageable in terms of their ability to be simulated. A list of these criteria includes streamflow, sediment load, temperature and the geomorphic template of the river system under consideration.

Planning of the models was guided by development of conceptual models of the fundamental components that influence the model itself. The input parameters, model subjects and output form the crux of the model. Input to the model may be seasonal flow indices (in the fish model) or geomorphic units (riparian vegetation model). Model outputs are states of the model subject. Rules utilised in the model define the way the input parameters influence model subjects, based on rules developed from available data and current expert understanding. The exact manner in which rules operate may be altered by mediators. Mediators are aspects in the system that is being modelled which do not exert a direct influence on model subjects as inputs do. Their influence exists, but is indirect.

The scale of the model defines a temporal and spatial domain within which the model must operate. Scale choice depends on model objectives and the resolution of current understanding of the system that is being modelled.

1.4.1 Knowledge-based Modelling

The differences between "traditional" quantitative modelling approaches and knowledge-based systems, such as QRBMs which use "rules" to govern the simulation are explained in section 1.3. Once the model has been planned, and the entities relevant to the problem at hand recognised, i.e. i) above, it was necessary to define the relationships between entities making up the model. This process is commonly termed "Knowledge Engineering" and is normally defined as the process of transferring knowledge from the expert to the model. In the development of the models in this project, we have made use of matrices to identify and quantify these relationships, examples of which are given the following chapters.

We have also made use of the concepts of the "frame" and "state" In many systems, the temporal dynamics can be partitioned into several distinctive states. For example, the progressive alluviation a particular channel type may follow a succession of stages of alluviation before it may be classified as a different channel type completely. A geomorphologist could characterise these stages, and establish rules which describe when the channel type would switch from one stage to another. In order to create a model of this system, each stage may be termed a state and is represented by an independent sub-model known as a frame. This sub-model then simulates the processes that have been identified as the key processes of interest relevant to that state. The model is coded to recognise a combination of conditions that precipitate a switch from one frame to another, and, when they are met, it stops using the one sub-model and begins to use another (Starfield *et al.*, 1993; Nicolson and James, 1995). Thus in the geomorphology model, each different channel type included in the model may be represented by a different frame as the erosion/sedimentation processes differ according the channel type under consideration. In the case of a fish model, different frames could be developed for different seasons or climatic conditions. Further breakdown into sub-frames is also possible.

1.4.2 Model Coding

Model development followed an operational prototyping methodology (Davis, 1992), where simple models were developed quickly and used as "straw dogs" to identify problem areas, but were built on rather than discarded thereafter. Problem areas included lack of adequate data, unsuitable selection of operational scale, philosophical and scientific problems with some assumptions made. These are described in more detail in the chapters relevant to the three models developed. Refinement of the models is ongoing.

The models are coded using the FORTRAN 77 programming language. Advantages of using FORTRAN in this exercise include its "English-like" syntax, thus enabling non-programmers to follow the programming logic, easy and inexpensive accessibility, and support from others with FORTRAN experience in the KNPRRP (e.g. staff of the CCWR involved in the TITT sub-program). Different frames within each of the models are represented a separate sub-routines in the program.

There are distinct disadvantages in using FORTRAN however. These include difficulties for those without experience in FORTRAN in making minor alterations to modelling code and the use of a DOS based program whilst operating in a graphical environment (ICIS). Furthermore, it is envisaged that if the models are further refined, and the rule-base continues to grow and become more complicated, it will be necessary to utilise true "expert system" shell software. This will enable the rules to be separated from the model code and thus, stored more efficiently, as well as allowing relatively easy updating and maintenance of the rule base.

1.4.3 The distinction between local hydraulic conditions and hydrologic effects

To avoid confusion in this document, it is necessary to clarify the difference between components, which can be described as hydraulic, and those, which are **hydrologic**. In the context of these models, hydraulics refers to local flow conditions e.g. flow depth or velocity at a point. Hydrological components are those which can be defined by a particular flow or sequence of flows over space or a period of time, e.g. floods or droughts. To further clarify this, a flood can be determined hydrologically i.e. a 1:10 year flood. The depth or velocity of the flow, at a point in the river or at a particular time, are hydraulic components of that flood.

The modelling system described in this document performs only hydrologic simulations using the ACRU model. No estimates of hydraulic parameters are made. Hydraulic conditions within the river are implicitly included as biotic preferences are related directly to the prevailing geomorphologicalcharacter of the modelled reaches, rather than local water depth or velocity. The approach of relating biotic preferences to geomorphology directly is a pragmatic step governed by a lack of adequate data and the simplifying assumptions made in the development of the models, as described in later chapters.

1.5 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" i.e. the spatial and temporal scale at which managers are most comfortable making decisions and the application of scientific findings to it.

"Scale Issues" have been the subject of at least two international hydrological conferences (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 e.g. workshops on ecological issues of scale held in Great Britain (Giller *et al*., 1994), Australia in 1995 and Sweden in 1996 (Norberg *et al*., 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 longer 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 usually 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, 1996). 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).

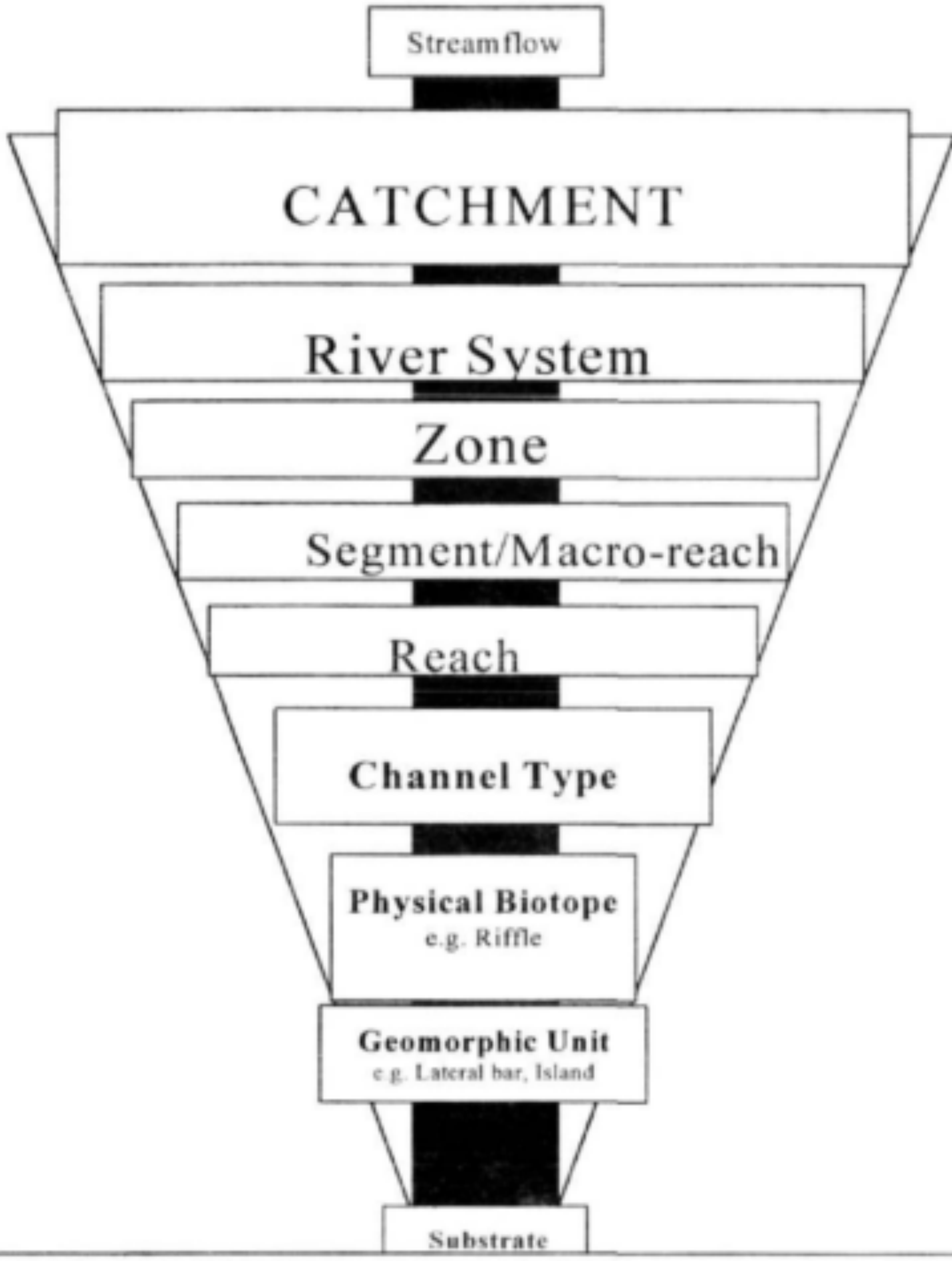
Spokespersons for hydrologists (Klêmes, 1983) as well as ecologists (Wiens, 1989) have identified the problem that humans appear to have the best grasp of things which are within anthropocentric scales and, thus, for which humans have an "intuitive feel". Klêmes (1983) suggested that hydrologists have 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".

The question of appropriate scale for integration of simulation of ecology, geomorphology and hydrology is a problematic one. The question "How can one most efficiently link predictive models from various disciplines, when these may operate on differing and varying spatial and temporal dimensions?" is often asked (Loucks *et al.*, 1985). The scale is primarily dependent upon the spatial and temporal response of the system being modelled and the planning or policy 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.

Traditionally, physical geographers and hydrologists have close links and tend to approach problems in a similar way - they are aware of each other's 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, 1993). 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 1.9 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, 1994). 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 a 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 *et al.*, 1995) and the KNPRRP (Breen *et al.*, 1994) and needs to be made.

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. In this project, abiotic hydrological and geomorphological processes, such as a flow event which mobilises sediment, and fish and riparian ecological responses, such as changes in population, are linked. These biotic responses are observed at fixed spatial and temporal scales and interpolation beyond the extent of the observations cannot be performed with any confidence. Thus, linking of these abiotic components to a biotic response requires the ability to simulate at varying spatial and at asynchronous temporal scales, i.e. linking of catchment abiotic and biotic components involves a relativistic rather than fixed view of time and space. An integrated catchment modelling system, therefore, needs to include spatial scales that allow simulation of the processes affecting biotic responses at the scale at which those processes occur, as well being able to output information at the scale of the biotic responses. The scale at which some of these abiotic processes occur does not necessarily coincide with the spatial and temporal extent of the observation of the biotic response. A freshet is an example of a flow event which is critical to the seasonal fish response, but can only be identified at a temporal scale of a day or less. If the observation scale is greater than the scale of such an event, it will not be observed, unless, coincidentally, it occurs on the day of observation.



Catchment - The area defined by the topographical area of surface water drainage (100's - 1000's km^2).
River System - The linear area of the catchment in which the river flows . (100's -1000's km)
Zone - A stretch of the river system differentiated by geology and regional slope differences (10 - 100 km) (van Niekerk and Heritage, 1993)
Macro-reach - Relatively homogenous stretches of the river in terms of discaharge sediment input and slope (5 - 20 km) (van Niekerk and Heritage, 1993)
Reach - A stretch of river characterised by particular groupings of channel types with a functional relationship to each other (100m - 5 km) (van Niekerk and Heritage, 1993)
Channel Type - A channel type is defined and characterised by a particular combination of geomorphic units (10's m - 100's m) (van Niekerk and Heritage, 1993).
Physical Biotope - A homogenous area that satisfies the physical habitat requirements of a biological community (2m - 25m)
Geomorphic Unit - A sedimentary or bedrock structure forming a feature in the river channel, e.g. a pool or bar (1m - 10's m).
Substrate - The material forming the bed of the river at the point of interest, e.g bedrock, silt (cm to 1m)

Figure 1.9 Decreasing spatial scales of catchment components

In the scope of the overall modelling strategy applied to the Sabie River Catchment, the minimum time-step utilised is 24 hrs, or daily. This is the temporal scale at which the hydrological models which simulate catchment hydrology and sediment generation operate (Chapter 2). The **window** that we look at the impacts of these daily inputs (flow and sediment) is variable. In the fish model (Chapter 4), we fix this window at 6 months, in the geomorphology model (Chapter 3), it is annual, thus reflecting gross changes to the channel type over the year. In the riparian vegetation model (Chapter 5), changes are based on the occurrence of a particular geomorphic change, and the temporal scale is variable. To facilitate easy programming however, output from the models is presented at regular intervals - seasonally in the case of the fish model and annually in the case of the geomorphology and riparian vegetation models.

1.5.1 The Representative Reach Concept

All the models developed in this project utilise the concept of the representative reach in an effort to address problems associated with spatial scale. Within a river zone (Figure 1.9), there are a number of reaches which are similar to each other in having the full range of biotopes and geomorphological features found in the zone (King and Tharme, 1994). A single reach may then be selected as being representative of the river zone in question.

The larger the sample size, the greater the degree of confidence that the biotic responses identified by ecologists can be quantified. The larger the data set, the greater the statistical 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 response to a single point in space (Levin 1992). For example, applying any of the models produced to a single particular reach of the Sabie River and expecting the models to simulate accurately 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, much of this variability may be caused by processes not accounted for in the model, for example biological interactions. However, if the reach being simulated is thought of as representative of all such reaches within the spatial extent in which the biotic processes 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.

In conclusion, it is assumed that reaches at which model estimates will be made are representative of all such reaches in the system, not a single specific channel. Electing to run the models at a pool-rapid representative reach will produce results applicable to all such reaches in the KNP, in other words average conditions, rather than results applicable to Site X. at Location Y.

A more detailed explanation of the scales selected for each of the models concerned is given in the chapters relevant to each of the models.

2 THE SABIE RIVER CATCHMENT

G.P.W. Jewitt, G.L. Heritage, J.A. Mackenzie, and D.C. Weeks

The Sabie River lies within the Incomati 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 drains a catchment area of over 6000km^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 Incomati. 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 Incomati 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 24E30' to 25E15' S and longitudinally from 30E40' to 32E10' E (Figure 2.1).

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 2.1)

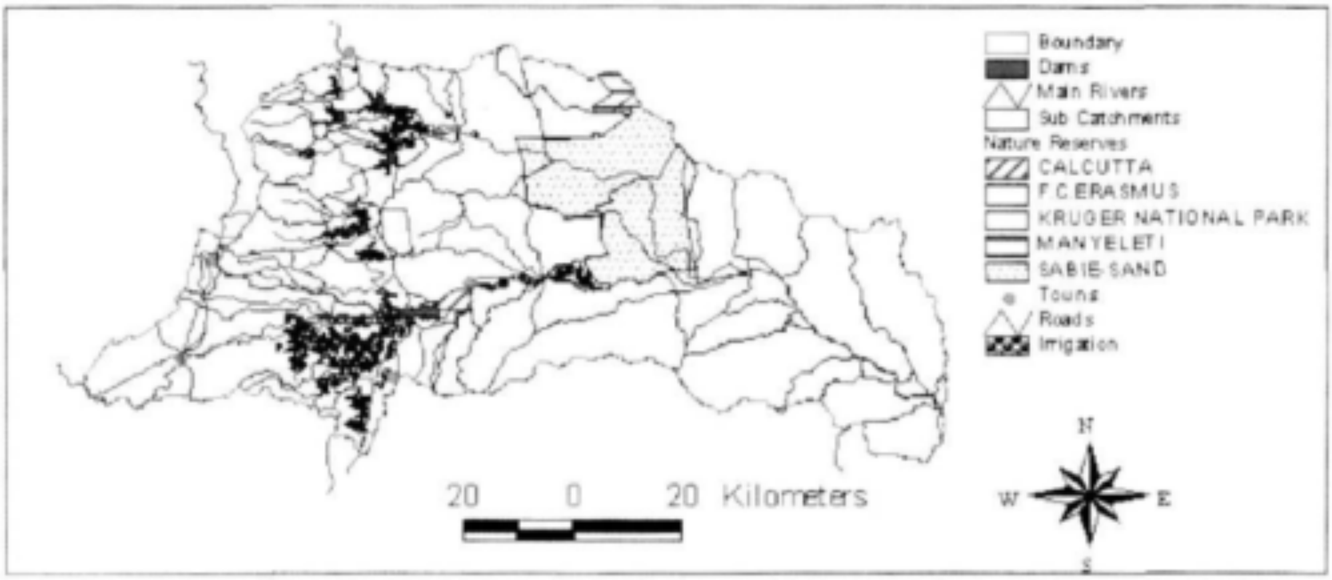


Figure 2.1 Landuse and ACRU subcatchments of the Sabie catchment

The models developed in the KNPRRP "Links" project utilise observed and simulated values of streamflow and sediment load at various timesteps as input. Observed values of streamflow have been obtained from the South African Department of Water Affairs and Forestry (DWAF). For the purposes of this project, the ACRU agro-hydrological modelling system (Schulze, 1995) was used to provide simulations of daily streamflow and sediment production in the Sabie-Sand catchment.

2.1 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 63^3x10^6 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 450-650mm.p.a. over the Lowveld and Lebombo geomorphological zones. In contrast evaporation is lower in the west (1400mm) rising to 1700mm 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 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 (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 and are listed in Appendix A. The Sabie River Catchment is typical of many in South Africa in that the quality of 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 station 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 storgae 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^3per annum and 500 000 m^3 are pumped out of the Sabie catchment area to supply water to Pretoriuskop and KaNgwane respectively (DWAF, 1996a; Pike *et al.* 1997).

2.2 GEOMORPHOLOGY OF THE SABIE RIVER

The Sabie River in the semi-arid Mpumulanga Lowveld 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 , 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).

Bedrock anastomosing

Bedrock anastomosing channels were first identified on the Sabie River by van Niekerk and Heritage (1993) and are dominated by bedrock features. Kale *et al.* (1996) have recognised similar multi-channel bedrock distributary reaches on the Narmada River, India. Typically the incised macro-channel is widened in places to extend across an area three to four times its average width. This effect extends for several kilometres downstream, but is variable as the size of the feature is a function of the local geology. Geomorphological diversity is high with many features occurring at a low density. Numerous steep-gradient, active channel bedrock distributaries exist within the incised channel, describing a tortuous route over the resistant rock. These distributaries display very few alluvial features within their bedrock channels with sediment accumulation being restricted to lateral deposits and alluvium in pools in the form of armoured clastic lags and finer deposits in dead zones. Bedrock features include pools, rapids, cataracts and small waterfalls. The macro-channel is characterised by bedrock core bar deposits (van Niekerk *et al.* 1995) and occasional larger islands that cover the areas between distributary channels. Elevated bedrock areas are common and may exist as exposed bedrock pavements.

Pool-Rapid

The pool-rapid channel type is also geomorphologically diverse and displays many bedrock features. Detailed field investigation of the geological controls reveals a number of reasons for this, including localised chemical differences similar to the bedrock anastomosing situation and differing lithologies (Cheshire 1996). These factors create active channel pool-rapid sequences, the scale of which is dependent on local geological variability and channel gradient. Typically the rapids are free of sediment apart from occasional boulders and bedrock core bars. The pool areas are more variable ranging from sediment free bedrock areas to bedrock lined pools incorporating a variety of bar types, particularly mid-channel bars and lateral deposits. The active pool-rapid typically occupies only a portion of the macro-channel. Large-scale sedimentary features have covered much of the bedrock across the rest of the incised channel.

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. Although the active channel may be straight or sinuous, the freedom to make planform adjustments is restricted to the width of the incised macro-channel. Few geomorphological features were recorded in the active channel, which is composed largely of deep alluvial pools with rare mid-channel and lateral bars. The macro-channel consists wholly of lateral bar and bank morphologies with a complete absence of bedrock features.

Braided

The degree of braiding in the Sabie River, as defined by the number of braid distributaries, is low and appears restricted to the deposition of mid-channel and lateral bars within an active channel, the banks of which are well protected by vegetative cover. Geomorphological diversity is lower than for those channel types directly influenced by bedrock. Quantification of the features present along 4.5 km of braided channel reveals a significant reduction in bedrock features being restricted to a small area of reduced rapids. Alluvium is present over bedrock in the form of bedrock core bars and in the active channel as mid-channel and lateral deposits. All pools show some degree of alluviation. The macro-channel areas are also dominated by lateral alluvial features with only very rare outcrops of bedrock.

Mixed anastomosing

Mixed anastomosing channel types exhibit a high geomorphic diversity. These display multiple bedrock, mixed and alluvial distributary channels that divide and rejoin over a distance much greater than the distributary width. A small percentage of the active distributary channels are filled with alluvial material in the form of lateral, mid-channel and lee bars; pools are also seen to contain some sediment. The macro-channel also exhibits extensive lateral alluvial deposits, islands and bedrock core bars. The multi-channel planform appears to be relatively stable with the river reverting largely to its old course following floods greater than the capacity of the active channels.

2.3 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, *viz. Opsaridium peringu* is considered rare. 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.

Many of the fish species in the Sabie system are dependent upon overhanging marginal vegetation and river banks for cover, whilst others are reliant upon cover offered by the substrate of the river bed. Most of the fish species found are reliant on minor floods to stimulate breeding. The major fish groups identified and used in this project are described briefly below and in more detail in Chapter 4.

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.

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.

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.

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.

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.

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 substrates.

2.4 RIPARIAN VEGETATION OF THE SABIE CATCHMENT

A description of the riparian vegetation along the Sabie River inside the KNP has been conducted (van Coller and Rogers, 1995). Riparian vegetation patterns have been elucidated in this study, and patterns have been related to physical habitat templates. Discontinuities in the distribution patterns of species suites have been used 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 characteristics of hydrological and geomorphological regimes.

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 and are found in close proximity to the active channel. This vegetation type predominates in the granitic and rhyolite geological substrates, and can be found along most of the length of the Sabie.

The Phragmites *mauritianus* vegetation type

This is predominantly a reed vegetation type, but includes certain shrub species as well. This vegetation type is mainly associated with alluvial geomorphic features that are seasonally or more regularly influenced by river flow. They form an important suite of species because they provide browsing for many of the herbivores that utilise the riparian zone, as well as breeding sites for certain fauna. 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 is therefore a role player in sediment dynamics.

The *Phyllanthus reticulatus* vegetation type

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

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. Because this group is deciduous it is important for its organic input to the riparian zone.

The *Diospyros mespiliformis* vegetation type

This vegetation type is characterised by an evergreen to semi-deciduous tree canopy and 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. These species are more drought resistant than species in the previous four vegetation types, and occur on steep moisture gradients. This is an important group as it forms a boundary between the riparian with the terrestrial zones.

The *Spirostachys africana* vegetation type

This vegetation type is characterised by a deciduous tree canopy and 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, occur on steep moisture gradients, and can persist in mesic areas outside of the riparian zone. It is an important group as it also forms a boundary between the riparian zone with the terrestrial zone, and comprises some terrestrial species which colonise the riparian zone.

Some exotic invasives have become a concern along the Sabie river riparian zone, in particular *Lantana camara* and to a lesser degree *Melia azedarach*. Higher up in the catchment outside of the Kruger national Park, many *Pinus* and *Eucalypt* species occur as a result of commercial forestry.

2.5 CONFIGURATION OF ACRU FOR HYDROLOGICAL SIMULATIONS OF THE SABIE CATCHMENT

The ACRU model is 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. Technical details of the ACRU model and procedures outlined and mentioned in this report are all covered by Schulze (1995) and Smithers and Schulze (1995).

The Sabie catchment was further divided into 56 sub-catchments for the purposes of this exercise. Sub-division of the catchment is needed in order to account for heterogeneity of catchment rainfall, land cover and soils and to facilitate output requirements at specific sites within a catchment, such as dams, weirs or representative reaches. The subcatchment breakdown is also shown in Figure 2.1.

The ACRU model operates at a daily timestep, thus allowing hydrological output at any timestep larger than a day to be calculated by means of simple aggregation.

2.5.1 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 and where no observed data is available, to ensure that sensible values are generated.

In this study, the poor quality of streamflow data in the Sabie catchment has limited the effectiveness of such a verification exercise. Nevertheless, the model does seem to effectively simulate streamflow at various points in the catchment as shown in Figure 2.2. 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 achieved by comparison with results of sediment studies in the Sabie Catchment, such as those of Rooseboom *et al.* (1992).

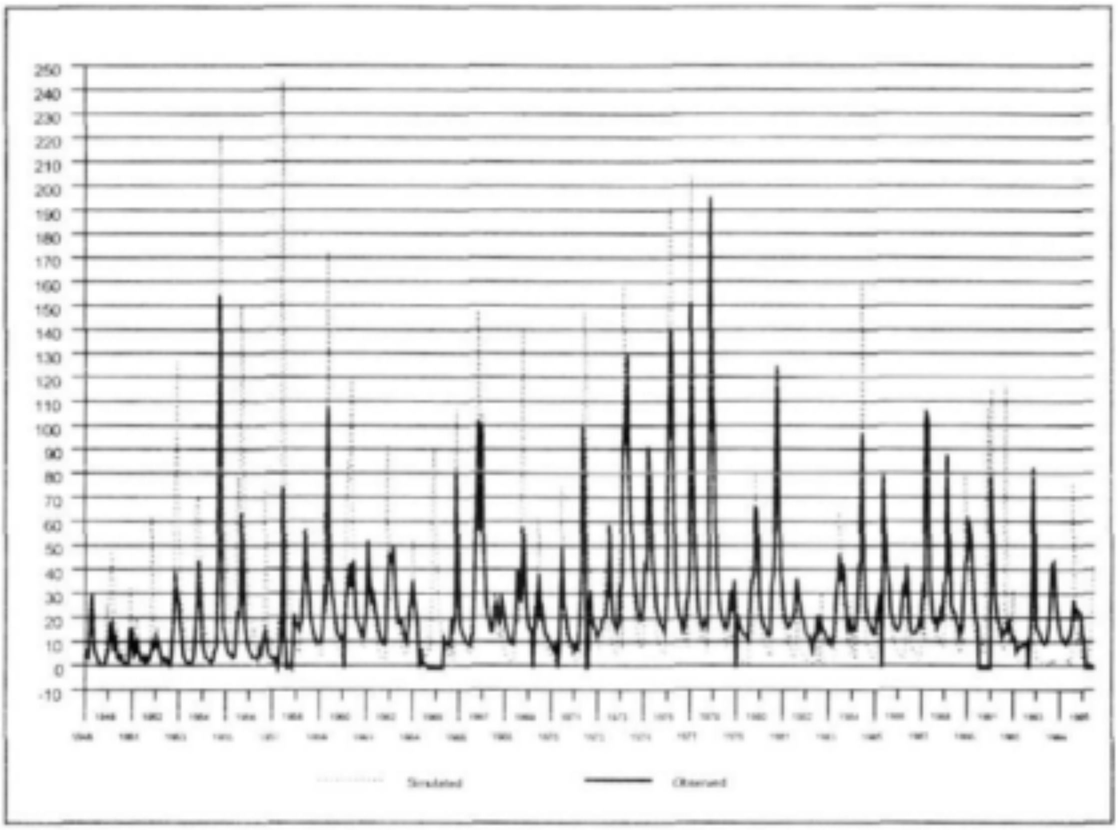


Figure 2.2 Comparison of ACRU Simulated and Observed Monthly Streamflow at Perry's Farm (X3H006) for the period 1948 – 1996.

3 THE GEOMORPHOLOGY MODEL

G. L. Heritage, G.P.W. Jewitt, A.W. van Niekerk and A.L.Birkhead.

This section details the background to the development of the geomorphology model designed to predict the distribution of physical habitat available for fish and vegetation on the Sabie River in the Kruger National Park. Information is presented on the conceptual framework behind the model, a description, and justification of, spatial and temporal scales on which the model currently operates, and the nature of the input data.

The form of inputs (sediment from the catchment, present channel condition) and outputs (change in geomorphic unit composition) to and from the model are discussed with respect to the hydrological regime. In addition, the matrix of rules for each of the channel type sub-models is presented for each generic channel type and justified with reference to field evidence of channel change on the Sabie River. The results of model testing and validation are presented based on a scenario that generates a prediction of the fish assemblage present for the average pool-rapid channel type in the Lowveld Zone of the Sabie River and this is compared to collected assemblages based on the work of Pollard *et al.* (1996) and Weeks *et al.* (1996) in Chapter 4 of this document.

Finally the limitations of the present model are discussed and research requirements are highlighted that will improve the predictive accuracy of any refined model.

3.1 BACKGROUND AND OVERVIEW

The need for a geomorphological approach to linking river response and ecological functioning has been explained in Chapter 1.3 and is illustrated in Figure 1.3. The use of this approach in the KNPRRP BLINK programme requires that some form of geomorphic predictive system must exist in order to provide input to the fish and riparian vegetation models. This system should provide an estimate of the composition of the selected representative reach in terms of the geomorphic units in that reach.

Simulation of the geomorphic composition of a channel is normally performed with mechanistic type models such as MOBED (Krishnapan, 1981), HEC6 (HEC, 1977) and

Fluvial 14 (Chang, 1982). The Sabie is such a complex system, however, that collection of the data needed to run these programs would be prohibitive. 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).

3.2 SPATIAL AND TEMPORAL SCALES SELECTED

The geomorphology model is designed to accept discharge data for any point on the Sabie River in the form of a daily average flow rate. Sediment input data are also simulated on a daily timescale through the ACRU simulation model (Schulze, 1995) for 57 sub-catchments (Figure 2.1). The Sabie River is sub-divided into 40 linked units, which represent the spatial extent of alternating channel types (bedrock, mixed and alluvial anastomosing, bedrock and mixed pool-rapid, alluvial single thread and braided) along the river. A description of the simulation process is given below.

3.2.1 Hydrological Input

The hydrological regime is simulated using the ACRU model for any point on the Sabie River. The flow regime has been divided into four categories which are used to drive the channel change matrices presented below (Table 3.1):

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.

3.2.2 Sediment Input

Sediment enters the Sabie River at tributary junctions, with many of these tributaries flowing ephemerally and introducing sediment on a sporadic basis. This is then reworked by the perennial flows of the Sabie River according to local channel competence as defined by the channel types downstream (bedrock anastomosing channel types have been shown to be more competent to transport material than pool-rapids, braided and single thread channels (Van Niekerk *et al.*, 1995)). Sediment transport rates were computed on a daily basis using cross-sectional and channel roughness data collected and analysed by the Centre for Water in the Environment (Broadhurst *et al.*, 1995). The ACRU sediment production model has been used in this project to simulate catchment degradation on a daily timescale. Data are available to generate separate daily values for the 57 sub-catchments of the Sabie cacthment located inside and outside of the Kruger National Park (Figure 2.1).

Generation of a sedimentation index along the Sabie River

Two simple indices were generated to define the relative levels of sedimentation expected in each channel type segment along the river. This involved the calculation of a normalised sediment input parameter (SEDIN) for each tributary junction and a normalised flow parameter (FLO) for each channel type downstream:

$$\text{SEDIN} = \frac{\text{annual average sediment input}}{\text{40 year average annual sediment input}} \qquad (3.1)$$

$$\text{FLO} = \frac{\text{annual average flow volume}}{\text{40 year average annual flow volume}} \qquad (3.2)$$

These indices were then used to calculate the range of potential sedimentation values experienced over the last 40 years on the Sabie River. Examination of the normalised data allowed appropriate ranges to be assigned to categories of potential sedimentation (Table 3.1.)

Table 3.1 Categorisation of the flow and sedimentation parameters used to define the process states in the geomorphological model.

Flow regime categorisation		**Potential sedimentation categorisation**	
Flow state	'FLO' index range	Sedimentation state	'SEDI' index range
Base		Low	<0.7
Freshet	These parameters	Reduced	0.7-1.0
Annual flow	are defined in	Moderate	1.0-1.3
Flood	Section 3.2	High	> 1.3

3.2.3 Geomorphological Input

Use of the geomorphological template to predict fish habitat takes place at three spatial scales (Figure 3.1). Initially, the channel type is recognised (i.e. pool-rapid) and secondly, geomorphological units are identified (Table 3.2). These units are in turn characterised by a sub-set of cover and substrate categories as discussed in Chapter 4.5. The riparian model uses geomorphological input at the geomorphological unit scale (Chapter 5.5).

Table 3.2 Description of the geomorphological units found on the Sabie River in the Kruger National Park (after van Niekerk *et al.* 1995).

Geomorphological Unit	Description
Rapid	Steep bedrock sections, high velocity concentrated flow.
Bedrock pavement	Horizontally extensive area of exposed rock.
Isolated rock	Discrete small outcrop of bedrock.
Pool (bedrock, mixed and alluvial)	Topographic low point in the river channel associated with a downstream bedrock or alluvial control.
Braid bar	Accumulation of sediment in mid-channel causing the flow to diverge over a scale that approximates to the channel width.
Lateral bar	Accumulation of sediment attached to the side of the channel, may occur sequentially downstream as alternate bars.
Point bar	Accumulation of sediment on the inside of a meander bend.
Bedrock core bar	Accumulation of finer sediment on top of bedrock in bedrock anastomosing areas.
Lee bar	Accumulation of sediment in the lee of flow obstructions.
Distributary (bedrock, mixed and alluvial)	Individual active channel in an anastomosing system.
Island	Large mid channel sediment accumulation that is rarely inundated.
Anastomosing bar	Accumulation of coarser sediment on top of bedrock in bedrock anastomosing areas.
Macro-channel lateral bar	Large accumulation of fine sediment on the sides of the incised macro-channel

The model has a baseline geomorphological template consisting of the distribution of channel types along the Sabie River (Figure 3.2), and these are used as the basis on which to route sediment inputs from the sub-catchments. Internally, the changing sediment balance within each channel type causes a change in the geomorphological composition at the scale of morphologic unit, and these are simulated with rules developed by geomorphologists with detailed knowledge of the Sabie River.

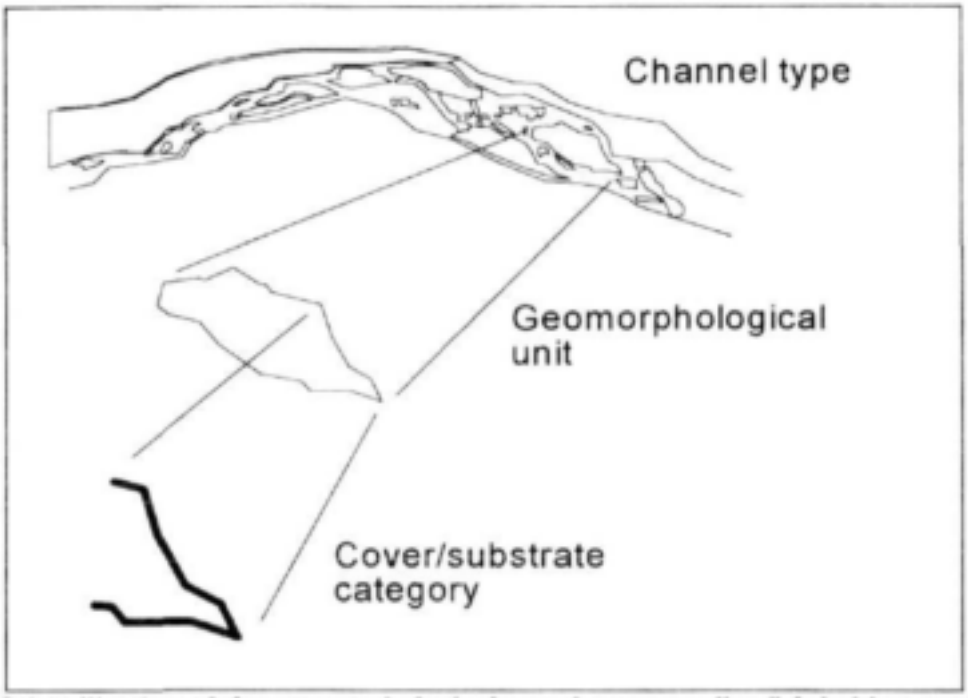


Figure 3.1 Utilisation of the geomorphological template to predict fish habitat operates at three scales.

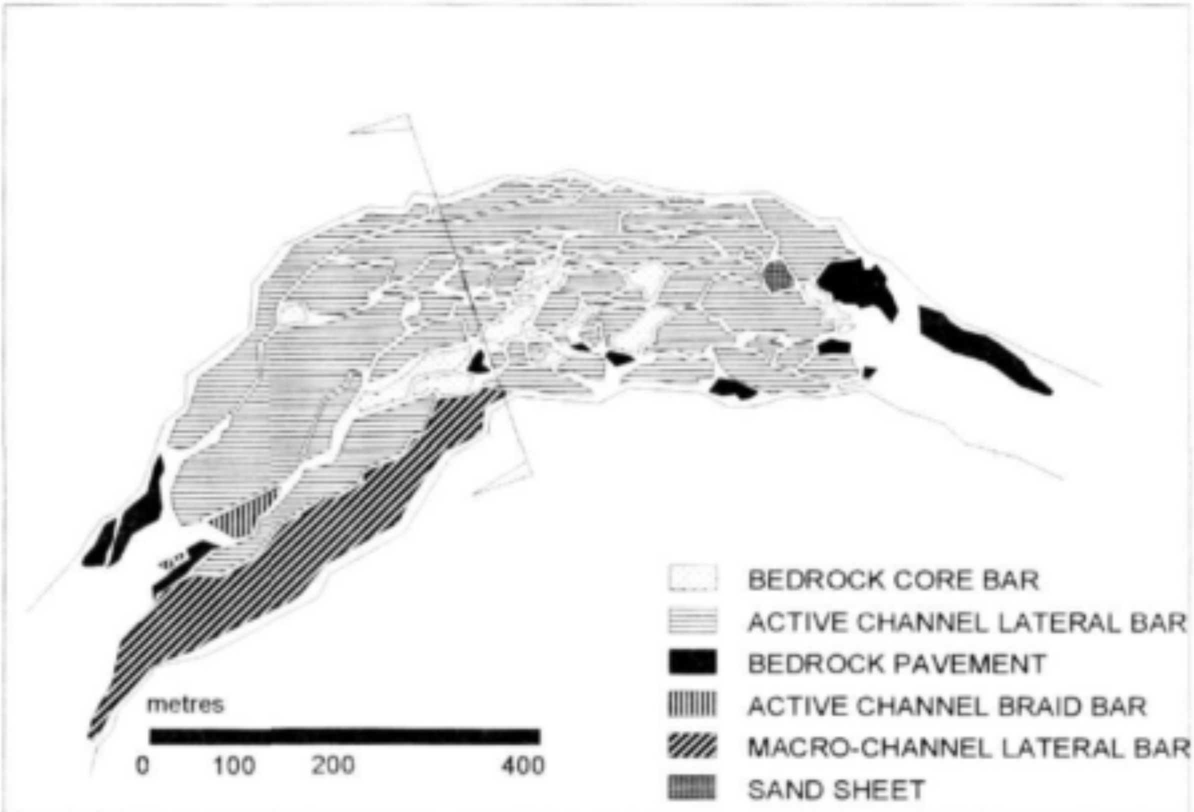


Figure 3.2a Pattern of channel types observed on the Sabie River in the Kruger National Park (bedrock anastomosing).

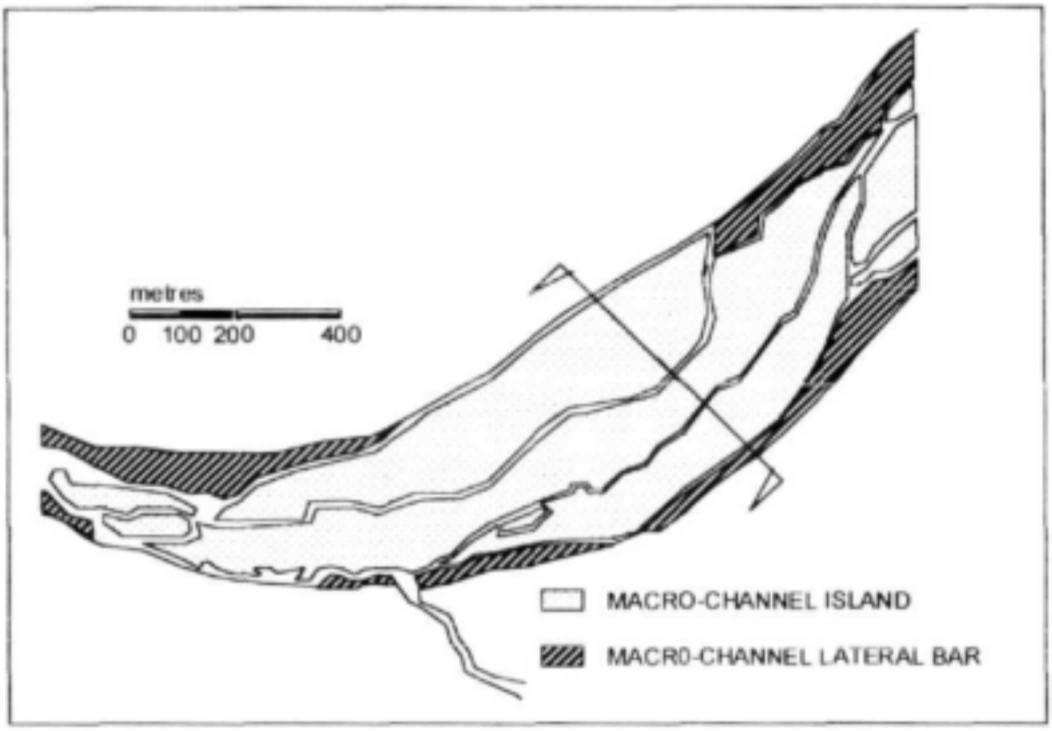


Figure 3.2b. Pattern of channel types observed on the Sabie River in the Kruger National Park (alluvial anastomsong).

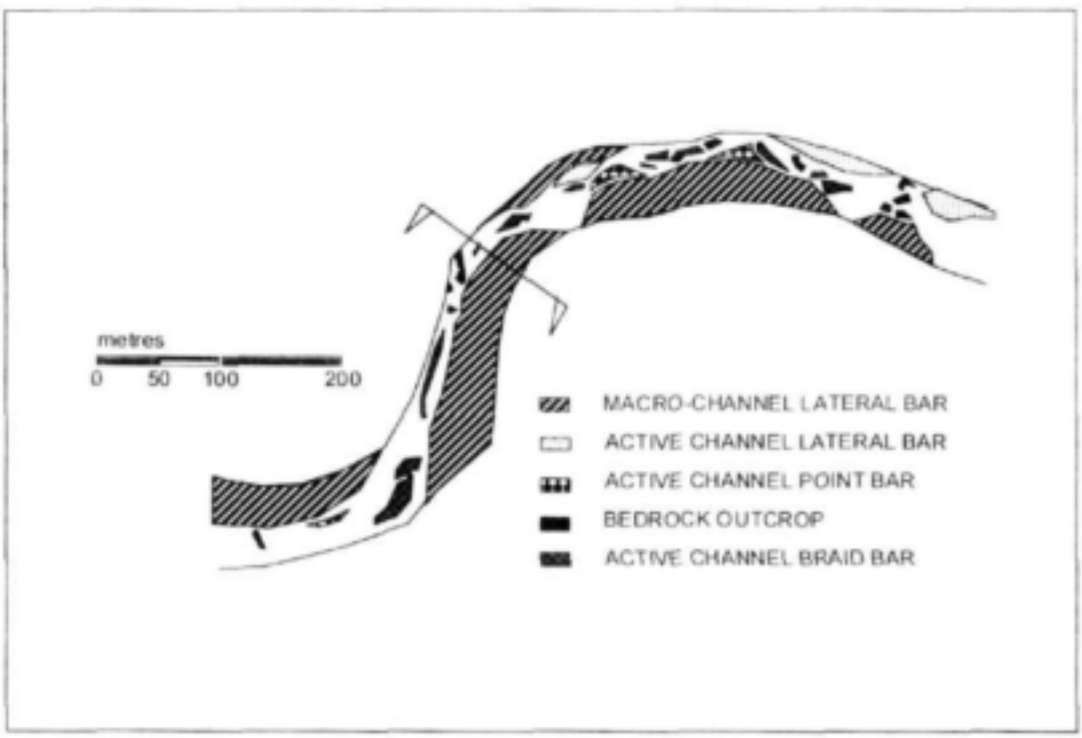


Figure 3.2c. Pattern of channel types observed on the Sabie River in the Kruger National Park (braided)

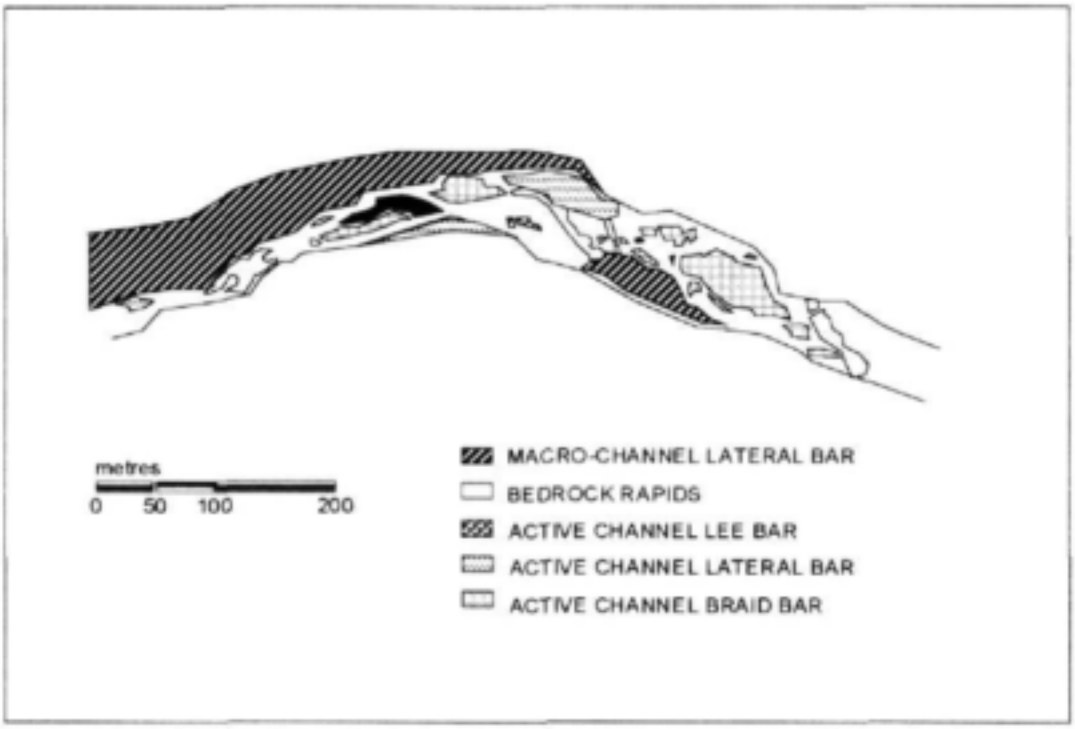


Figure 3.2d. Pattern of channel types observed on the Sabie River in the Kruger National Park (pool-rapid)

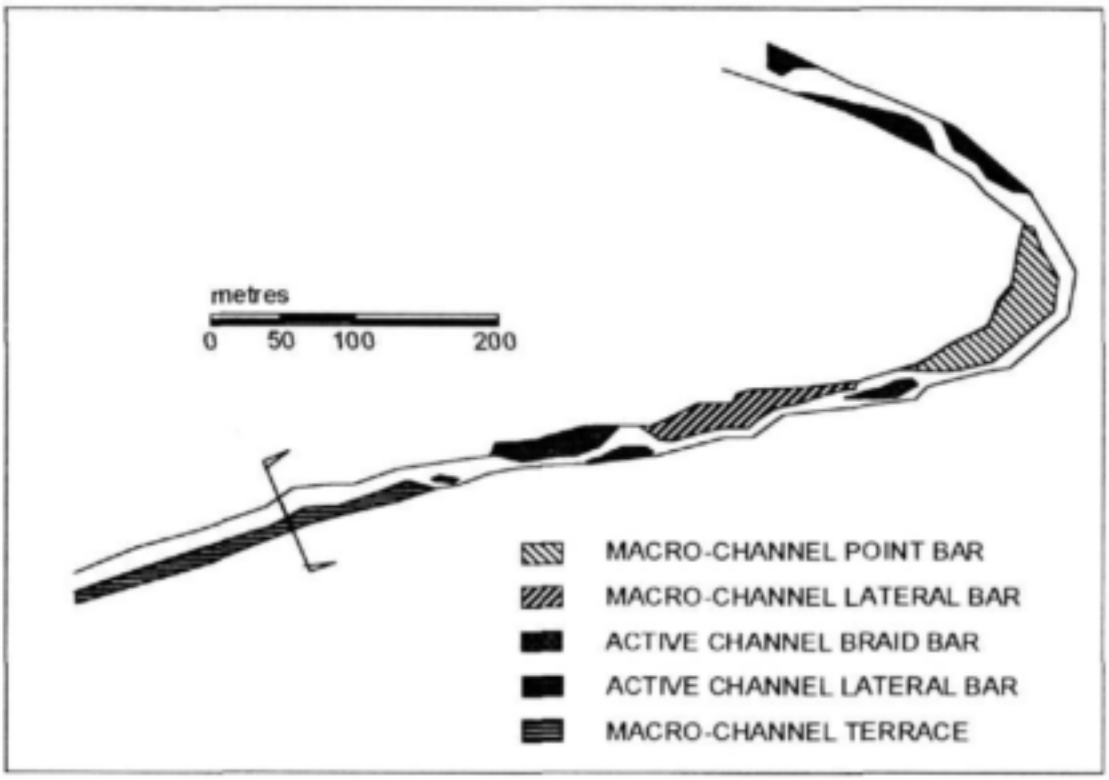


Figure 3.2e. Pattern of channel types observed on the Sabie River in the Kruger National Park (single thread).

3.3 RULE DEVELOPMENT AND CODING

Expert knowledge gained through extensive field experience, detailed examination of temporal aerial photographic sequences and space for time substitution (Van Niekerk and Heritage 1993, Heritage and Van Niekerk 1994, Carter and Rogers 1995, Heritage *et al.* 1996, Broadhurst *et al.* 1996, Moon *et al.* 1996) have allowed rules to be developed concerning geomorphological change in the Sabie River in the Kruger National Park in response to changing flow and sediment regimes. The rules are presented below as a set of matrices defined by the controlling parameters SEDIN and FLO. Three matrices have been constructed to simulate geomorphological change in three generic channel types. The anastomosing channel matrix defines changes for bedrock, mixed and alluvial anastomosing channel types; the pool-rapid matrix defines changes in bedrock and mixed pool-rapids and the alluvial matrix concerns change within braided and alluvial single thread channels.

Each of the generic channel types is initially defined by a base morphologic state as determined by quantitative analysis of 21km of river channel within the Kruger National Park (5km bedrock anastomosing, 6.5km pool-rapid, 8km mixed anastomosing, 1km single-thread and 4.5km braided). The results reveal the composition of geomorphic units within each channel type based on aerial coverage and average percentage cover for each unit is presented in Table 3.3.

A set of rules has been imposed on each matrix as follows:

- Erosion of alluvial features within the active channel (braid bars, lateral bars, point bars, lee bars) results in an identical percentage gain of submerged morphologic features (bedrock pools, mixed pools, alluvial pools).
- Erosion of alluvial features outside of the active channel (bedrock core bars, anastomosing bars, islands, macro-channel lateral bars) results in an identical percentage gain in bedrock features (bedrock pavement, rapids, isolated rock).
- There is internal redistribution of sediment within the submerged depositional features (bedrock pools, mixed pools, alluvial pools) in response to erosion and deposition.

Where features are totally eroded, a hierarchy has been set up that transfers the loss to another alluvial feature. The order is: bedrock core bar, anastomosing bar, island, macro-channel lateral bar for the features outside of the active channel and lee bar, lateral bar/point bar, alluvial pool, mixed pool, for in-channel morphologic units.

Table 3.3 Morphologic composition of the generic channel types on the Sabie River in the Lowveld based on mapping of 25km of river (for unit description see table 3.2).

Geomorphologic unit	Generic channel type		
	Anastomosing (%)	Pool-rapid (%)	Alluvial (%)
Braid bar	3	1	15
Lateral/point bar	5	20	20
Lee bar	2	1	0
Bedrock core bar	51	10	0
Anastomosing bar	5	0	0
Rapid	5	4	1
Isolated rock	2	1.5	1
Bedrock pool	9	2.5	0
Mixed pool	15	15	3
Alluvial pool	1	20	35
Island	0	0	0
Bedrock pavement	2	0	0
Macro-channel lateral bar	0	25	25

Each change matrix is presented as Tables 3.4 to 3.6. The pool geomorphologic units are listed twice, the first time accounts for changes with alluvial deposits, the second represents internal redistribution of sediment. In the case of the pool-rapid channel type, the matrix states that braid bars increase most in a year when the flow regime displays a freshet or the annual flood combined with moderate to high sediment ratios. Conversely, they are eroded during years experiencing a major flood with reduced or low sediment inputs. In the case of the matrix for the anastomosing channel type the formation of anastomosing bars is favoured in years where major floods occur coupled with a high sediment ratio. In contrast bedrock core bars increase during years experiencing a major flood linked to a moderate sediment ratio.

Switching between channel types is controlled by a set of critical geomorphological unit values. Two principle pathways are coded into the model: the first accounts for changes within anastomosing channels, and the second between pool-rapid, braided and single thread channels. The channel switching rules are defined as follows:

Bedrock anastomosing

Bedrock pools > 10% and (bedrock core bars <80% or anastomosing bars <80%)

Mixed anastomosing

Bedrock pools > 0% and < 10% and (bedrock core bars <80%, or anastomosing bars <80%)

Alluvial anastomosing

Bedrock pools = 0% and (bedrock core bars <80% or anastomosing bars <80%)

Where bedrock core bars or anastomosing bars exceed 80% the generic channel type switches to pool-rapid and the following rules, governing the second priciple pathway are observed:

Bedrock pool-rapid

Rapids > 5%

Mixed pool-rapid

Rapids between 2 and 5%

Mixed braided

Rapids > 1% and < 2% and braid bars > 10%

Mixed single-thread

Rapids > 1% and < 2% and braid bars > 0% and < 10%

Braided

Rapids < 1% and braid bars > 10%

Alluvial Single thread

Rapids < 1% and braid bars > 0% and < 10%

Overall, the matrices may be seen to function in two basic ways. Active channel features respond to baseflows to generate minor changes. Under low sediment inputs there will be minor erosion, switching to minor deposition under high sediment input conditions. Changes are muted, as the flows are not generally competent to redistribute sediment. As flows increase through freshets to the annual maximum flows and finally flood flows so these changes are accentuated such that major erosion occurs under low sediment inputs and major deposition occurs under high sediment inputs (Figure 3.3 a).

The macro-channel geomorphic system responds differently to the flow and sediment conditions. Under baseflows and freshets there is no change to the macro-channel features since they are not inundated. Under flows of the order of the annual maximum flood there will be some minor erosion given low sediment inputs altering to minor deposition given high sediment inputs. Given an extreme flood these effects are intensified with major deposition under high sediment input conditions and major erosion under low sediment input conditions (Figure 3.3b)

These rules and routines to calculate SEDIN and FLO (see Section 3.2.2) were coded into the FORTRAN 77 programming language. Each of the matrices is represented as a different frame in the model, the structure of which is shown in Figure 3.4. Each frame is represented in the model as a subroutine, with the main program determining the existing channel type, and thus the subroutine to be utilised at each model time step.

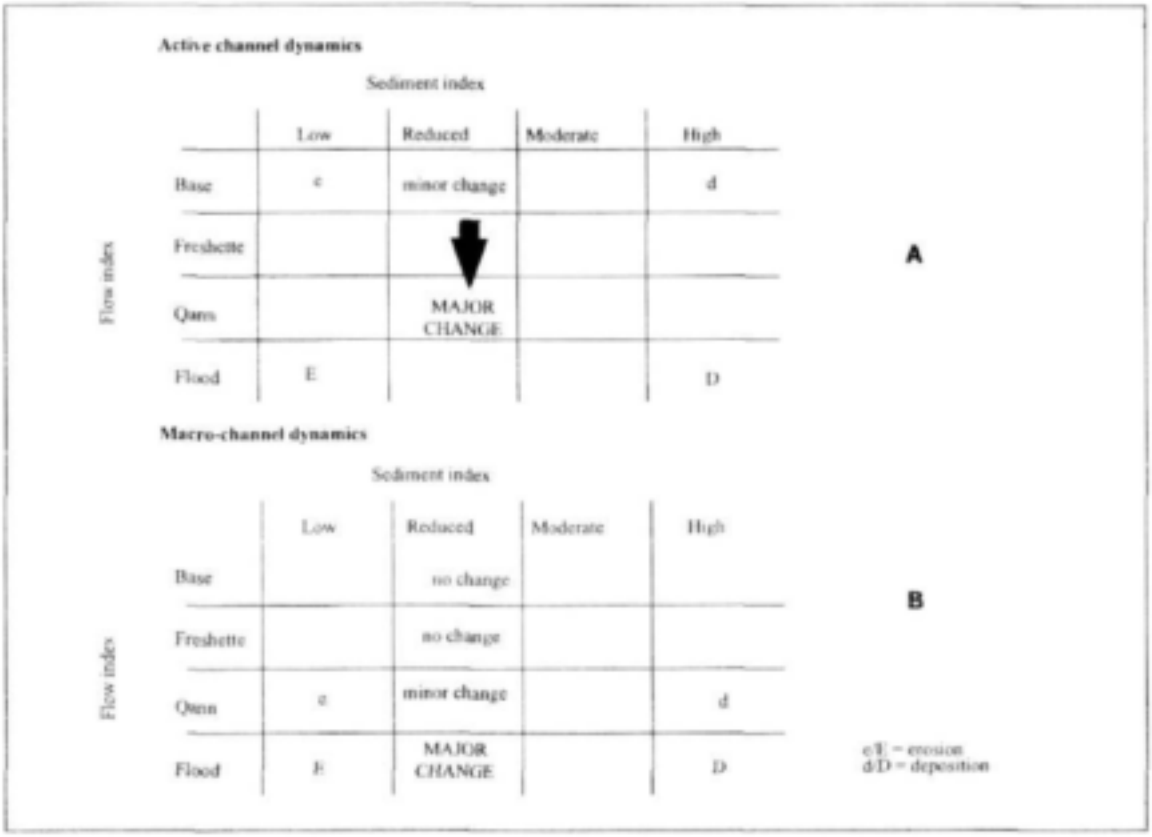


Figure 3.3 Active and macro-channel geomorphological response to flow and sediment regimes.

Model output consists of an area bar graph representing the percentage that each geomorphic unit makes up of the reach being simulated, and a hypertext trace of each rule invoked in the coarse of each model run. Tools to display the model output were developed by the KNPRRP TITT sub-programme by staff at the CCWR. An example of the model output is shown in Figure 3.5.

Thus, through this approach, long term channel change can usefully be predicted at the scale of geomorphological unit (pools, rapids, bar types, etc.) (Figure 3.6) and new geomorphological associations following channel change can be predicted using the geomorphological model and data on the annual flow regime (FLO) and potential sedimentation (SEDI). The new range of geomorphological units predicted by the model can be used by fish and riparian vegetation ecologists as determinates of available habitat as explained in Sections 4.5 and 5.5.

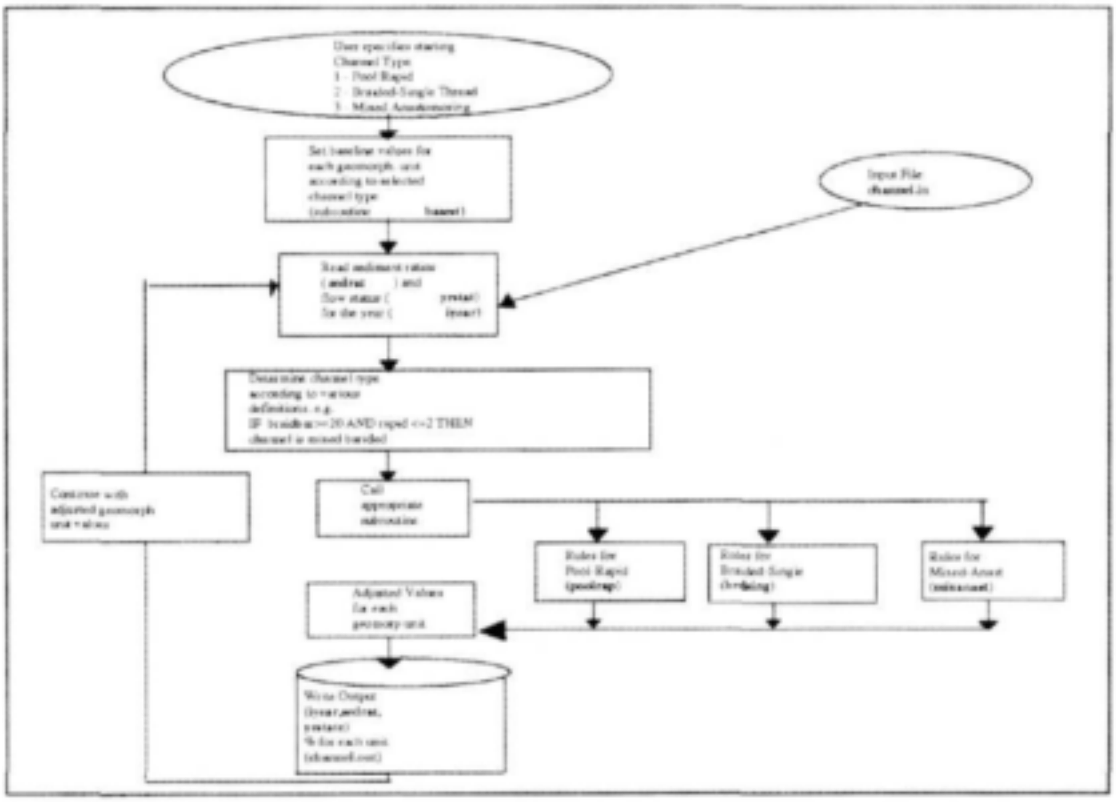


Figure 3.4 Schematic Structure of the Geomorphology Model

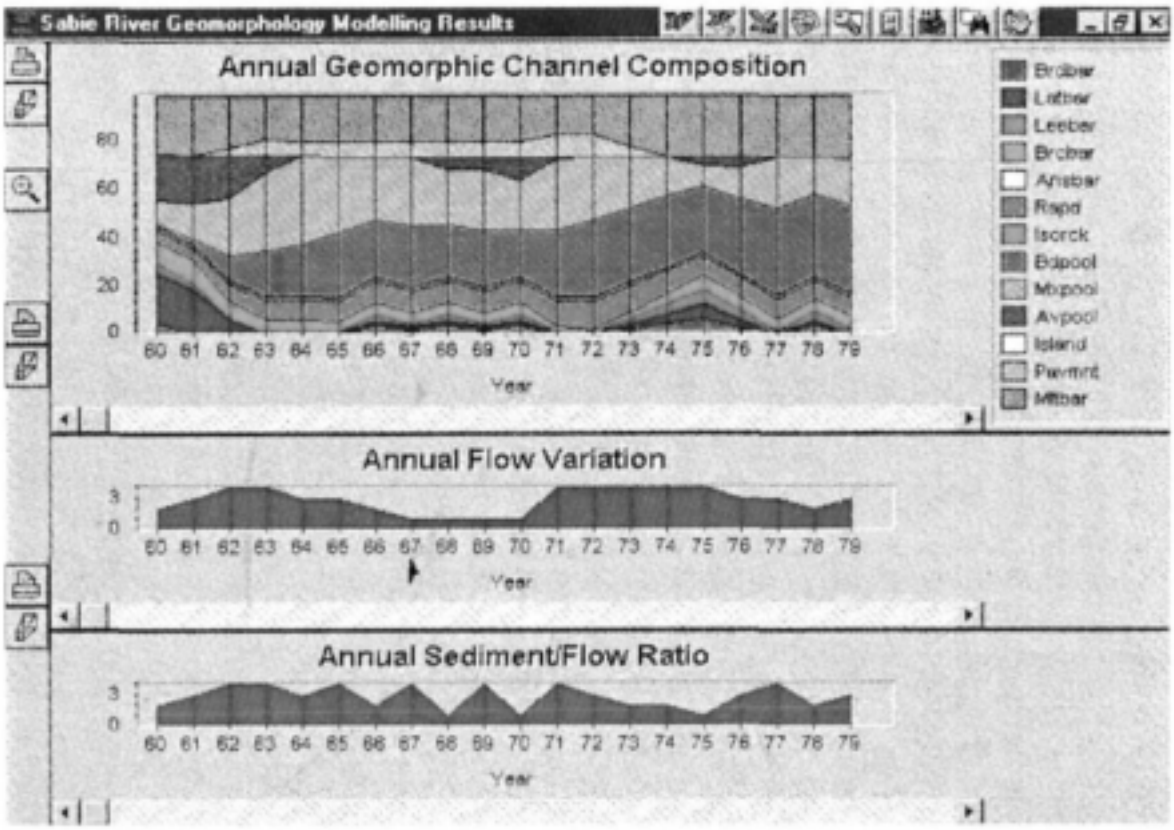


Figure 3.5 Sample output from the Geomorphology Model

Table 3.4 Morphologic unit change matrix for the pool-rapid generic channel type

MORPH UNIT	SEDIMENT RATIO HIGH				SED RATIO MODERATE				SED RATIO REDUCED				SED RATIO LOW			
	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood
BRAID BAR	1	4	5	2	1	3	4	2		-2	-4	-3	-1	-3	-4	-5
LAT /POINT BAR	1	3	4	2	1	2	3	2		-2	-2	-3	-1	-3	-4	-5
LEE BAR	2	4	3	2	2	3	2	2	-1	-2	-2	-3	-2	-3	-3	-5
BED CORE BAR			1	2				1				-1			-1	-2
ANAST BAR																
RAPID			-1	-2				-1				1			1	2
ISOLATED ROCK																
BED POOL	-2	-2	-2	-1	-2	-2	-2	-1		1	2	2	1	2	2	3
MIX POOL	-1	-2	-3	-2	-1	-2	-3	-1		2	3	3	1	2	4	4
ALLUVIAL POOL	-1	-7	-7	-3	-1'	-4	-4	-4	1	3	4	4	2	5	6	8
BED POOL	-2	-2	-2	-1	-1	-1					1	2	1	2	3	5
MIX POOL	-4	-5	-8	-6	-2	-3	-3	-2	1	2	3	3	1	2	5	5
ALLUVIAL POOL	6	7	10	7	3	4	3	2	-1	-2	-4	-7	-2	-4	-8	-10
ISLAND																
PAVEMENT				-3				-5								3
MACRO-LAT BAR				3				5								-3

Table 3.5 Morphologic unit change matrix for the alluvial generic channel type

MORPH UNIT	SEDIMENT RATIO HIGH				SED RATIO MODERATE				SED RATIO REDUCED				SED RATIO LOW			
	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood
BRAID BAR		2	4	8		1	3	6		3	4	5		-1	-8	-12
LAT /POINT BAR		2	4	8		1	3	6		-6	-8	-10		-2	-8	-10
LEE BAR																
BED CORE BAR																
ANAST BAR																
RAPID			-1													1
ISOLATED ROCK			-1													1
BED POOL																
MIX POOL			-1	-2			-1	-2		1	1	2			6	12
ALLUVIAL POOL		-4	-7	-14		-2	-5	-10		2	3	3		3	10	10
BED POOL																
MIX POOL																
ALLUVIAL POOL																
ISLAND																
PAVEMENT				-3				-5								3
MACRO-LAT BAR				3				5								-3

Table 3.6. Morphologic unit change matrix for the anastomosing generic channel type

MORPH UNIT	SEDIMENT RATIO HIGH				SED RATIO MODERATE				SED RATIO REDUCED				SED RATIO LOW			
	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood	Base	Freshet	Qann	Flood
BRAID BAR			1	2			0.5	1		-0.5	-1	-2		-1	-2	-3
LAT /POINT BAR			1	2			0.5	1		-0.5	-1	-2		-1	-2	-3
LEE BAR				1												-1
BED CORE BAR			1	3			1	5			1				-2	-8
ANAST BAR			1	5			1	3			-1	-2			-2	-8
RAPID				-2				-1				1				2
ISOLATED ROCK				-1				-0.5				0.5				1
BED DISTRIB			-1	-1				-1								
MIX DISTRIB			-1	-3				-3				-1				-3
ALLUVIAL DISTRIB				1										3		-1
BED DISTRIB				-2			-0.5	1		1	1	3		1	3	4
MIX DISTRIB				-3			-0.5	1			1	1		1	2	3
ALLUVIAL DISTRIB				1				0.5								-1
ISLAND																
PAVEMENT			-2	-3			-2	-3			1	2			4	10
MACRO-LAT BAR																

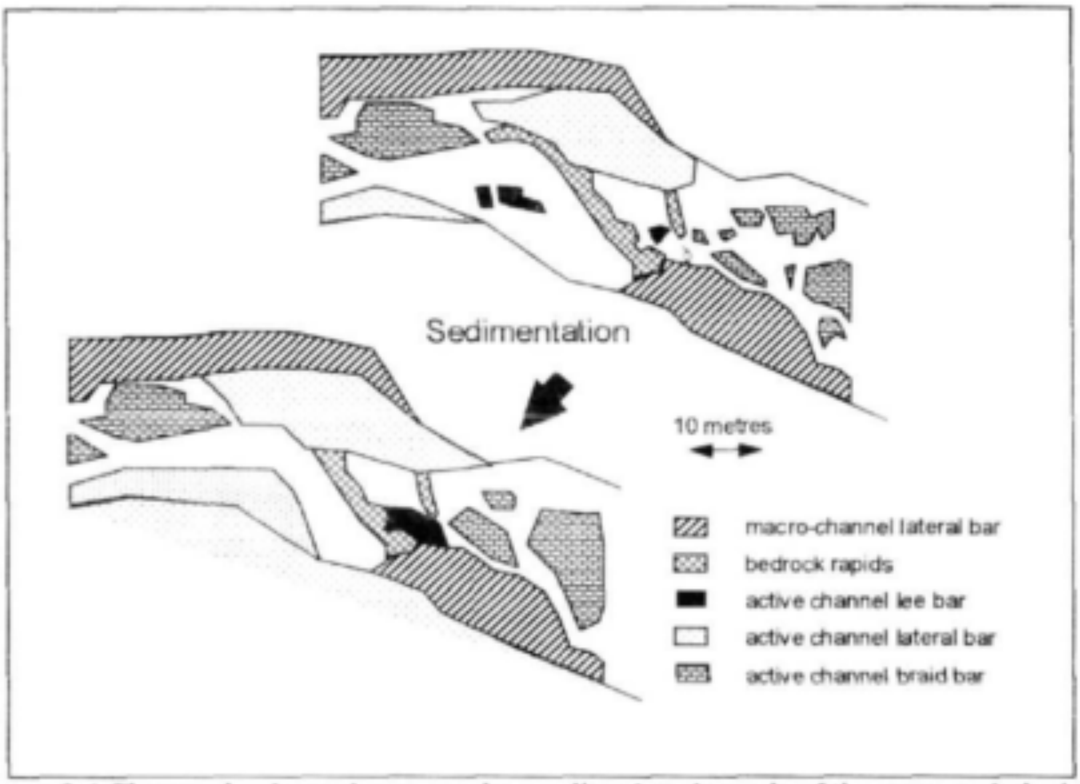


Figure 3.6 Changes in channel type can be predicted at the scale of the geomorphological unit

3.4 PRESENTATION OF MODEL RESULTS

A simulation was carried out in order to test the predictive strength of the geomorphological model. However, it must be noted that observed data which is required for rigorous testing of the model is not available. Model output follows the trends observed by geomorphologists in the field. However, it is accepted that this form of confirmation of the model results may be highly subjective. In the absence of the geomorphological data required for confirmation of model results, the fish assemblage related to the average geomorphological composition of a pool-rapid in the Lowveld was simulated and this was compared with an observed fish assemblage. This exercise is explained in Section 4.5.2. and illustrated Figure 4.9.

3.5 MODEL LIMITATIONS

At present the model suffers from several limitations as listed below:

- Inaccurate matrix rules due to the poor quality of expert knowledge.
- Uncalibrated sediment input predictions.
- Untested morphological change hierarchies.

- Inadequate system of predicting the degree of local erosion and deposition at the channel type scale.
- Model testing does not cover the full range of channel types recorded on the Sabie River in the Lowveld.

3.6 CONCLUSIONS AND SUGGESTED FURTHER DEVELOPMENTS

From the model tests it would appear that there is considerable evidence to support the hypothesis that the fluvial geomorphological template strongly influences the long term fish assemblage as explained further in following chapter.

The geomorphological model could be improved in the following ways:

- Continued testing and refinement of the operating matrices based on simulations of each of the 40 channel type segments on the Sabie River.
- Improved correlation between the morphologic unit and fish habitat composition through field data collection.
- An investigation of the dynamics of sediment erosion and deposition at each of the 40 channel type sections on the Sabie River utilising data already available.

4 THE KNPRRP LOWVELD FISH MODEL

D.C. Weeks, G.P.W. Jewitt, G.L. Heritage, A.W. van Niekerk, J. O'Keeffe and M. Horn

4.1 BACKGROUND AND OVERVIEW.

The fish model is another version of a QRBM which uses "rules" to predict the relative abundance of specific fish groups characteristic of shallow Lowveld sections of the Sabie-Sand river system to both varying flow conditions in the catchment, and potential changes in the channel type of the representative reach at which it operates. The model operates at a 6-monthly time step, thereby accounting for different responses of fish in "wet" and "dry" seasons. Input to the model is a file describing the hydrological status of each season in which the fish response is to be estimated and the habitat available within the channel at the simulation site.

Thirty-nine indigenous species of freshwater fish are resident in the Lowveld reaches of the Sabie-Sand system. Using standard electro-fishing techniques and data spanning three and a half years, twelve species were found to typically make up more than 81% of the catch in shallow water habitats and these have been used to define a Lowveld baseline assemblage for the system. These abundant species have been further grouped using shared taxonomic and life-history traits to further simplify model development and interpretation. It is the changing patterns of abundance established for the species groups, both for normal and for extreme seasonal conditions, that form the basis of this predictive model. The development of methods allowing information relating to change in fish habitat due to geomorphic change is presented.

Model output is presented in a graphical form consisting of an hypertext trace of the rules invoked at each time step, and an output file of the abundance of each fish group for 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 in the case of the fish relative abundance states.

4.2 SPATIAL AND TEMPORAL SCALES SELECTED

The fish model operates at a twie-annuall time step, producing predictions of fish response in May and in November. These periods are selected to provide an estimate of changing fish abundances for the preceding six month period representative of wet (summer) and dry (winter) seasons respectively. In the early stages of development, attempts were made to use an annual time step, 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 in the available data. Conveniently, quarterly data could be lumped into two six month periods that corresponded well with the identified hydrological seasons. This enables the simulation of fish responses to the preceding wet or summer season and the preceding dry or winter season to be modeled. Geomorphic input is provided annually, utilising the concept of asynchronous time-steps explained in Chapter 2.6.

May 15 and November 15 have been selected as output dates corresponding to the end of each hydrological season. A number of reasons are presented:

- Analysis of the long-term hydrological record of the Sabie-Sand system shows that the dry season effectively runs from May to November, with the lowest flows most commonly occurring in September and October.
- By the end of November, flows have usually increased as the summer rainfall begins. By May, the river has once again reached a "baseflow" level, with the highest flows most commonly occurring in January and February. Occasional periods of high flow may continue through March and April.
- From an ecological perspective, May is important as the river has receded and is fishable, while the data collected reflect the nature of the preceding wet season and the fishes responses to it.
- November is a month in which fish data were regularly collected. These data reflect the response of the fish to the preceding dry season while the river remains at fishable levels.

While fish data is sampled from the pool/rapid reach type, the fish model has no finite spatial component. 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. In this model, the assumption has been made that geomorphic composition of the reach and thus, available habitat, is a major controlling factor of abundant fish populations.

4.3 ECOLOGICAL INPUT TO THE MODEL.

Fish species responses are modeled individually, with the exception of cichlids and minnows, which are grouped. The model produces a value indicative of the abundance of fish making up each of the species/groups.

4.3.1 Fish species and groups of the Lowveld

Of the 45 indigenous species of freshwater fish resident in the Sabie-Sand system, 39 are recorded in the Lowveld reaches. Using standard electro-fishing techniques and data spanning three and a half years, the most abundant or ecologically important species were identified. Twelve species typically make up above 81% 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 (Figure 4.1) (Weeks *et al.*, 1996). It is the changing patterns of seasonal abundance established for these species both for normal (Figure 4.1a-d) and extreme (i.e. drought) seasonal conditions, that form the basis of the ecological input to this predictive model.

To simplify inputs into the model, the shall-water species are, where possible, grouped according to shared life-styles (Table 4.1).

A cluster analysis, using PRIMER (a statistical tool) of six life-history traits identified three lifestyle groups at 90% similarity (Figure 4.2) namely cichlids, minnnows and large cyprinids. Minnows and cichlids were grouped, while mudfish and yellowfish were treated individually because sufficient data was available to do so. In future refinement of the model, it will be attempted to treat each species individually. Species/groups as used in this prototype model are:

1. Cichlids- *Oreochromis mossambicus, Pseudocrenilabrus philander, Tilapia rendalli*
2. Minnows - *Barbus annectens, Barbus trimaculatus, Barbus radiatus, Barbus unitaeniatus, Barbus viviparus*
3. Yellowfish - *Barbus marequensis*
4. Mudfish - *Labeo molybdinus*
5. Rock Catlets - *Chiloglanis anoterus*
6. Robbers - *Micralestes acutidens*

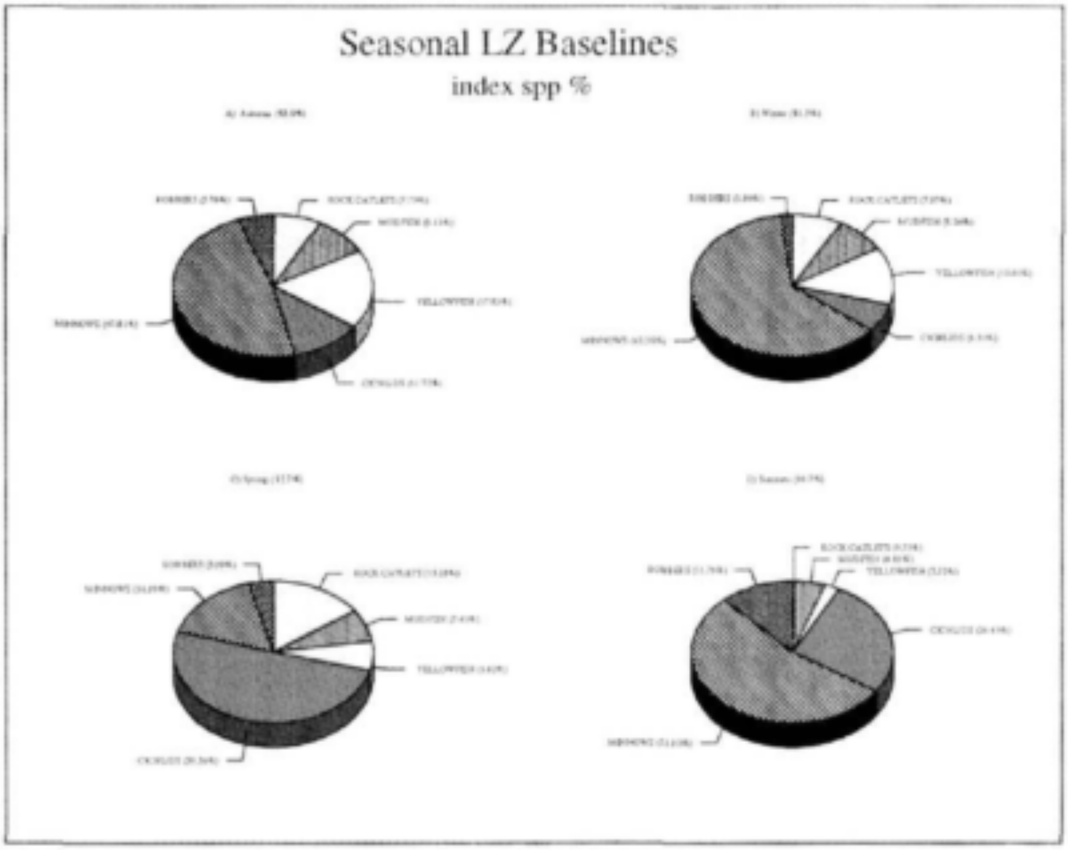


Figure 4.1 Seasonal and baseline pie diagrams for small fish electrofished in the Lowveld of the Sabie & Sand rivers excluding drought (1990-91). Pies are percent averages for species standardised (STD unit = fish/min). Pie (a) is the year average while pies (b)-(e) are seasonal averages.

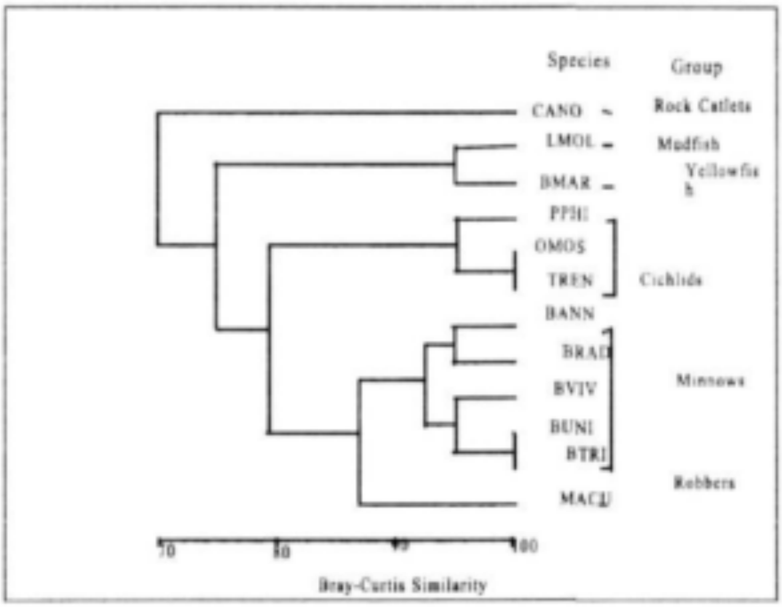


Figure 4.2 Cluster analysis of abundant Lowveld fish species using 6 life-style attributes showing the reasoning for treating cichlids and minnows as groups.

1. **Cichlids**

Cichlids are secondarily freshwater fishes considered to be evolutionarily advanced. The three cichlids important in shallow Lowveld reaches in the Sabie River all fall within the tilapiine group of the family Cichlidae. Tilapiines feed mainly on sediments or plant matter and are typical of placid or lentic habitats. They 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. Although both *Tilapia rendalli* and *Oreochromis mossambicus* flourish in drought conditions, only the latter is able to survive extreme drought condition by breeding at a stunted size. *Pseudocrenilabrus philander* specialises in extremely shallow habitats and is generally less affected by flow extremes.

2. **Minnows**

Minnows, like all cyprinids, are primarily freshwater species. These small species are common, often being observed in shoals in sluggish to moderate flow velocities. They are opportunistic feeders feeding on smaller creatures and detritus. Five species commonly make up the largest component of the Lowveld shallow water assemblage, particularly following the rains on which they depend to breed. Breeding takes place in pairs but parental care is absent and small adhesive eggs are simply scattered over suitable substrates. *Barbus* *viviparus* is often the most numerous fish sampled in the Lowveld, where it enjoys particularly shallow habits across a range of intermediate flows. Adults of both *Barbus annectens* and *Barbus radiatus* are more commonly found in deeper placid pools, while the ubiquitous *Barbus trimaculatus* is one of the first species to breed following drought conditions, often with the first freshet.

3. **Yellowfish**

Like minnows, yellowfish are barbine cyprinids but they grow to much larger sizes. Adults of the large-scaled yellowfish *Barbus marequensis* are common in deeper Lowveld river runs while juveniles, like the mudfish, favour the shallow habitat of rapids for cover.

4. **Mudfish**

Like yellowfish, mudfish or Labeos are cyprinids, and often growing to a large size. They have specialized diets, feeding mainly on "aufwuchs", algae and detritus which they gather from the substrate using well developed inferior mouths. Most Labeos are good swimmers and are frequently adapted to strongly flowing water. Mass migrations often precede seasonal breeding and large numbers of eggs are released. Adult *Labeo molybdinus* are found utilising cover in both strongly flowing and more placid waters of deeper habitats such as deep pools, while juveniles prefer shallow habitats and faster flows afforded by riffles.

5. **Rock Catlet**

The Chiloglanids belong to the largest African family of catfishes, the Mochokidae. Members of the genus Chiloglanis are all small localized species adapted to life in fast currants feeding on macro-invertebrate larvae and algae grazed from the loose substrates secured by their strongly adhesive sucker-mouths. *Chiloglanis anoterus* is the most common species in the cooler upper reaches of the Sabie River but it does occur in the Lowveld in suitable riffles. Breeding takes place in summer with only a few large eggs produced. Parental care probably occurs. *C. anoterus* is unable to survive in oxygen-poor waters and therefore drought or no-flow conditions in the Lowveld. Coupled with its limited breeding potential and sedentary nature, this species must be considered a sensitive species in the Lowveld assemblage.

6. **Robbers**

Robbers better known as Characins are primary freshwater fishes found in mainly tropical waters of both Africa and the Americas. They are characterised by well developed teeth and an adipose fin. The Silver Robber (*Micralestes acutidens*) is a small, large-eyed and highly mobile omnivore that takes a wide range of small prey items while moving in shoals. Like minnows, robbers are seasonal spawners, simply scattering their eggs in suitable substrates.

4.3.2 Defining Fish States of Abundance

The fish model utilises a measure of abundance derived from an adjusted measure of Catch Per Unit Effort (CPUE) partitioned into states as its basis. CPUE represents the amount of effort required when fishing, using generally accepted fishing techniques. Units are usually fish per minute.

Because CPUE is affected not only by actual changes in population number, but by the effects of concentration and dilution due to varying flow volumes, an adjustment that would effectively produce a more comparable abundance measure within and between sites was sort. The CPUE values obtained by Weeks *et al.*, (1996) were adjusted by using a correction factor dependent upon actual wetted perimeter as derived from a rated transect of the river channel for each fishing site at the time of data collection.

There are any number of hydraulic parameters which could be used for this adjustment and the use of several of these were discussed. It was decided to use wetted perimeter as the results more or less fitted those expected by the ecologist (which is entirely consistent with the philosophy of rule-based modelling). It may be possible to come up with one that more closely fits the way that the fish data were collected. This topic will be further explored with refinement of the model.

The abundance of each fish group/species is modelled according to a "state-based" approach. According to this method, the entity to be simulated is divided into a number of discrete states, each state indicative of a particular phase of that entities' abundance (Using CPUE as a measure of abundance).

Seven discrete states were defined for each group as follows;

1. Absent (0)

2. Remnant (0-0.005)
3. Rare (0.006-0.025)
4. Visible (0.026-1)
5. Numerous (1.1-2.5)
6. Abundant (2.6-6)
7. Saturation (>6)

These states represent a semilog scale representative of the exponential growth and decay of the fish groups in response to varying flow and changing geomorphic conditions.

4.4 HYDROLOGICAL INPUT TO THE MODEL

Initial hydrological input is a time series of daily flow values. A pre-processing program is used to analyse the daily hydrological record in order to calculate indexes of events to which fish will respond per time step, i.e. categorise the preceding season's flow into the classes which form the input to the model.

Important indices, which require daily flow records to be calculated, are numbers of freshets and zero flows. For the purposes of this model, a freshet is 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 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 1:10-year 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 1:20-year daily high flow 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". Analysis of the daily flow records show that values are not normally distributed, but skewed towards the dry end of the spectrum. Thus, the use of a 1-in-10-year flow to determine whether to classify a season as "dry" whilst a 1-in-20-year flow is used to determine if a season is wet.

When operating the model, the user selects an observed (gauged) flow record that is to act as a baseline for any analyses of flow. Flow statistics for this supposedly representative sequence are calculated and reflect the long-term average conditions for the area under consideration. The user then stipulates the flow sequence for which a fish response is to be simulated. Choosing the same flow sequence as that selected for the baseline sequence, effectively forces the model to simulate the fish response to the existing observed flow sequence (i.e. current day conditions). Other flow sequences selected are likely to be simulated time series reflecting different catchment development scenarios. The statistics from the simulated time-series are then compared to those of the baseline sequence and the deviation from the observed record determined. Thus, a new input time-series is created for each model run.

4.5 GEOMORPHIC INPUT TO THE MODEL .

As explained in Section 1.4, Thoms *et al.* (1990) recognised that fluvial geomorphology is the logical integrating discipline to link river response to ecological functioning, as it is the geomorphology that forms the physical template for habitat development. Utilisation of the geomorphological template to predict fish habitat operates at three scales (Figures 3.1 and 4.3). Initially the channel type is recognised (i.e. pool-rapid); secondly geomorphological units are identified and thirdly these units are in turn characterised by a sub-set of cover and substrate categories (Table 4.1). It is at this lowest level that fish preferences are related to the geomorphology.

Figure 4.3 shows a hierarchy of "building blocks" used by the geomorphology and ecology disciplines. The figure also shows that substrate is identified as a "building block" common to both geomorphological unit and biotope and thus forms part of a "common language" for biotic and abiotic scientists in the KNPRRP.

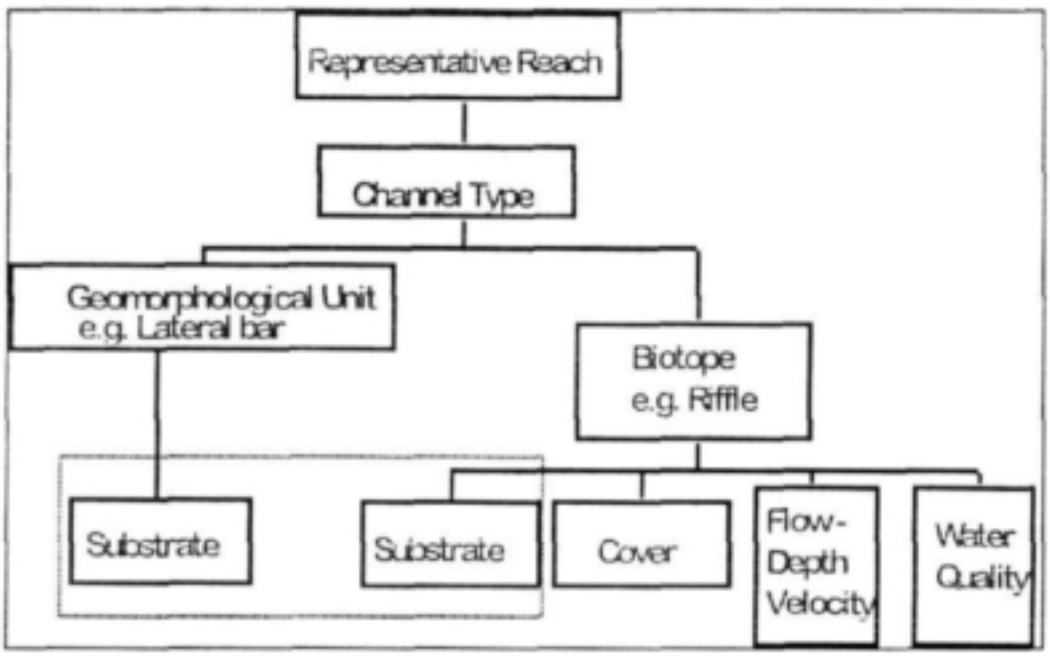


Figure 4.3 Hierarchy of units for fish and geomorphology links

Species	Lngt.[1]	Egg[2] Size/ No.	Par.[3] Care	Nat.[4]	Behv.[5]	Flow[6] Needs
Labeo molybdinus	3	1	1	2	2	4*
Barbus marequensis	3	1	1	2	3	4*
Barbus viviparus	1	2	1	3	2	2
Barbus annectens	1	2	1	3	2	1
Barbus radiatus	2	2	1	3	2	1
Barbus unitaeniatus	2	2	1	3	2	2
Barbus trimaculatus	2	2	1	3	2	2
Chiloglanis anoterus	1	3	2	1	1	4
Oreochromis mossambicus	3	3	2	2	2	1
Pseudocrenilabrus philander	2	3	2	2	2	1
Tilapia rendalli	3	3	2	2	2	1
Micralestes acutidens	1	2	1	3	3	3

Life history attributes ranked as;

1) Length: 1 = #10 cm, 2 = >10#15 cm, 3 = >15 cm.

2) Egg size/number: 1 = large/few, 2 = intermediate, 3 = small/numerous.

3) Parental Care: 1 = no, 2 = yes

4) Nature: 1 = solitary, 2 = sociable (pair or family groups), 3 = schooling.

5) Behaviour: 1 = cryptic, 2 = locally active, 3 = highly mobile.

6) Lifestyle flow requirements: 1 = backwaters/pools, 2 = marginal to flow, 3 = runs, 4 = shoots/rapids.

- Juvenile requirements.

The flow of water is fundamental to the work being done and is implicit in any of the research regarding analysis of channel types and changes to them over time. It is the movement of water which carries sediment, and determines where plants grow and fish exist. However, errors in prediction and measurement of flow components are amplified with decreasing spatial scale. Thus it has been necessary to deal implicitly with indicators of flow, rather than actual values of flow depth and velocity in the channel.

Furthermore, in this project, early attempts 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 is usually collected and analysed at a spatial scale of $1 m^2$, both a practical and a meaningful scale to the fish ecologist. At this scale, the processes that determine fish habitat are identifiable and, practically, 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. 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 the fishes' preferences to specific water depths and current velocities and preferred substrate at this 1 m^2 scale are typically produced as part of ecological studies (Weeks *et al.* 1996), an example of which is shown in Figure 4.4. For the purposes of this model, which deals with primarily shallow water species, it was felt that simulation, and indeed conversion of observed geomorphological data to show water depth and current velocity at the scale of 1m^2 and even the channel type was not justified and could not be done accurately. Thus, the assumption made that the substrate is an indicator of the flow characteristics of the preceding season, was used (ASCE, 1992). The substrate that is found at particular points in the river bed, is found there because of the flow defined by the physical characteristics at that location. The finest substrate category used (silt & organics 0-0.2 mm) proving particularly sensitive to recent/local flow conditions.

The cover type also addresses the issue of including hydraulic flow components in the model. Cover, as defined in this project (Section 4.5.1), has both a visual and a physical component. It is dependent on various bank and channel features as well as vegetation and substrate, with physical or velocity cover defined *in relation to flow,* e.g. substrate/cover coding for a cobble bed in backwaters would score differently from that found instream. This is an assumption supported by the ASCE Task team on Sediment Transport and Aquatic Habitat(1992) 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". Furthermore, the substrate size reflects a synthesis of ecologically meaningful hydraulic conditions (Resh, 1979 cited by ASCE, 1992).

Using data compiled by an experienced fluvial ecologist, the "common language" of the substrate is developed further, by reducing each geomorphological unit into habitat sub-categories, each of which is assigned a specific substrate and cover code combination. Thus, sediment size and cover whether visual and/or velocity cover are classified. 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. Only underwater 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. 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 the geomorphological map of the study reach into a habitat availability map (Figure 4.5) and to calculate the percentage availability of each habitat category present. Finally, accepting the assumptions inherent within the model at present, this can be related to the habitat preference curves generated for each of the species present in the river to estimate the likely long-term fish assemblage. By quantifying and analysing the associations of substrate with the geomorphic units making up the channel type, a prediction of change in the channel type means that the change in substrate/cover can be estimated.

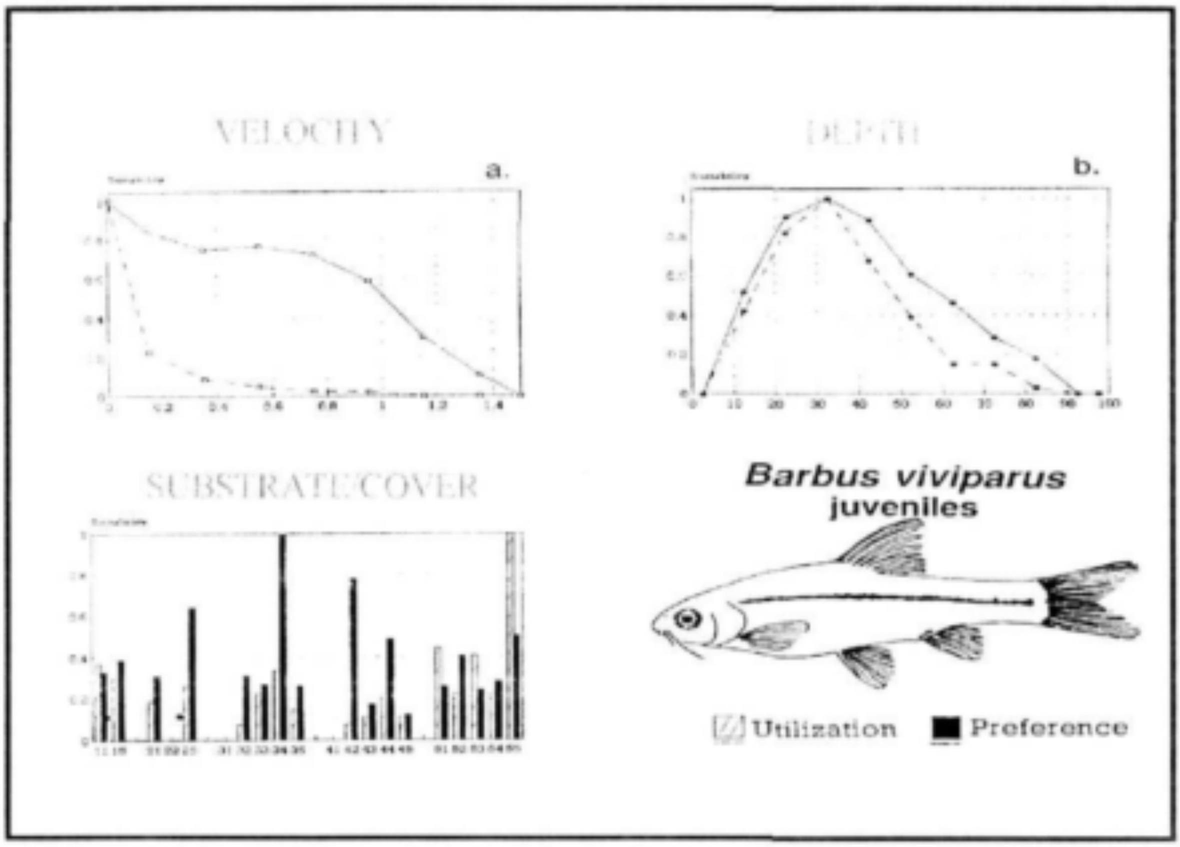


Figure 4.4 Micro-habitat preference for Barbus viviparus from Weeks et al., 1996.

The use of substrate as a common building block has several inherent advantages. Substrate is identified as the least temporally variable of the micro-habitat variables used for SI curve development. It is also the most easily measured of these components and thus, its association with geomorphological units is most easily and accurately quantified. Furthermore, by using substrate 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 substrate 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 substrates) using information which was derived from, for e.g. a pool-rapid channel type.

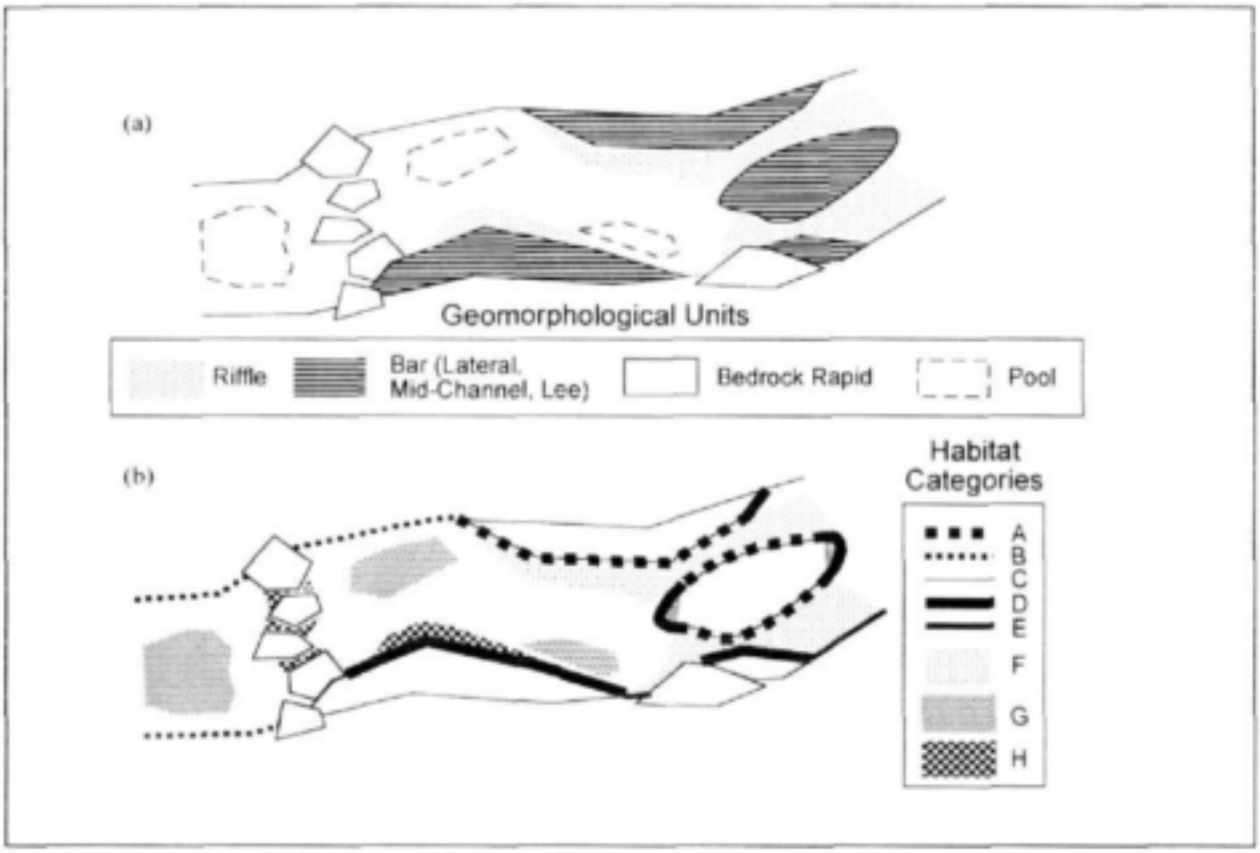


Figure 4.5 Geomorphological associations (a) translated into related fish habitat (b).

A range of cover codes categories are assigned to each unique geomorphic unit. By analysing several of each type of geomorphic unit, a trend could be identified which reflects a typical composition of each geomorphic unit in term of the cover categories assigned to it. An example, for a typical pool-rapid reach is shown in Table 4.1 below. Here the geomorphological unit "active channel braid bar" is defined by only two habitat categories making up 98 and 2 percent by area respectively.

This classification process can be performed for all units making up a particular channel type, and a typical composition for each channel determined in terms of these cover codes i.e. each channel type will have a unique set of cover code classifications. As argued, these cover codes implicitly represent flow conditions in the channel under consideration.

Table 4.2. Geomorphological units and substrate-cover habitat characteristic of pool-rapid channel types in the Sabie River.

Morphological unit	Habitat category	Percentage of habitat
Active channel braid bar	no cover, sand	98
	offstream overhead, sand	2
Active channel mixed pool	no cover, sand	24.5
	no cover, boulder	1
	vegetation in water, sand	45
	no cover, sand	14.5
	no cover, gravel	3
	no cover, bedrock	0.5
	velocity shelter, gravel	0.2
	velocity shelter, cobble	0.2
	velocity shelter boulder	0.5
	vegetation in water, sand	0.5
	no cover, sand	5.5
	offstream overhead, sand	0.3
	vegetation in water, sand	3
	vegetation in water, boulder	1
Active channel bedrock rapid	All cover, bedrock	76.5
	All cover, boulders	8.5
	no cover, bedrock	6
	velocity shelter, cobble	0.1
	velocity shelter, boulder	0.5
	vegetation in water, bedrock	3
	All cover, gravel	0.1
	All cover, cobble	0.1
	All cover, boulder	0.2
	no cover, sand	2
	no cover, bedrock	1.5
	velocity shelter, sand	0.05
	velocity shelter, bedrock	0.05
	vegetation in water, cobbles	0.125
	vegetation in water, boulders	0.125
Macro-channel lateral bar	no cover, sand	5
	offstream overhead, sand	20
	velocity shelter, sand	2
	vegetation in water, sand	63
	all cover, sand	10
Macro-channel bank	offstream overhead, sand	75
	vegetation in water, sand	20
	all cover, sand	5
Active channel lateral bar	no cover, sand	25
	offstream overhead, sand	15
	vegetation in water, sand	60
Active channel lee bar	no cover, sand	95
	offstream overhead, sand	5

4.5.1 Coding for Substrate and Cover

Hydraulic input to the model is provided implicitly in two ways by using the adapted substrate-cover codes as integrators of ecologically meaningful flow (Table 4.3). Firstly, it is the flowing water which moves and sorts the sediment creating the habitat template which in turn determines where plants grow and fish exist within their microhabitats. Hydrological input (e.g. freshets), is obtained from the hydrological component of the model. Secondly, the codes assigned to the different habitat areas in this project are based on, but differ from, the model used by the IFIM (Bovee, 1982) interpretation. Besides recording substrate size and visual cover, we coded hydraulic cover as measured, opposed to potential hydraulic cover. For example, cobble in standing water is classed as providing no hydraulic cover, in contrast to Bovee who scores the potential of cobble to provide hydraulic cover.

Table 4.3: Channel Index Codes as used for substrate and cover.

TENS	TYPE	REFUGE VALUE
10	No cover	None
20	Offstream overhead	Visual cover (indirect)
30	Instream object	Velocity shelter
40	Instream overhead	Visual cover (direct)
50	Combination	Velocity & visual cover
UNITS	DOMINANT PARTICLE BY PERCENTAGE AREA OR SIZE WHERE AREAS ARE EQUAL	MODIFIED WENTWORTH SCALE (mm)
0	Fines (silt + organic)	0- 0.2
1	Sand	0.2-2
2	Gravel	2-75
3	Cobble	75-300
4	Boulder	>300
5	Bedrock	Slabs

Members of the KNPRRP Biotic-Abiotic Links project workshop group expressed several concerns regarding this process. The first of these was that the interpretation and assignment of these codes is highly subjective. However, it was agreed that all such processes would be subjective.

Secondly there was a problem of coding ambiguity when the substrate itself did not provide hydraulic cover, i.e. in the cases of sand and bedrock in flowing water. For example, "no cover" or "overhead cover over sand" could be in a backwater, or in flowing water (King 1996). This was particularly problematic as sand and bedrock make up a large proportion of the Lowveld rivers substrate. After further field investigations, the category 0 to reflect fines (silt and organic particles) was instated in the original cover codes to reflect the hydraulic conditions. This is because it was noted in the field, that pure sand does not exist where flow is absent within the Lowveld rivers, it is invariably "fines" which are found in these conditions where energy is low and suspended matter deposited. Cover codes representing this idea are found in Table 4.3.

What remained was to link geomorphology and fish habitat to the model as a whole.

4.5.2. A Habitat Suitability Index for the Sabie River (FIN).

From the onset of the project in October 1995, the geomorphology-fish link envisaged was that of a species-specific value of habitat worth, i.e.a factor of microhabitat suitability that would both evaluate the quality of the available habitat, as output by the geomorphological component of the model, and adjust the target species performance. For this purpose, a habitat suitability index termed FIN (Fish Index of Niceness - van Niekerk, 1996) was developed to show the suitability of a particular channel type for each fish group. FIN is a unitless index of river reach suitability, evaluating the habitats potential to support defined states of fish abundance as measured in a Catch Index (CI) (section 4.3). FIN simply shows an increase/decrease in fish habitat suitability, not an absolute number reflecting this. Fish abundance states are determined using field data alone, with FIN being merely one factor which has the potential to affect change in fish numbers.

Suitability Indices (SI) indices have been established for all abundant species in the Sabie-Sand Lowveld (Figure 4.4), (Weeks, *et al.*, 1996). Only substrate/cover data (Figure 4.4c) is used to calculate the habitat suitability index or FIN for the reach, for each fish species/group. FIN is simply calculated by adding the product of a species preference for each unique substrate/cover code (SI value), and the area of each unique code found in the reach. Appendix IV sets out a sample FIN calculation.

Should the same exercise be performed at a later date following some change in the geomorphic composition of the channel, another FIN value for each fish species will be produced. The change in FIN as recalculated each time the geomorphological make up of the channel type under consideration is altered is passed onto the fish model, at the temporal scale of the year. This single value indicates whether the initial fish habitat has increased, decreased or remained constant.

Input from ecologist colleagues raised a number of concerns in this regard (King *et al.*, 1996; King., 1996; Schael, 1996). The most serious objection related to the multiplication of a habitat area by a preference or suitability index. They maintain that, based on problems experienced in the IFIM procedures, this is not a valid exercise as it is unclear what is produced, and what units of measurement it would have. This issue is, as yet, not fully resolved, however, it is suggested that the use of FIN as a unitless index, is justified. Logical trends in FIN between reach types, as well as Fin's ability to predict the relative frequencies of a reach type that mirrors the assemblage actually fished, lends further support to the concept.

FIN trends

To reveal trends in FIN for each species/group *between* reach types, FIN values were normalised using pool/rapid reaches. This was done because the fish data was collected from this reach type. This enables comparison with the sampled data set, both in space (between reach types) and time (using space-time substitution), where one reach type is argued to evolve from another (Figure 4.6). Trends seen in FIN between species/groups and reach types, suggest that our single value index is behaving logically both in the direction and magnitude of change. For example, FIN normalised on the pool/rapid reach has a value of 1 for each species (Figure 4.6). FIN for *Chiloglanis anoterus* shows a drastic decline in value in both sandier reaches or with increased sedimentation within a reach type. Other species/groups characteristically show less dramatic effects on FIN, but specific trends are evident and intuitively correct. This supports our understanding of *Chiloglanis anoterus* as the most sensitive of species.

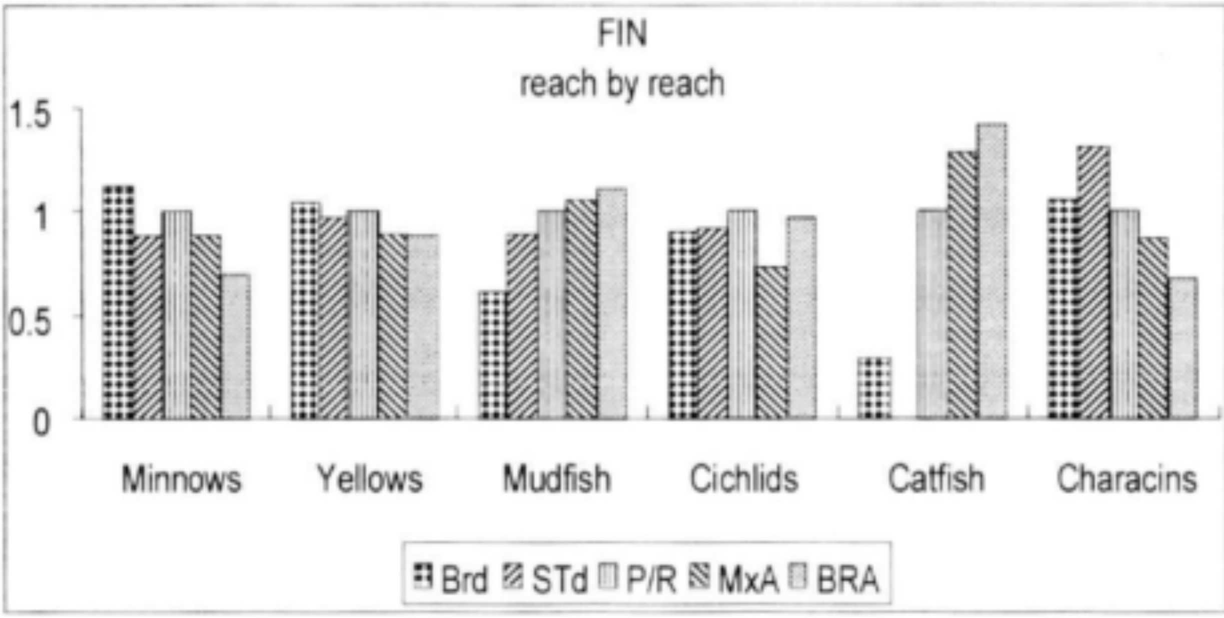


Figure 4.6 FIN values for species/groups normalised on the Pool/Rapid reach. Reaches are arranged in order of decreasing sedimentation. Brd = braided, STd = single thread, P/R = Pool/Rapid, MxA = mixed anastomosing & BRA = bedrock anastomosing.

Testing of FIN

Further more, we tested FIN's performance in pool-rapid reaches using individual species FIN values to predict the relative frequency of occurrence of the Lowveld species assemblage (Figure 4.7b) vs. the actual Lowveld baseline assemblage fished (Figure 4.7a). The frequencies of the virtual assemblage are remarkably similar to those sampled, lending support to the use of FIN. This holds true even between species that have been grouped. The frequencies of each of the three cichlid species grouped are calculated in the order of frequency actually observed, with O. mossambicus the most numerous and P. philander least common.

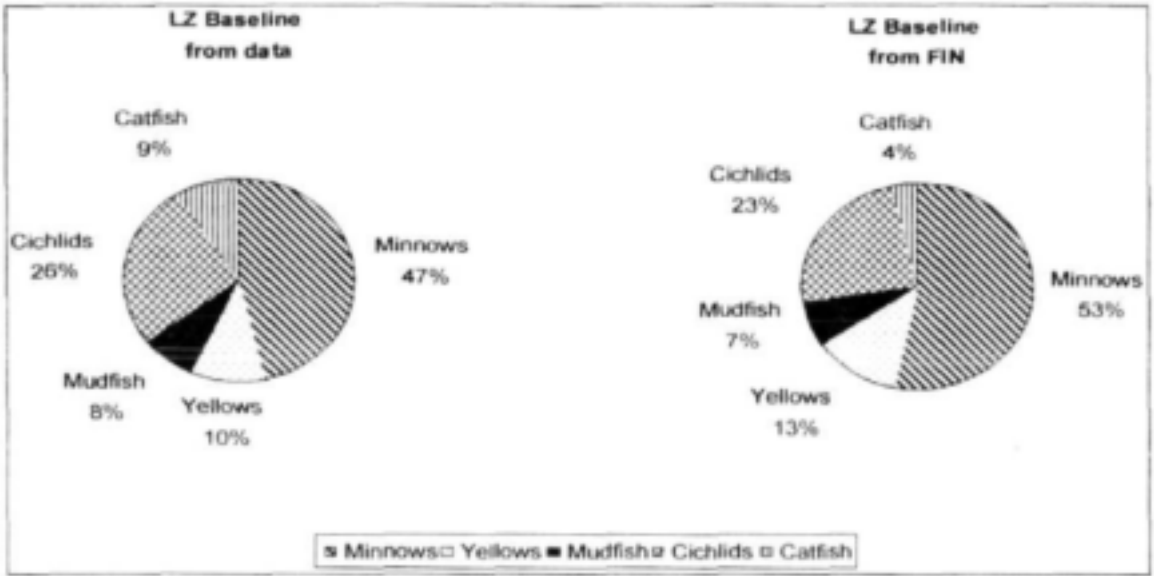


Figure 4.7 Frequency of occurrence of Lowveld zone baseline fish assemblage derived from (a) species/group FIN values and (b) field data.

Why FIN may work in this project

We agree with Mathur et al., (1985 cited by Tharme, 1996) that WUA cannot be correlated with abundance/biomass, as two sampling occasions with different biomasses could predict similar species habitat suitability. It is accepted that the implied relationship between WUA and abundance/biomass is "the most serious misconception in the IFIM procedure" (Gore & Nestler, 1988).

Unlike the IFIM procedure, the use of FIN in this project does not derive the units of the output results. FIN is merely a reach "index of suitability" which operates by modifying pre-defined abundance states. FIN as seen in the test pie diagram (Figure 4.7a) does not set an abundance for each species/group, but rather the relative frequencies of occurrence predicted for the hypothetical Lowveld assemblage. Abundance states reflect both recent historical conditions (preceding years) and the previous seasons hydrological condition.

The striking similarities between calculated and observed Lowveld assemblage pies may be successful precisely because the model simulates abundant species and invokes FIN at low-flow, both of which can be argues to be ecologically meaningful considerations. Our focus on the abundant species, those making up more than 6% of any catch regionally, selects biologically robust species, that are free of life cycle "bottlenecks". The poor biotic-habitat link seen in many IFIM studies, may be the result of using target species with populations otherwise limited (such as exploited game fish species, Orth (1987)). Similarly, the biotic-

biotic link is calculated during low-flow, combining habitat availability and suitability precisely when microhabitat can be argued as being most limiting (Orth, 1987).

4.6 RULES DEVELOPMENT AND CODING

The rules developed to explain fish response to seasonal hydrological variation were based on the matrix shown in Table 4.4. The ecologist, using a combination of expert knowledge of the river system and the fish responses therein and collected data made estimates of the response of each fish group to various hydrological scenarios. The rules were then coded according to the information shown in this matrix.

Table 4.4. Matrix of Fish Response to Seasonal Hydrology.

	WET		(Summer)	DRY		(winter)
	Dry	Normal	Wet	Dry	Normal	Wet
Minnows	-	+	++	-	-	=
Cichlids	+	=	--	+	=	=
Mudfish	=	+	++	-	-	=
Yellowfish	=	+	+	-	-	=
Rock	-	=	+	-	=	=
Robber	=	+	+	-	-	=

++ large increase -- large decrease = unchanged

+ small increase - small decrease

The rules developed are shown in Appendix V. These rules were coded into a computer using the FORTRAN programming language.

In order to provide geomorphic input to the model, the FIN values obtained for each fish group for the typical channel types of the Sabie River were normalized relative to that of the Pool-Rapid channel type in which the fish data were collected and for which the hydrological rules were developed, and an adjustment factor obtained. Predicted fish state- of-abundance can then be adjusted by this factor in order to provide a fish group prediction for each different channel type.

Thus, the response of the fish groups in different channel types is accounted for. Furthermore, if catchment conditions cause a change in the channel type of the representative reach under consideration , as predicted by the geomorphology model, the predicted fish assemblage can reflect this. This is not likely to occur in short simulations, but may occur of long model runs (100 years) with changing catchment conditions. Only extreme cases is a change in channel type noted. Further refinements to the model will include a more dynamic FIN allocation, thus making the model sensitive to annual geomorphic variation.

A full overview of the model linkages is provided in Figure 4.8.

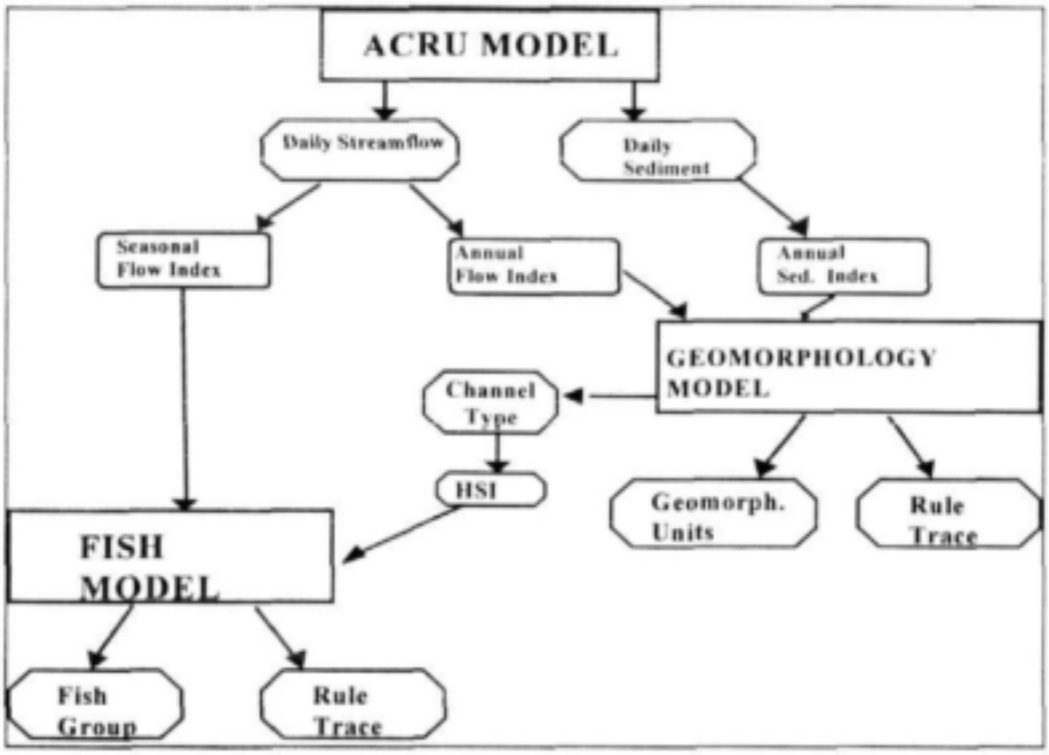


Figure 4.8 Overview of the links in the Fish Model

4.7 PRESENTATION OF THE MODEL AND RESULTS.

The model is used in an Integrated Catchment Information System (ICIS) developed within the KNPRRP by the CCWR with input from the different research projects. This ICIS provides the user with a user friendly ArcView based GUI from which the model can be run and its= output displayed as explained in Chapter 1.6.

Model output consists of an hypertext trace of the rules invoked at each time step, and file of 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 Figure 4.9 and Figure 4.10.

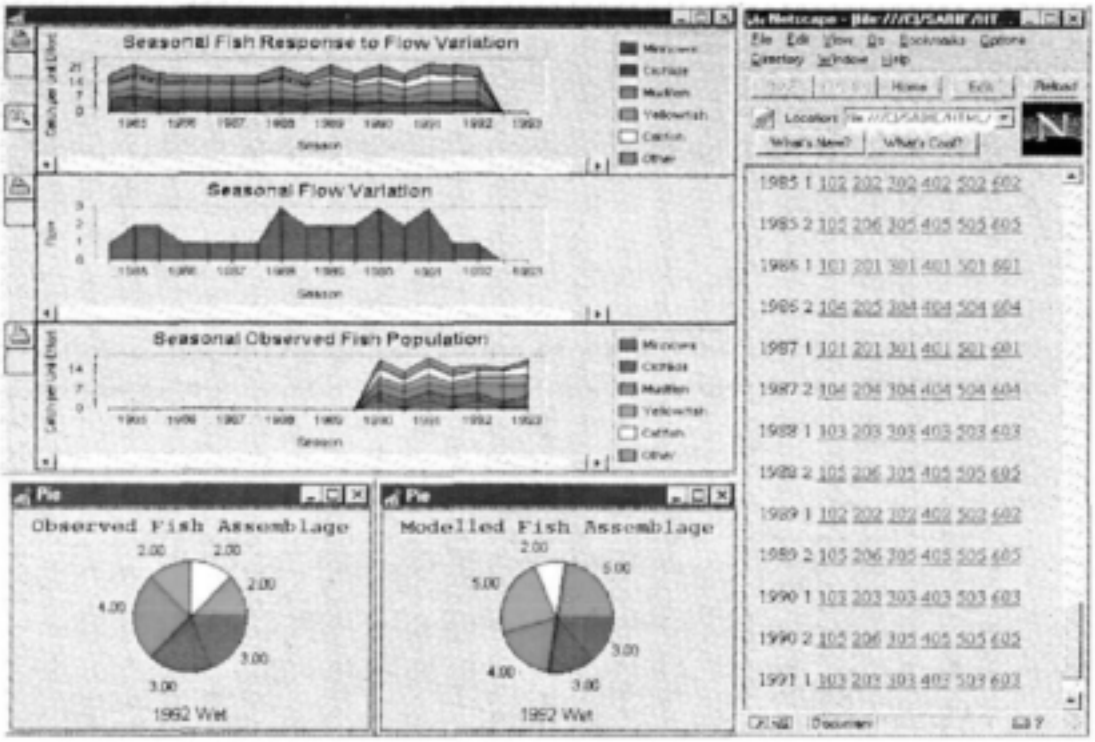


Figure 4.9 Sample output of the fish model.

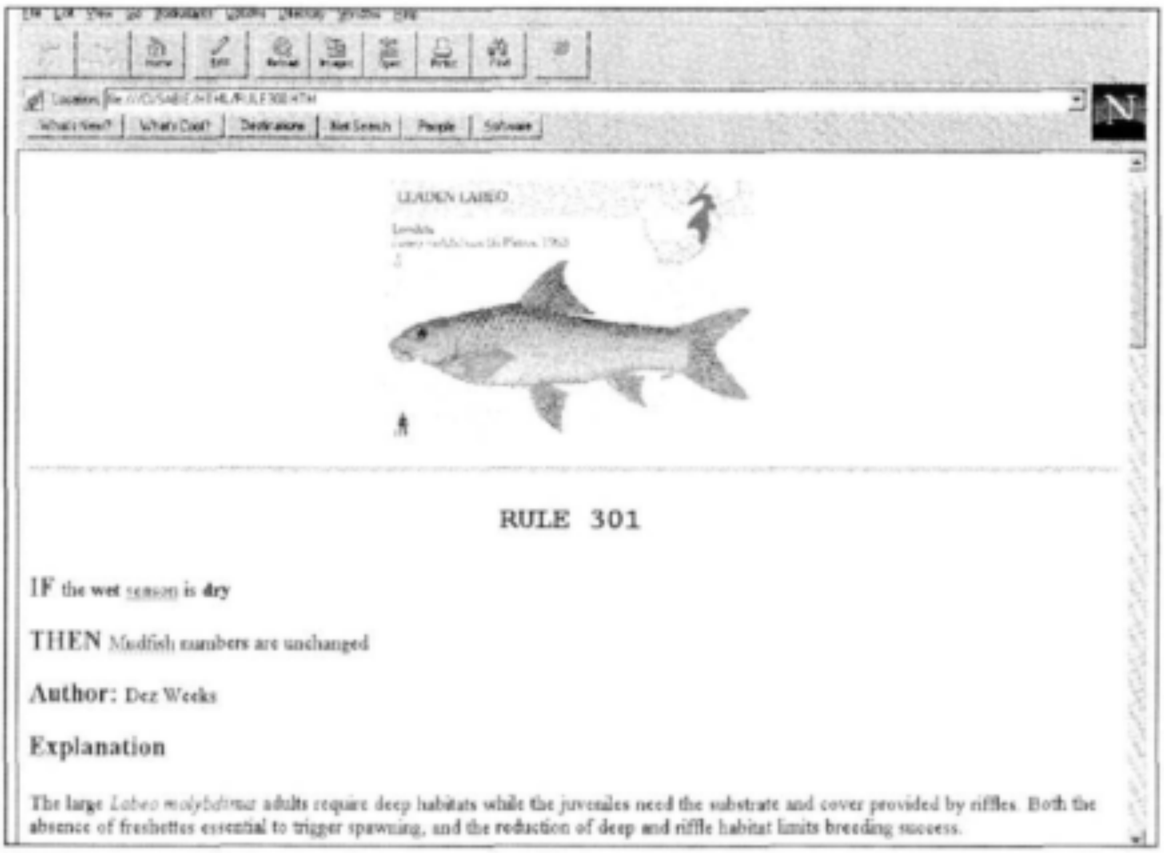


Figure 4.10 Sample of hypertext explanation of a fish rule.

4.8 MODEL VERIFICATION.

Although the expert knowledge used in the development of this model was gleaned over many years of published information, the model was created based on field data collected over a fairly limited period of time, i.e. 1990-1993. In order to use the model 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, in this case fish ecology, 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 in this way, 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, but we are able to produce a transparent system which supplies the user with information, rather than a system which merely generates numbers. This information includes explanations of the grouping of the fish, the classification of each season as hydrologically "wet", "dry", or "normal" etc.

Model output produced does show close resemblance to observed data collected for Pool-Rapid reaches (Figure 4.9). 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, 1996). In particular, it is noted that in dry cycles, cichlids (blue in Figure 4.9) tend to dominate the fish assemblage and fish numbers in general are reduced. In wetter periods, minnows (green in Figure 4.9) 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 4.11, 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 4.11) 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 alluvial sections of river such as braided/single thread reaches. Cichlids (blue, Figure 4.11) do not show much variation across channel types, which is consistent with their less specialized microhabitat requirements.

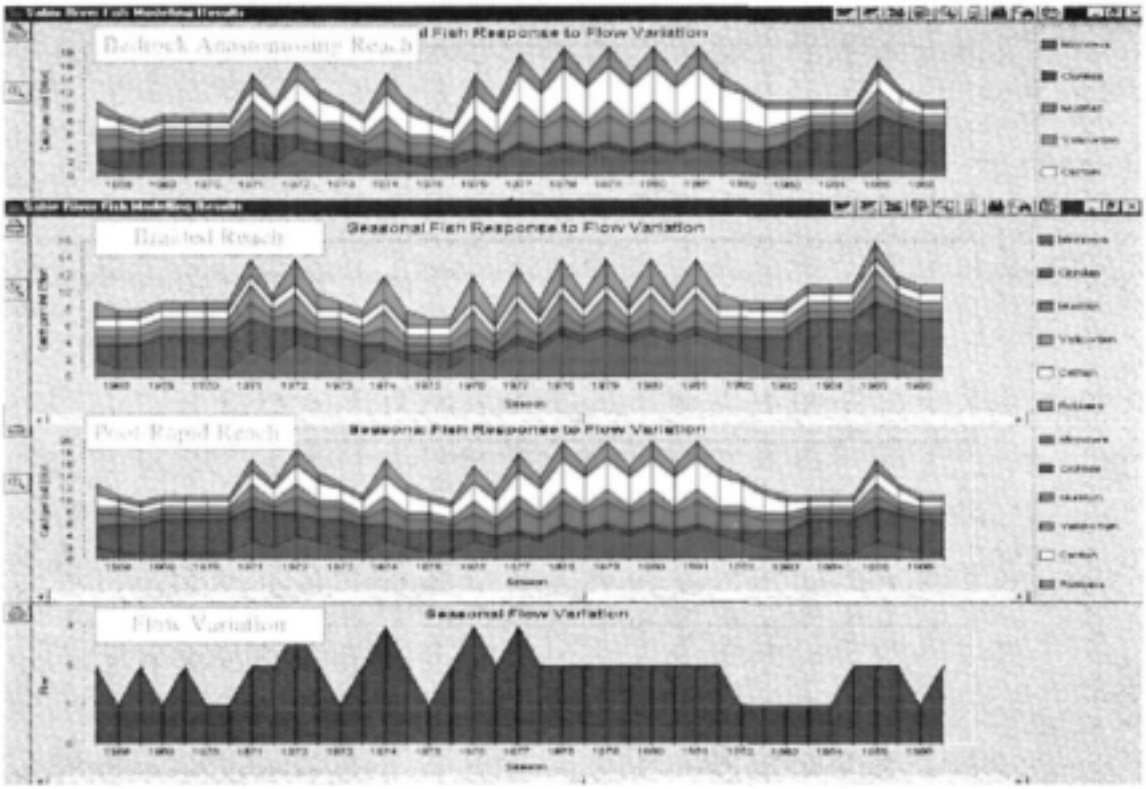


Figure 4.11 Fish model output showing effect of geomorphic template

4.9 MODEL SHORTCOMINGS AND LIMITATIONS

We recognise that the model, as are all models, is a simplification of the real world. Many simplifying assumptions have made and are explained in previous sections of this chapter. The model does seem to provide output with an acceptable degree of accuracy. However, it is important to note the following limitations of the model:

- The model is effectively one which simulates fish assemblage response to seasonal hydrological variation in shallow reaches of the Lowveld section of the Sabie-Sand system. This is a consequence of a sub-set of the available fish data being used in the development of this model. Although all available habitats were sampled during the fish survey, the model focuses on the characteristic assemblage of shallow-water species. This is due to the detailed level of microhabitat information required for this modeling exercise. These shallow-water species lend themselves to detailed microhabitat analysis due to their accessibility and catchability using electro-fishing techniques. The deeper water fishing techniques do not provide the detailed level of microhabitat information required for the development of this model, although basic survey information does exists. It is argued that even though we have focused on a spatially limited but detailed data set, the clear patterns in abundance seen maybe useful through the model as a tool for managers in the Lowveld ecosystem as a whole due to a shared species assemblage.

- The morphologic unit - fish habitat correlation figures developed are based on limited field data. Further field work is required in order to extend this data set..
- The model has 3 possible input parameters for each time step i.e. dry, normal or wet, and these may result in one of 5 possible changes in "states" for each fish group, i.e. increase, increase a lot, decrease, decrease a lot, decrease a little. Consequently, the model output is highly sensitive to the input value, and sensitivity analyses show extremely sensitive 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. This would involve changes to the rule base, and is being considered for a version II of the model. The model is written in FORTRAN. Depending on the number of rules required, a more complicated model may require the use of some form of expert system shell.
- The hydrology rules would benefit by refinement of ecologically important flows, e.g. the identification of which level of flood inundates fish breeding areas and what volume constitutes a breeding cue. This would allow an ecological definition of a freshet to be built into the model rather than the arbitrary rule now used.
- The use of implicit measures of flow velocity instead of explicit has been a constant criticism and warrants further investigation.
- FIN as presented although innovative, is still debateable and needs rigorous testing and possibly some rethinking.

4.10 CONCLUSIONS - AND FUTURE SUGGESTED DEVELOPMENTS

The prototype model accurately simulates the response of minnows and cichlids. It seems to adequately simulate catfish. Some refinement is needed in the cases of mudfish and yellowfish.

FIN and its derivation generated a lot of debate. Although we feel justified in our use of FIN in this prototype model, and are confident that FIN does serve its function as an "index", we remain open to further suggestions. It is conceded that there may be better approaches, possibly using direct local hydraulic information, although we suspect that more detailed models, such as IFIM, which have demanded explicit hydraulic inputs, have precluded exploring simpler alternatives. We do need to further explore FIN's nature and confidence limits.

With respect to further development of the model, it is felt that the route followed in terms of the geomorphic input needs to be explored fully. A great deal of mapping of geomorphological units in the field is needed in this regard.

5. THE RIPARIAN VEGETATION MODEL

J.A. Mackenzie, G.P.W. Jewitt, G.L Heritage, and K. Rogers

The objective of the riparian vegetation model is to predict a riparian vegetation response to an altered hydrological regime and associated change in geomorphological structure along the Sabie river. The scale at which a riparian vegetation response is predicted must also be a scale that is applicable to potential management actions that may be implemented for biotic manipulation. The model must communicate at resolutions that present clarity and not confusion. In river systems this is usually a coarse scale, but that is facilitated by finer scale dynamics. The model must therefore begin at coarse scales.

The riparian vegetation model is a knowledge-based model that utilises rules as the model engine. As such, it can be termed a QRBM (Starfield *et al*, 1990). Because it is rule-based, qualitative (as well as quantitative) data are of value in its development. Although quantitative data of vegetation species distribution patterns are available, qualitative vegetation states have been utilised in the model. The model predicts a change in vegetation type abundance (as opposed to species) as a response to a change in the proportion of geomorphological units within a selected representative reach. As with the fish model, the change in vegetation type abundance is given by a vegetation state change over time. The states of vegetation types used are "not present", "uncommon", "intermediate", and "abundant".

The six vegetation types that were defined by van Coller and Rogers (1995) were utilised as vegetation units because

- the use of vegetation types in predicting a vegetation response met model objectives in that the link between vegetation and abiotic factors was sufficiently portrait, and at the same time maintained simplicity in the model by resulting in more general and fewer rules, and
- vegetation type dynamics occur at sufficiently broad scales so as to be applicable to potential management actions (such as hydrological manipulation).

5.1 SPATIAL AND TEMPORAL SCALES SELECTED

The spatial and temporal scales selected for simulation of riparian vegetation along the Sabie River are governed by various factors. These include the spatial and temporal distribution patterns of vegetation types, the resolution of input data, and the required resolution of the output.

5.1.1 Spatial Distribution Patterns

The spatial scale implemented in the model was determined primarily

- by the understanding of relationships between riparian vegetation and geomorphology,
- the implementation capacities of management options, and
- achievable resolution within the constraints of the inputs, outputs, model objectives and practicalities of the modelling process.

Along the Sabie River, the interaction between hydrology and fluvial geomorphology is critical to understanding vegetation spatial patterns. Strong environmental gradients (vertically, laterally and longitudinally) in the form of flooding frequency, water availability from the water table, soil type and nutrient availability, combined with a highly patchy geomorphological setting, give rise to an extremely diverse and dynamic environment that influences species distribution patterns (van Coller and Rogers, 1996).

Discontinuities in species distribution patterns along these gradients and geomorphological features have been used to define vegetation types. A vegetation type refers to a suite of species that have similar distribution patterns. The term "vegetation type" is comparable to vegetation community, but vegetation types occur as groups of species within the riparian vegetation community. Six vegetation types have been defined (Van Coller and Rogers, 1995) and are named according to the dominant species:

1. The *Breonadia salicina* vegetation type
2. The *Phragmites mauritianus* vegetation type
3. The *Phyllanthus reticulatus* vegetation type
4. The *Combretum erythrophyllum* vegetation type
5. The *Diospyros mespiliformis* vegetation type
6. The *Spirostachys africana* vegetation type

A full list of species within each vegetation type is given in appendix VII.

The cross sectional morphology of the river valley (macro-channel) within the Kruger National Park gives rise to two broad groups of vegetation types. There is a clear distinction in species composition between the vegetation types that are associated with the **macro-channel bank** and the vegetation types that are associated with the **macro-channel floor** (Figure 5.1)(van Coller and Rogers, 1996). Two vegetation types have been identified along the **macro-channel bank.** The *Spirostachys africana* vegetation type, which consists of species from the surrounding terrestrial zone but that occur with greater abundance in the riparian zone, and the *Diospyros mespiliformes* vegetation type, which consists of species found outside of the riparian zone but only in more mesic regions. Along the **macro-channel floor** four main vegetation types have been identified. They consist of species confined to the riparian zone. The *Breonadia salicina* vegetation type is characterised by a closed evergreen tree canopy and understorey shrubs, the *Phyllanthus reticulatus* vegetation type by shrubs, the *Phragmites mauritianus* vegetation type by reeds and shrubs, and the *Combretum erythrophyllum* vegetation types by open deciduous and semi deciduous canopy trees interspersed by shrubs (van Coller and Rogers, 1996).

The contrasting morphology of the macro-channel bank and macro-channel floor, as well as their vertical and lateral position relative to the active channel, result in very different environmental processes, which are reflected in the differences in vegetation distribution patterns. Although the **macro-channel bank** is relatively stable and is moulded largely by sub-aerial processes, experiencing low sedimentation, the steep slopes result in strong vertical gradients of flooding frequency and availability of water from the water table. Consequently vertical gradients exist in the distribution of the vegetation, where species of the *Diospyros mespiliformes* vegetation type are found lower down on the macro-channel bank than species of the *Spirostachys africana* vegetation type.

In contrast to the macro-channel bank, frequent flooding, sedimentation and erosion along the relatively wide irregular topography of the **macro-channel floor** provides a dynamic and geomorphologically diverse setting for the establishment of riparian plants. The degree of bedrock influence along the macro-channel floor is seen to be critical in influencing the distribution of the four vegetation types.

There is a trend from species of the *Breonadia salicina* vegetation type in bedrock dominated areas (e.g., bedrock and mixed anastomosing channel types), to species of the *Phyllanthus reticulatus* and *Phragmites mauritianus* vegetation types in both bedrock and alluvial dominated areas (e.g., mixed anastomosing, pool-rapid, and braided channel types) to species of the *Combretum erythrophyllum* vegetation type in alluvial dominated areas (e.g., braided channel types). This change in vegetation type in relation to the degree of bedrock control is also evident at the scale of geomorphological units (Figure 5.2).

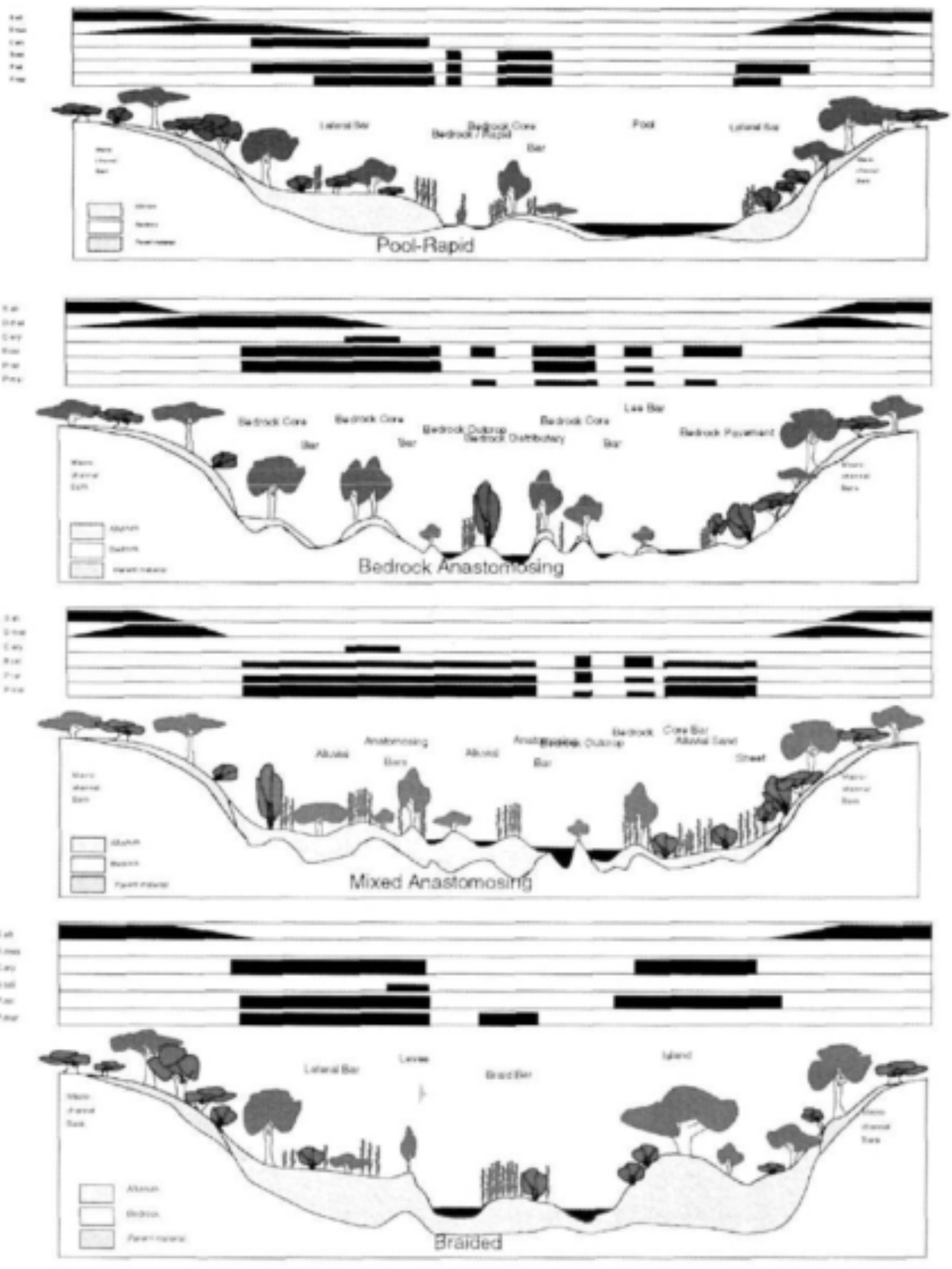


Figure 5.1 Diagrammatic profiles of the distribution of the six vegetation types on different geomorphological units at different channel types. The vegetation types are indicated by the shaded boxes which represent their distribution as a relative proportion.

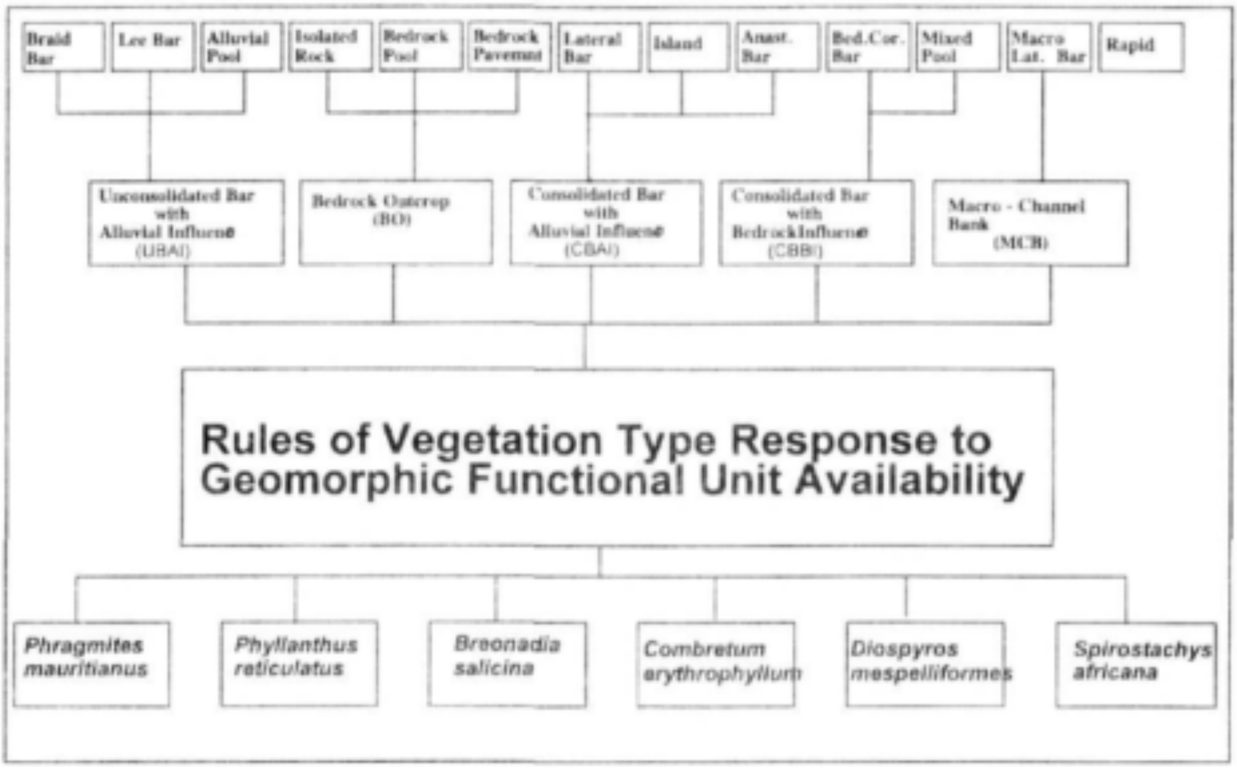


Figure 5.2 Overview of the riparian vegetation model.

The relationship of the four vegetation types along the macro-channel floor with the different channel types gives rise to distinct differences in the distribution of the vegetation types of the macro-channel floor along the length of the Sabie River. An alternation between the channel types along the length of the Sabie River is mirrored by a change in the vegetation types that are associated with that channel type (van Coller and Rogers, 1996). Because channel types are characterised by suites of geomorphic units, this relationship of the four vegetation types along the macro-channel floor is also prevalent at the geomorphic unit scale.

While the four vegetation types along the macro-channel floor are closely related to differences in the degree of bedrock control and the type of geomorphological unit, there are also differences in their vertical distribution relative to the active channel, indicating a likely relationship with flooding frequency. Species of the *Breonadia salicina* and *Phragmites mauritianus* vegetation types occur at lower elevations above the channel and are therefore more frequently inundated than species of the *Phyllanthus reticulatus* and *Combretum erythrophyllum* vegetation types, which are found at higher elevations above the active channel (Figure 5.2).

In addition to the relationship between vegetation type distribution and the fluvial geomorphology and environmental gradients, it has been shown from aerial photographs that at the landscape level, the state composition (proportion of water, sand, rock, reeds, herbaceous and woody vegetation) along the Sabie River is closely related to change in geology down the length of the river. It has been shown that there is more woody vegetation and less water and reed cover where the river traverses granite in its upper reaches as well as in the rhyolite reaches of the Lebombo mountains, while in the basalt reaches more of the river landscape was covered by reeds (Carter 1995).

The spatial scales that were selected for use in the riparian vegetation model have been governed by the relationship between riparian vegetation distribution and geomorphological features. Because six distinct vegetation types were defined and because they differ significantly in their distribution to geomorphic features, it was decided to use the "vegetation type" as a vegetation unit. This also reduces the complexity of the model because only six vegetation states require rules and coding instead of numerous species if it had been done at the species level. Because the distribution of vegetation types in space is constrained by geomorphic features, it was decided to use geomorphic units as the spatial scale. Geomorphic units have been functionally grouped to form functional geomorphic units in the model. This is discussed in more detail below.

The spatial scale at which model output is presented is, as with the geomorphology and fish models, that of the representative reach.

5.1.2 Temporal Distribution

Changes in the distribution of vegetation over time have been addressed at the landscape scale of state composition (the proportion of water, sand, rock, reeds, herbaceous and woody) defined by Carter (1995). Using a series of aerial photographs dating back to 1940, Carter showed that non-vegetated sites, usually open sand areas, became increasingly dominated by vegetation after 1940, initially by reeds and then by woody vegetation. This change was however different over space, where the granite reaches became increasingly dominated by woody vegetation, while downstream of the granite (with the exception of the rhyolite of the Lebombo mountains) the reeds became the dominant vegetation. This landscape-change in the Sabie River since 1940 appeared therefore to follow a directional process involving the sequential colonisation of non-vegetated areas by herbaceous vegetation, reeds and woody vegetation, which became more strongly directional with time (Carter 1995).

We thus know that a change in riparian vegetation distribution patterns (as defined by the states "reeds", "herbaceous vegetation", and "woody vegetation") is observable within 40 to 50 years. What we do not know however is the longevity of any of the organisms we are dealing with. This makes it difficult to select a meaningful temporal scale over which to run the riparian vegetation model so as to predict a vegetation response in time. Because riparian vegetation distribution is so well correlated to physical geomorphological structure, it was decided at present to replace time with space in the vegetation model. This means that in the model the riparian vegetation responds to a geomorphic change in space, the response being temporally dependant on the time taken for such a geomorphic change to occur past a defined critical stage (see geomorphic states below). **Vegetation states** (defined below) therefore change according to the rules which govern their change only once **geomorphic states** change critically.

5.2 MODEL CONCEPTUALISATION

A conceptual model of the fundamental components that influence the riparian vegetation itself (Figure 5.2) guided planning of the riparian vegetation model. The goal and purpose of the model dictates an "atmosphere" that guides and constrains model development. The goal and purpose is to predict a vegetation state change.

The inputs, model subjects and outputs form the crux of the model. Both inputs and outputs are states while the model subjects are vegetation types. Rules utilised in the model define the way inputs influence model subjects (based on data and current understanding), and altered model subject states are predicted as outputs. Mediators may alter the exact manner in which rules operate. Mediators are thought of as aspects in the system that is being modelled which do not exert a direct influence on model subjects as inputs do. Their influence exists, but is indirect.

The scale of the model defines a temporal and spatial domain within which the model must operate. Scale choice depends on model objectives and the resolution of current understanding of the system that is being modelled.

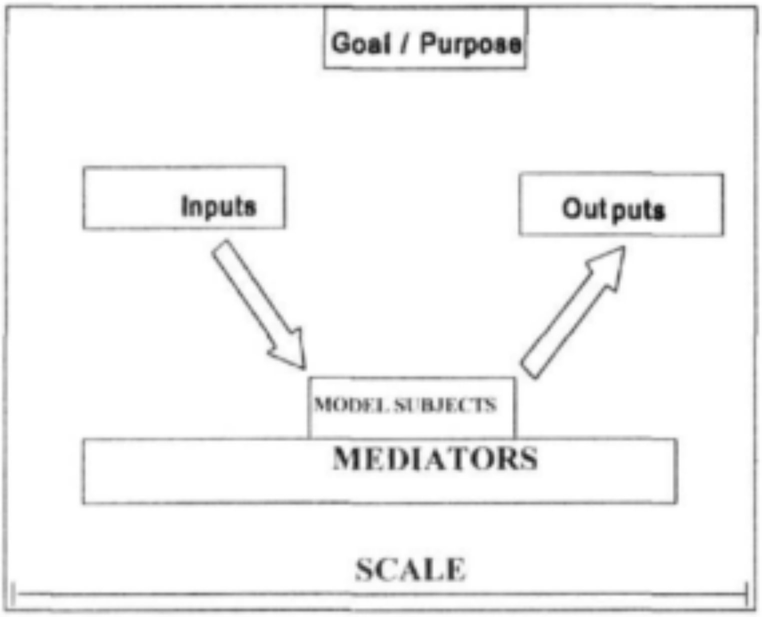


Figure 5.3 Conceptualisation of Model Components

5.3 A PRIORI MODEL CONSTRAINTS

The riparian vegetation model has been developed with certain limitations. These have been recognised *a priori* and have not been addressed in the present model due to resource constraints. Limitations are listed below in order of priority for future developments to the model:

1. Hydrological influence on the distribution of riparian vegetation will only be accounted for by the model in an indirect way. Hydrological influence is realised via its influence on geomorphic change. The riparian vegetation model as is does not include direct hydrological input such as the disturbance effect of floods, or mortality due to droughts. At present data are being collected that will allow the assessment of the influence of the 1996 flood on both riparian vegetation regeneration and mortality. Use of these data, as well as the data on tree mortality due to drought conditions, will be beneficial because a direct hydrological input to the model will result.
2. Although the model output is given on an annual basis, the vegetation change is independent of time and dependant on a geomorphic state change. Assessment of organism longevity and the time taken for seedlings to recruit into adult populations is needed so that the vegetation response can be made temporally explicit.
3. The riparian vegetation model will not explicitly include finer-scale vegetation dynamics such as regeneration and mortality. Inclusion of these will help define temporal scales and improve resolution within vegetation responses.
4. Along the Sabie river there is a clear geological influence on the distribution patterns of vegetation types. This will not be included in the riparian vegetation model in this exercise, and it is suggested that a geological mediatory effect be an improvement to the model.

5.4 INPUT TO THE MODEL

Input to the riparian vegetation model is derived from the output of the geomorphology model. The geomorphology model predicts the percentage composition of geomorphic states in selected representative reaches. These percentage changes for geomorphic units are summed for each functional group of geomorphic units (see below) and then input to the vegetation model.

5.4.1 Functional groupings of geomorphic units

The definition of functional groupings of geomorphic units involved a functional classification of geomorphic units. The two main reasons for using and defining functional groupings of geomorphic units in this way are;

- functional units reflect the known relationship between riparian vegetation and fluvial geomorphology, and will therefore effectively account for a riparian vegetation response to geomorphology, and

- by defining functional units the number of geomorphic states used in the model would be less and rule development and coding would therefore be less complicated.

Emphasis is placed on maintaining simplicity throughout model development because the model needs to be effectively utilised by other users. Simplicity also promotes model transferability and parsimony.

Five functional groupings of geomorphic units were defined:

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

The functionality of these is clear when one considers the distribution patterns of the six vegetation types: of the five functional groupings of geomorphic units only the macro-channel bank does not pertain to geomorphic features within the macro-channel floor, and two of the six vegetation types occur predominantly or only on the macro-channel bank i.e. the *Spirostachys africana* and *Diospyros mespilliformes* vegetation types. The remaining four functional groupings of geomorphic units occur on the macro-channel floor, and have been defined according to sediment characteristics and the degree of bedrock influence prevalent at geomorphic units. As outlined above, sediment characteristics and the degree of bedrock influence are major determinants of vegetation distribution patterns.

The bedrock outcrop functional group of geomorphic units consists of geomorphic units that predominantly constitute bedrock (Table 5.1). Consequently vegetation types that occur in association with bedrock (such as the *Breonadia salicina* vegetation type) will occur where the bedrock outcrop functional group of geomorphic units occurs (Table 5.2). Similarly vegetation types that occur in association with alluvia (such as the *Combretum erythrophyllum* vegetation type) will occur where alluvial influence predominates (such as the consolidated bar with alluvial influence functional group of geomorphic units (Table 5.1)), and not where bedrock influence predominates (such as the bedrock outcrop and consolidated bar with bedrock influence functional groupings of geomorphic units). Geomorphic units that do not belong to either the bedrock outcrop or macro-channel bank functional groupings of geomorphic units, have either been classified as consolidated or unconsolidated bars.

The grouping of geomorphic input to the model as geomorphic functional groupings of geomorphic units is shown in Table 5.1 and illustrated in Figure 5.2.

Consolidated bars refer to those geomorphic units where sediment characteristics confer stability of those units relative to unconsolidated bars where sediments are loosely packed and more prone to erosion. Consolidated bars also generally occur at a higher elevation than unconsolidated bars and are therefore hydrologically influenced only seasonally or ephemerally as opposed to year round hydrological influence on unconsolidated bars. Consolidated bars have been defined in two ways: those with bedrock influence and those without. Consolidated bars without bedrock influence have been called consolidated bars with alluvial influence because geomorphic units (such as lateral bars) that belong to this functional group of geomorphic units are alluvial in nature only. Consolidated bars with bedrock influence are those geomorphic units (such as bedrock core bars) that consist of both alluvia and bedrock.

Table 5.1. The classification of geomorphic units into five functional groupings of geomorphic units.

Geomorphic Unit	Functional group of geomorphic units
macro-channel bank	macro-channel bank
exposed bedrock	bedrock outcrop
bedrock core bar	consolidated bars with bedrock influence
braid bar	unconsolidated bars with alluvial influence
lateral bar	consolidated bars with alluvial influence
island	consolidated bars with alluvial influence
alluvial distributary	unconsolidated bars with alluvial influence
gravel distributary	consolidated bars with bedrock influence
bedrock distributary	bedrock outcrop
alluvial anastomosing distributary	unconsolidated bars with alluvial influence
braid distributary	unconsolidated bars with alluvial influence
alluvial anastomosing bar	consolidated bars with alluvial influence
lee bar	unconsolidated bars with alluvial influence
levee	unconsolidated bars with alluvial influence
bedrock pavement	bedrock outcrop

Predicting a vegetation response to the functional groupings of geomorphic units outlined in Table 5.1 would only yield a result if geomorphic change were to result in a channel type change. In other words, for the *Breonadia salicina* vegetation type to respond to a functional group of geomorphic units change according to Table 5.2 for example, geomorphic units that constituted "bedrock outcrop" would have to become geomorphic units that belonged to a different functional group of geomorphic units. This level of geomorphic change would correspond to the hypothetical directionality of channel type change proposed for the Sabie river (i.e. bedrock anastomosing to mixed anastomosing to alluvial anastomosing channel types for example) (Heritage *et al.*, 1996). A channel type change has not yet been observed however.

Because channel type change has not been observed the vegetation would therefore be predicted as stable with no observed change. We know that this is not the case from Carter's work (1995). It was therefore necessary to create geomorphic states within each functional group of geomorphic units to which vegetation would respond.

The frequency of occurrence of functional groupings of geomorphic units was related to different channel types. A k-means cluster analysis was then used to define five groups within the data. These five groups were used as geomorphic states within each functional group of geomorphic units (Table 5.3). Geomorphic states therefore represent a defined proportion of functional groupings of geomorphic units within any given channel type. The five geomorphic states are the same within all functional groupings of geomorphic units and are as follows:

1. represents less than 5% of the relevant functional group of geomorphic units,
2. between 5 and 15%,
3. between 16 and 25%,
4. between 26 and 35% and
5. more than 35%.

5.4.2 Vegetation States

Because the riparian vegetation model is a qualitative rule-based approach it utilises discreet states and predicts change between states. It has already been pointed out that the vegetation type has been selected as the biotic unit in this model, but different vegetation type states are needed for the model to run. These states must reflect relevance to management problems that call for the development of predictive models in the first place, for example, managers may be interested in biotic abundance along the Sabie river. Qualitative states that refer to vegetation type abundance have therefore been defined (Table 5.2).

Table 5.2. Vegetation states of vegetation types according to the functional groupings of geomorphic units used in the riparian vegetation model. Vegetation states pertain to vegetation type abundance and are: not present (N), uncommon (U), intermediate (I), and abundant (A).

	Functional groupings of geomorphic units				
Vegetation Types	BO	CBAI	CBBI	MCB	UBAI
Brsa	A	U	A	N	I
Coer	N	A	I	U	U
Phma	U	A	I	N	I
Phyl	I	A	A	U	I
Dime	N	I	I	A	U
Spaf	N	U	U	A	N

Where:

BO = bedrock outcrop

CBAI = consolidated bar with alluvial influence

CBBI = consolidated bar with bedrock influence

MCB = macro-channel bank

UBAI = unconsolidated bar with alluvial influence

Phma = *Phragmites mauritianus* vegetation type

Phyl = *Phyllanthus reticulatus* vegetation type

Brsa = *Breonadia salicina* vegetation type

Coer = *Combretum erythrophyllum* vegetation type

Dime = *Diospyros mespiliformis* vegetation type

Spaf = *Spirostachys africana* vegetation type

Vegetation type frequencies (from data collected on the ground) as per functional groupings of geomorphic units were used to define vegetation states. A state of "not present" was assigned to frequencies of 0.03 and less, "uncommon" to frequencies from 0.03 to 0.11, "intermediate" to frequencies from 0.11 to 0.26, and "abundant" to frequencies higher than 0.26 (Table 5.2).

5.5 RULE DEVELOPMENT AND CODING

Rules for the model were developed utilising the matrix outlined in Table 5.3. The rules are presented in Appendix VIII. The construction of the matrix in Table 5.3 needs some explanation and for this an example will be used. If we focus only on the *Breonadia salicina* vegetation type and only on the bedrock outcrop functional group of geomorphic units for example, vegetation states were defined for each of the geomorphic states in the following way:

In Table 5.2 the *B. salicina* vegetation type (Brsa) occurs as the ABUNDANT (a) vegetation state for the 5th geomorphic state of the BEDROCK OUTCROP (BO5) functional group of geomorphic units. It is UNCOMMON (u) for geomorphic states 1 and 2, and INTERMEDIATE for 3 and 4. When the proportional frequency of occurrence of *B. salicina* is related to geomorphic states within a functional group of geomorphic units for different channel types, (Table 5.4) the defined vegetation states become apparent. Data do not however support a vegetation state definition for the 2nd geomorphic state. In these instances expert experience is used to decide on a state.

Table 5.3. Vegetation states of vegetation types according to the geomorphic states used in the riparian vegetation model. Geomorphic states are defined as: 1 - <5%, 2 - 5-15%, 3 - 16-25%, 4 - 26-35%, and 5 - >35%.

Functional group of geomorphic units																									
Vegetation Type	BO					CBAI					CBBI					MCB					UBAI				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Brsa	u	u	i	i	a	u	u	u	u	u	n	u	i	i	a	n	n	n	n	n	n	u	i	i	I
Coer	n	n	n	n	n	u	i	a	a	a	n	u	u	i	i	n	n	u	u	u	n	n	u	u	u
Phma	n	n	u	u	u	n	u	i	a	a	n	n	u	i	u	n	n	n	n	n	u	u	i	i	u
Phyl	n	u	i	i	i	u	i	i	a	a	u	i	a	a	a	n	n	u	u	u	n	n	u	i	i
Dime	n	n	n	n	n	n	u	u	i	i	n	u	u	i	i	i	i	a	a	a	n	n	u	u	u
Spaf	n	n	n	n	n	n	n	n	u	u	u	u	u	u	u	i	i	a	a	a	n	n	n	n	n

Where :

Vegetation type, vegetation state and functional group of geomorphic units details are as in Table 2.

The vegetation state assigned to each vegetation type-functional group of geomorphic units combination in Table 5.2 is used in an overriding way to subsequently define vegetation states in Table 5.3 however. If the *B. salicina* vegetation type-bedrock outcrop functional group of geomorphic units combination in Table 5.2 for example had had a different vegetation state, then the vegetation state distribution in Table 5.3 would also have been different. If the vegetation state in Table 5.2 was for example INTERMEDIATE, then the most abundant vegetation state in Table 5.3 (geomorphic state 5 for the *B. salicina* vegetation type on bedrock outcrop) would have also been INTERMEDIATE. Other vegetation states for the remaining geomorphic states would then be relative to this INTERMEDIATE vegetation state. The *B. salicina* vegetation type would then have been NOT PRESENT for geomorphic state 1 and UNCOMMON for geomorphic states 2, 3 and 4.

Vegetation states were defined in the same way for each vegetation type-geomorphic state combination. Quantitative data do not support all values for vegetation states.

Columns in Table 5.3 display a certain amount of redundancy for some of the functional groupings of geomorphic units. Vegetation states are the same for example for MCB geomorphic state 1 and 2, as well as for 3, 4 and 5. This has occurred because although it was necessary to define 5 geomorphic states for each functional group of geomorphic units (e.g. no redundancy for CBBI 1-5), not all the functional groupings of geomorphic units occur as all geomorphic states. Five geomorphic states were kept for all functional groupings of geomorphic units to aid rule coding.

Table 5.4. Defined vegetation states for the *B. salicina* vegetation type according to frequencies of occurrence (Table 5.2) for different geomorph

Channel Type	Geom Func Unit	Geomorphic Func Unit proportion within Channel Type	Geom State	Frequency - *B. salicina*	Veg State
mixed anastomosing	bedrock outcrop	0.193	3	0.193	i
pool / rapid	bedrock outcrop	0.334	4	0.191	i
bedrock anastomosing	bedrock outcrop	0.435	5	0.559	a
braided	bedrock outcrop	0.037	1	0.055	u

Model coding involved the development of routines to aggregate geomorphic unit input to the functional units and to classify these into their respective states of abundance. Relationships defined in Table 5.3 were then encoded in FORTRAN 77 as "rules" using IF-THEN type statements. An overview of the model structure is presented in Figure 5.2.

5.6 PRESENTATION OF THE MODEL AND RESULTS

The output of the riparian vegetation model consists of a matrix of vegetation type states on an annual basis (Table 5.5). Although these are given as absolute numbers (0-3) per year, they are interpreted as 0 - not present, 1 - uncommon, 2 - intermediate, and 3 - abundant. The output is graphically displayed alongside the change in functional groupings of geomorphic units, also on an annual basis. Model output is displayed in and incorporated into the ICIS system (Figure 1.7).

Table 5.5 Results for the riparian vegetation model for selcted input parameters

Year	phma	phyl	brsa	coer	dime	apaf	BO	CBBI	CBAI	UBAI	MB
1960	2	2	2	1	3	3	3	1	1	4	3
1961	3	3	3	3	3	3	4	5	5	4	3
1962	3	3	3	3	3	3	5	4	4	3	5
1963	3	3	2	3	3	3	1	4	4	3	4
1964	2	3	2	3	2	2	1	3	3	1	2
1965	1	2	2	1	2	2	4	2	1	2	2
1966	2	3	2	2	2	2	4	4	2	1	2
1967	3	3	2	3	2	2	1	2	4	4	2
1968	1	1	1	1	3	3	0	0	0	0	5
1969	1	2	2	1	2	2	0	0	0	5	0
1970	3	3	1	3	2	2	0	0	5	0	0
1971	1	3	3	2	2	2	0	5	0	0	0
1972	1	2	3	0	2	2	5	0	0	0	0
1973	1	2	2	1	3	3	4	2	1	2	3

For purposes of testing the model, input geomorphic functional states were manipulated to create hypothetical situations to which vegetation types would respond according to defined rules. The output example is shown in Table 5.5. In 1968 for instance the MCB functional group of geomorphic units was set high and no value was given to any of the others. As expected, the *D. mespiliformis* and *S. africana* vegetation types were abundant in response. When CBAI were set high in 1970, the *C. erythrophyllum, P. mauritianus* and *P. reticulatus* vegetation types became abundant. When BO or CBBI were set high in 1972 and 1971 respectively, the *B. salicina* vegetation type became abundant. We also see that the *C. erythrophyllum* vegetation type for instance is not present when BO is set high in 1972. The same is true for the *P. mauritianus* and *P. reticulatus* vegetation types in 1968 when MCB predominates. The *B. salicina* vegetation type is uncommon when CBAI is set high in 1970. These responses are all in accordance with current understanding and data.

These are extreme-case scenarios, but under other more realistic scenarios of functional groupings of geomorphic units, as input, vegetation responses are generally in accordance with data trends and current understanding of vegetation distribution patterns.

5.7 MODEL ASSUMPTIONS AND LIMITATIONS

Clearly a model with a high degree of simplicity such as the riparian vegetation model will have a number of fundamental assumptions and associated limitations. Some of these have been listed *a* *priori* (section 5.3) and improving resolution in one or a number of these areas would be a suggested future development for model improvement.

The following assumptions apply to the model:

- A particular channel type or geomorphic unit will always be functionally the same in terms of a riparian vegetation response to those geomorphic features. This assumption facilitates the grouping of geomorphic units into functional groupings of geomorphic units with the premise that functional groupings of geomorphic units are functional.
- It is assumed in the model that the dispersal and presence of vegetation propagules is not limiting to such a vegetation response. A riparian vegetation response to an altered proportion of geomorphic features within a given channel type will, however, in part be dependant on the regeneration dynamics of vegetation.
- in conjunction with the point above, it is also assumed that once geomorphic change has occurred, site availability for recruitment will not limit a vegetation response. This means that as sites become available they are occupied by relevant vegetation types. The riparian vegetation model assumes therefore that these vegetation dynamics are taking place and predicts the expected outcome without modelling smaller scale dynamics.

6 SIMULATION OF IMPACTS OF POTENTIAL DEVELOPMENT SCENARIOS IN THE SABIE RIVER CATCHMENT

G.P.W. Jewitt, G.L. Heritage, D.C. Weeks, J.A. Mackenzie and A.H.M Görgens

The eventual role of these models beyond the prototype stage is to provide catchment managers 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. In order to demonstrate the effectiveness of this suite of models, the system was used to simulate the effects of various flow scenarios in the Sabie Catchment. These include historical flow conditions in the Sabie River over the past 35 years and some potential effects of a hypothetical dam on the Sabie River. For all scenarios, three simulations are performed at sites representative of the pool-rapid, bedrock anastomosing and braided/single thread channel types. Results are presented as colour graphs of the geomorphic, fish and riparian vegetation response using software developed by the CCWR and included in the KNPRRP ICIS.

6.1 SIMULATION OF HISTORICAL CATCHMENT CONDITIONS

Using observed flow data obtained from DWAF flow gauging stations on the Sabie River, or flow simulated using the ACRU model and ACRU generated sediment values, it is possible to simulate the historical condition of the fish and riparian vegetation of the Sabie River. The simulations are performed for the period 1960 to 1994.

Results from the geomorphology and riparian vegetation models are shown in Figures 6.2a-c. The different compositions of channel type in terms of their geomorphological unit classification for each channel type are seen clearly, together with the associated riparian vegetation assemblages. In all cases, increasing sedimentation is seen from the early 1970's until present. The increasing sediment has little effect on the braided channel but changes to the geomorphological unit in the pool-rapid and mixed anastomosing reaches are noted. The phragmites vegetation type is the most dynamic of the riparian vegetation groups simulated and shows the most variation in state.

Results from the fish model shown in Figure 6.1, illustrate a highly variable fish response corresponding to the natural flow variation. The minnow and cichlid fish groups are the most dynamic. In drought periods, cichlids tend to dominate the fish assemblage. In wet cycles, the minnows tend to dominate. Although all fish groups are detrimentally affected by low flow cycles, the other fish groups are less variable, and may be more sensitive to the habitat offered by the reach. The difference in fish numbers between the different channel types simulated can also be seen, especially in terms of the numbers of the rock catlet (yellow) present. In the braided/single thread reach, the rock catlet is rare. In bedrock anastomosing reaches, and to a lesser extent in the pool-rapid reach while favourable hydrological conditions prevail, it is common.

6.2 HYPOTHETICAL DAM SIMULATIONS

It was assumed that a dam was constructed on the main stem of the Sabie River just upstream of the KNP. The simulation sites selected are hypothetical reaches downstream of the confluence of the Sand and Sabie Rivers. It is assumed that the bulk of sediment in these reaches is produced by the Sand River, thus sediment production at the simulation site is unaffected by the construction of the dam and the historical conditions illustrated above are assumed.

The following hypothetical scenarios were generated and used as input to the models;

1. A dam with the capacity of the mean annual runoff (approx. 300 x 10^6 m^3) with a constant flow release of 4 $m^3.s^{-1}$ throughout the year providing water stored in the dam is sufficient to sustain this. All flow events are assumed to be trapped by the dam unless it is full, in which case these events continue downstream as spills from the dam. Flow events greater than the 1:5 year return period flood are assumed to be unaffected by the hypothetical dam and are represented as spills. This has the effect of removing freshets and minor floods from the wet season (summer in Mpumulanga) flow regime, and creating dry seasons (winter) with more flow than would normally be expected.
2. The dam is assumed to be extremely large, and all flood events smaller than the 1:50 year flood are stored by the dam. A constant release of 5 $m^3.s^{-1}$ occurs in the absence of any overflow, and zero release should the dam be empty. Thus, the dam's major impact is to impose a consistent flow regime on the Sabie River in the absence of any extreme events.

Results produced by a simulation of Scenario 1 are shown in Figures 6.3 and Figure 6.4. This scenario effectively produces drier than normal wet seasons and leaves dry seasons largely unchanged from the historical condition. The loss of freshets results in several seasons which are termed "failed" wet seasons by ecologists. The loss of these flows which stimulate breeding is clearly shown in the fish assemblages, especially in the minnow-cichlid relationship (figure 6.3a-c) for all reaches. For example, the period 1975-1980 displays a very different fish assemblage from that simulated for the historical situation. Cichlids are known to be opportunistic seasonal breeders, whilst other seasonal breeders including the cyprinids are dependent upon correct flow conditions to stimulate breeding. Thus, minnows no longer breed successfully unless flow events pass through the dam to the river below.

The channel geomorphic composition is less dynamic than the fish. Over a period of 30 years, an increase in alluviation can be seen relative to the historical condition. Over this relatively short period, this appears to have no significant impact on the fish population.

The relative stability in vegetation dynamics is due in part to the relatively short period of time that the model is run and in part to the stability of the geomorphic units. As the geomorphic heterogeneity remains stable over time, the vegetation will display the same stability.

Figures 6.5 and 6.6 illustrate the results from the "large dam" scenario. Model results suggest that the constant flow released from the dam results in very little variation in the fish assemblage and geomorphic habitat template for all reaches simulated. Cichlids dominate the fish assemblages and are numerous. All other fish are still present but in small numbers. Results from this scenario highlight some shortcomings of the modelling system. Over a period of such little flow variation, other factors such as seasonal temperature variation and biological interactions may become more dominant, and are not accounted for in the fish model, resulting in output showing no variation. Output from the geomorphic model illustrates a progressive alluviation of the pool-rapid reach. This is a result of incoming sediment from the Sand River no longer being redistributed by flood events and accumulating in the channel. This scenario appears to have very little impact on the stability of the other two channel types. This is to be expected in the alluvial single thread channel, but highlights a need for refinement of the rules governing responses in the mixed anastomosing channel. The Phragmites vegetation type response is dependent upon the alluvial geomorphic units. These are more variable than other geomorphic units in the pool rapid reach, thus, resulting in a more dynamic Phragmites vegetation type than the other vegetation types. The Phragmites vegetation type varies with varying alluviation, increasing with increased alluviation and declining with scouring of the reach following a flood. The Brenadia vegetation type shows some variation in the Pool-Rapid reach as a result of a decrease in the bedrock features as they are removed by sedimentation. In the other two channel types, the stable geomorphic conditions result in a stable riparian vegetation.

6.3 DISCUSSION

As explained in each of the chapters pertaining to the development of the models, rigorous verification of the model results has not been possible. The verification process has consisted of the ratification of the simulated model trends by other experts in the respective and limited comparison of the fish simulation results with observed data. Based on the assumption that these models perform adequately, the simulated hypothetical flow manipulation scenarios illustrate the potentially dramatic results of flow regulation on the fish, and to a lesser extent, the geomorphic structure of the river channel and riparian vegetation in the Sabie River. Results indicate that the dominant fish groups of the Sabie River are highly sensitive to the removal of both major and minor floods from the flow regime. Furthermore, results from the geomorphic model indicate that channel dynamism is lost with a flow regime from which floods have been removed. Increased sedimentation is the most likely consequence of the construction of major reservoirs on the Sabie River with no regulation of incoming sediment in the Sand River. This has long term effects for the fish population, with the rock catlet being the species most likely to lose significant areas of it habitat with increasing alluviation of the river.

In conclusion, results from scenarios 1 and 2 both show the overriding response of the fish of the Sabie River to seasonal hydrological conditions. The geomorphic response is one of increasing sedimentation to both of these scenarios. The riparian vegetation response to this is a slow increase in the abundance of the Phragmites vegetation type and decrease in the Brenadia vegetation type. As expected, the riparian vegetation response is the least dynamic of all those simulated. Limitations of the model in only explicitly simulating the effects of habitat and flow variability on fish are exposed in situations where simulated fish group abundances show no variability and other, unaccounted for processes may become important.

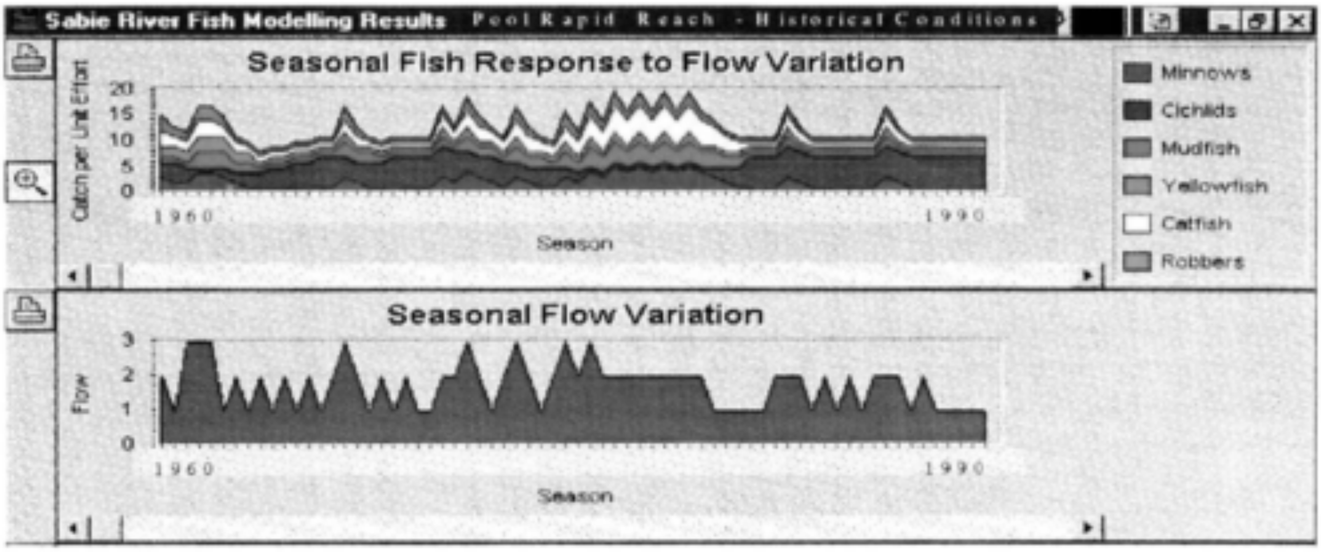


Figure 6.1a) Fish response to historical conditions in the pool-rapid reach.

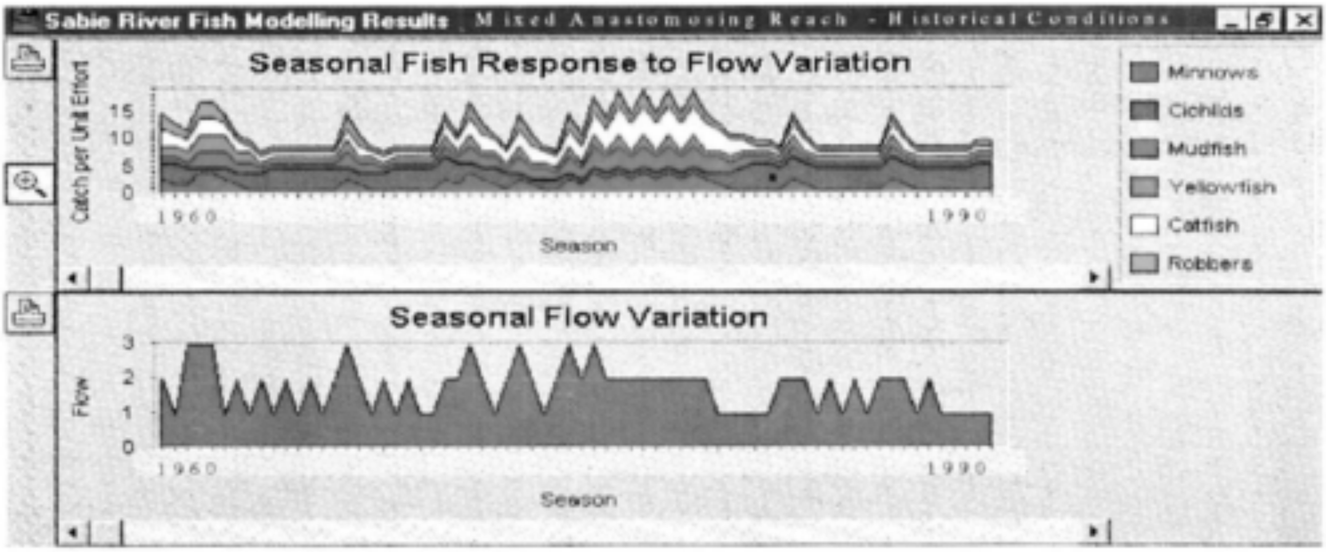


Figure 6.1b) Fish response to historical conditions in the mixed anastomosing reach

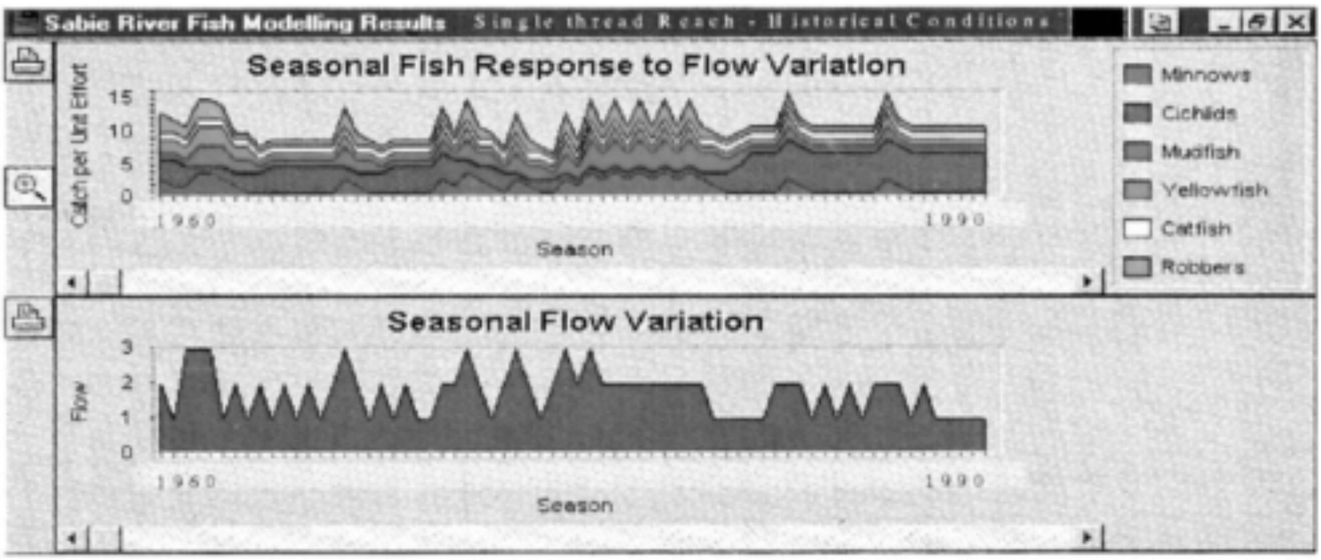


Figure 6.1c) Fish response to historical conditions in the single-thread reach

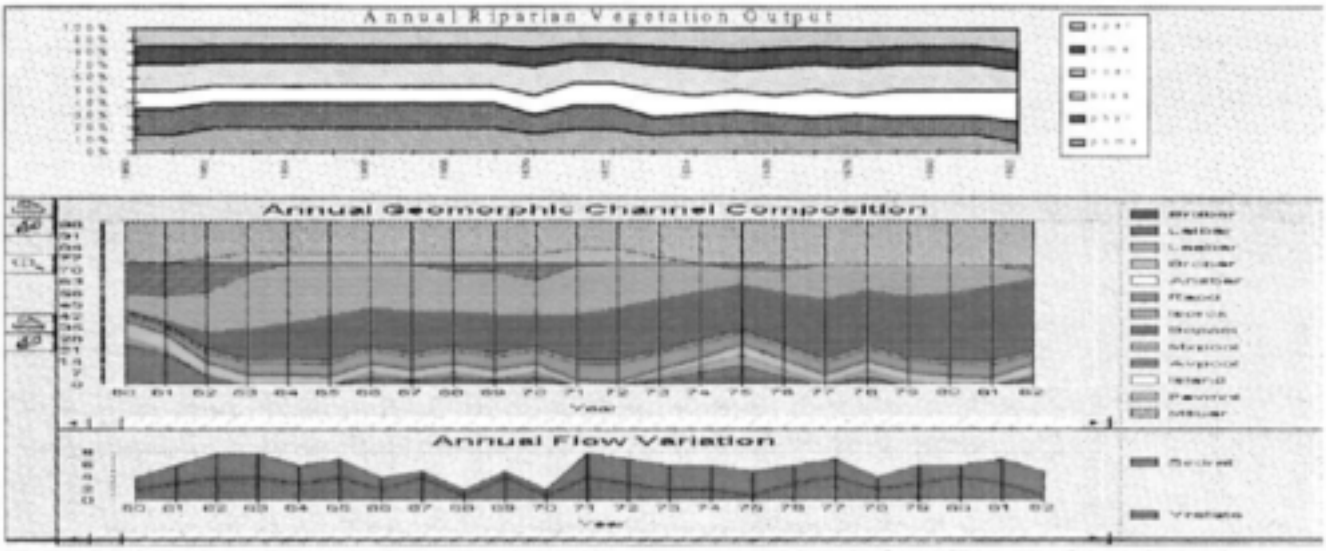


Figure 6.2a) Geomorphology and riparian vegetation response to historical conditions in the pool-rapid reach

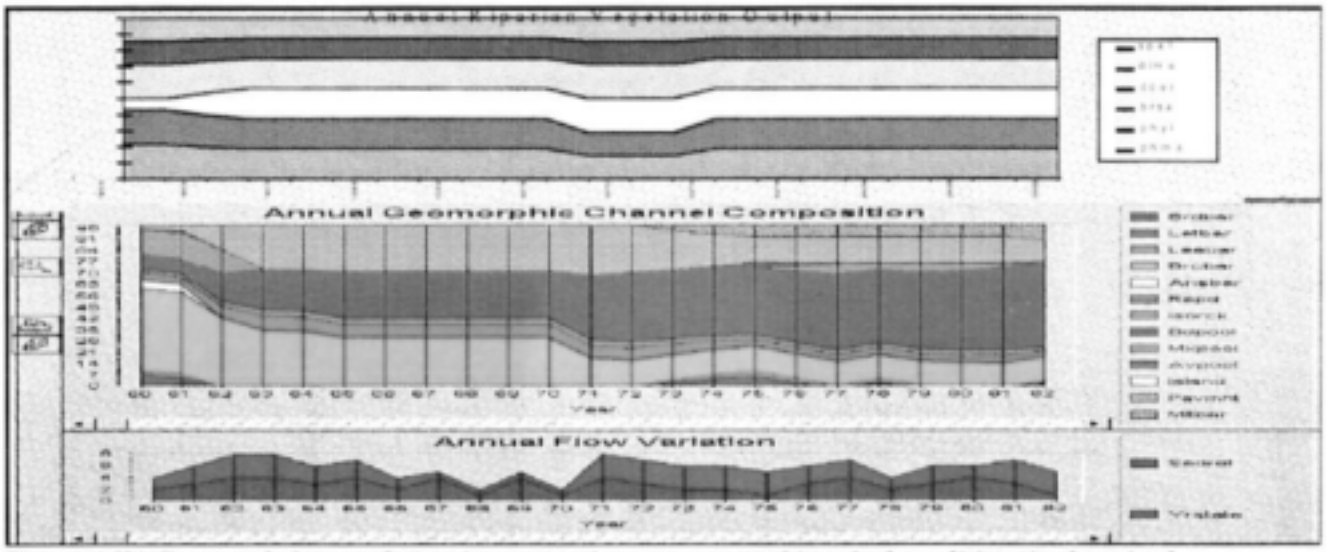


Figure 6.2b) Geomorphology and riparian vegetation response to historical conditions in the mixed anastomosing reach

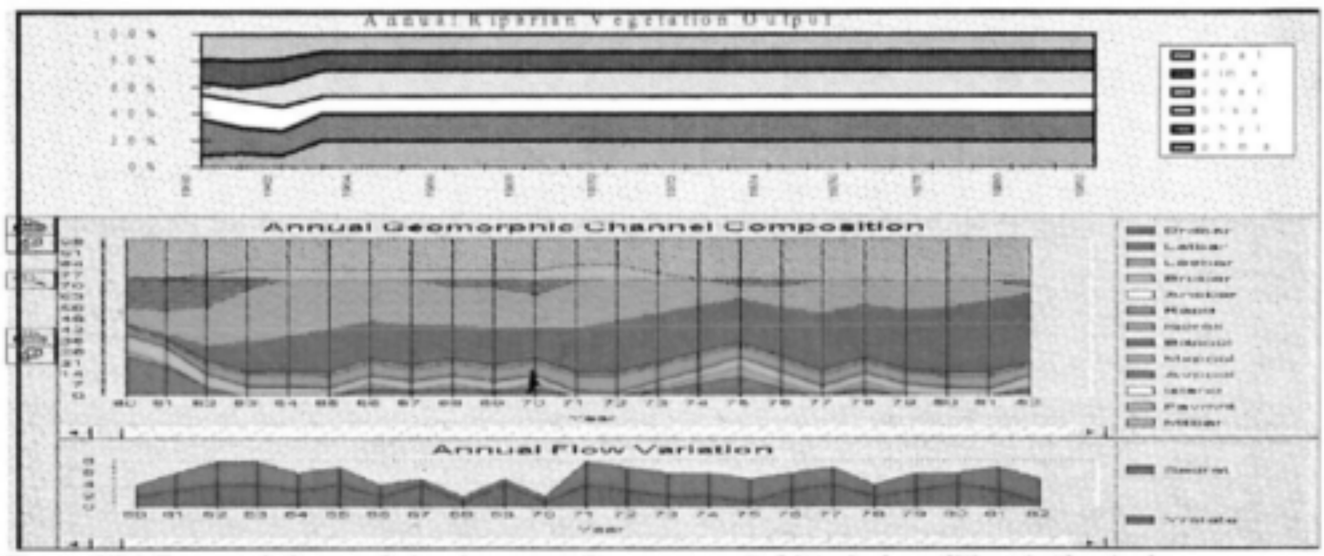


Figure 6.2c) Geomorphology and riparian vegetation response to historical conditions in the single-thread reach

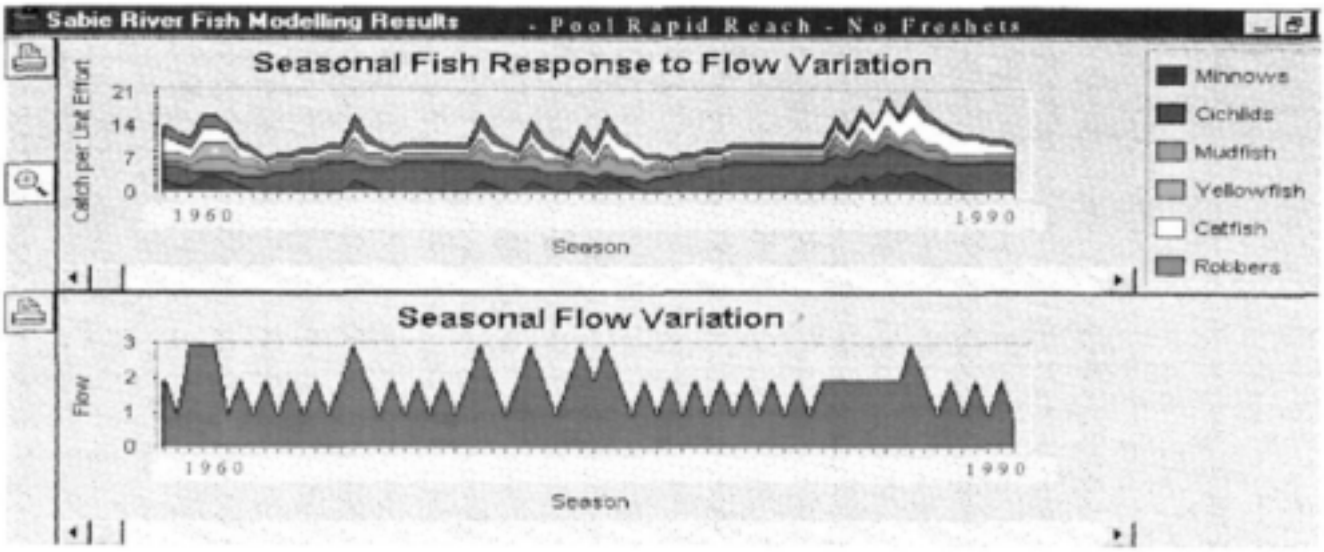


Figure 6.3a) Fish response to "no freshet" conditions in the pool-rapid reach

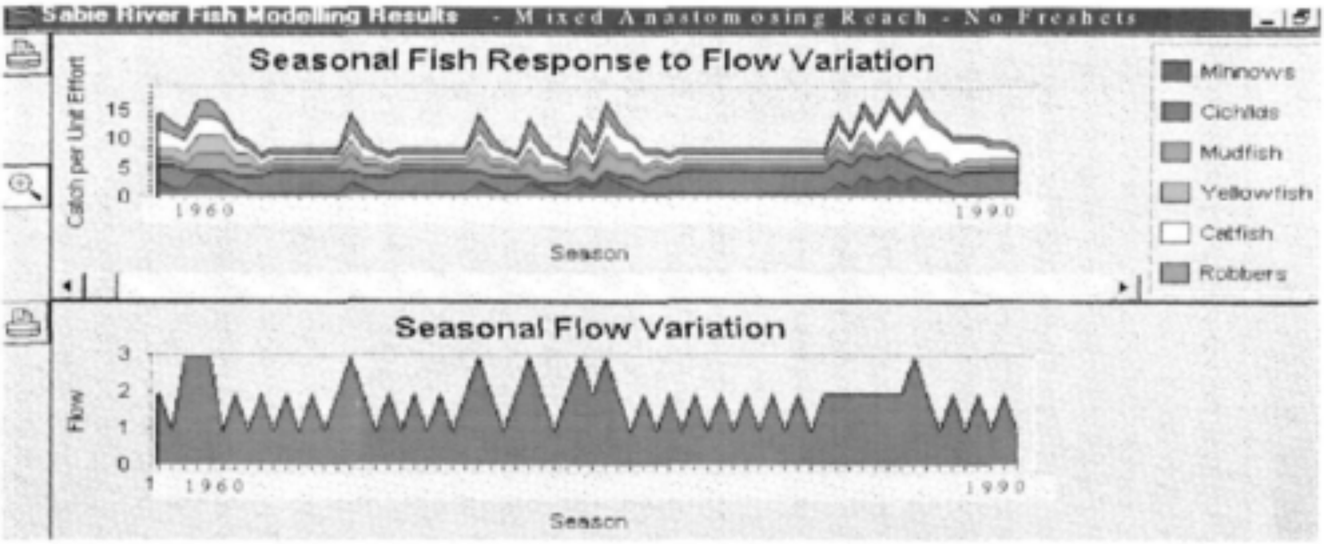


Figure 6.3b) Fish response to "no freshet" conditions in the mixed anastomosing reach

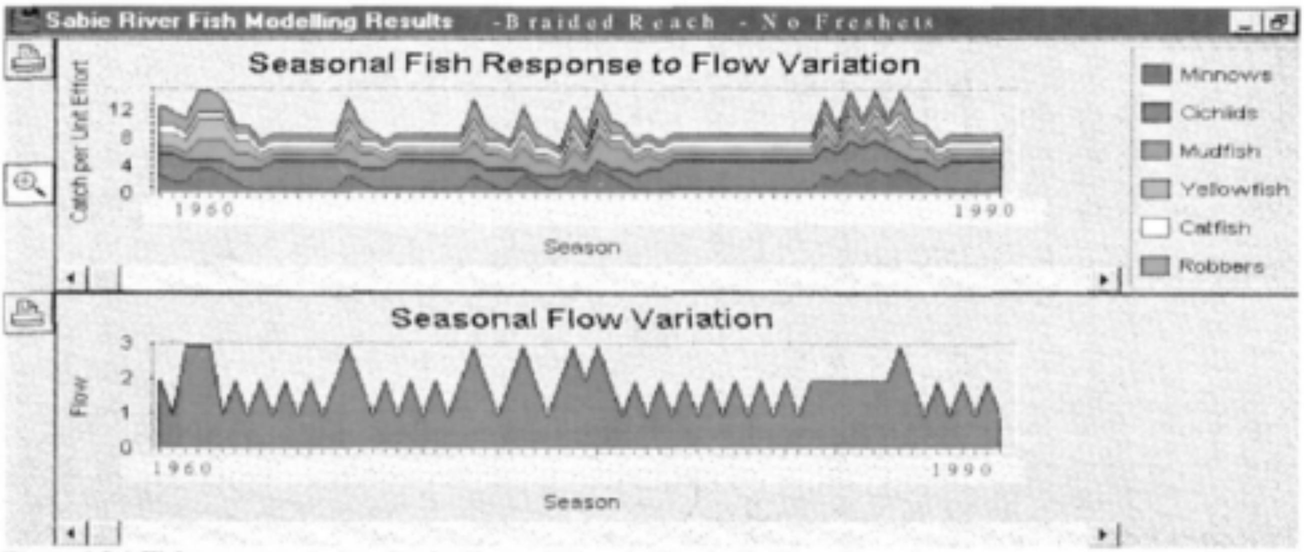


Figure6.3c) Fish response to "no freshet" conditions in the single-thread reach

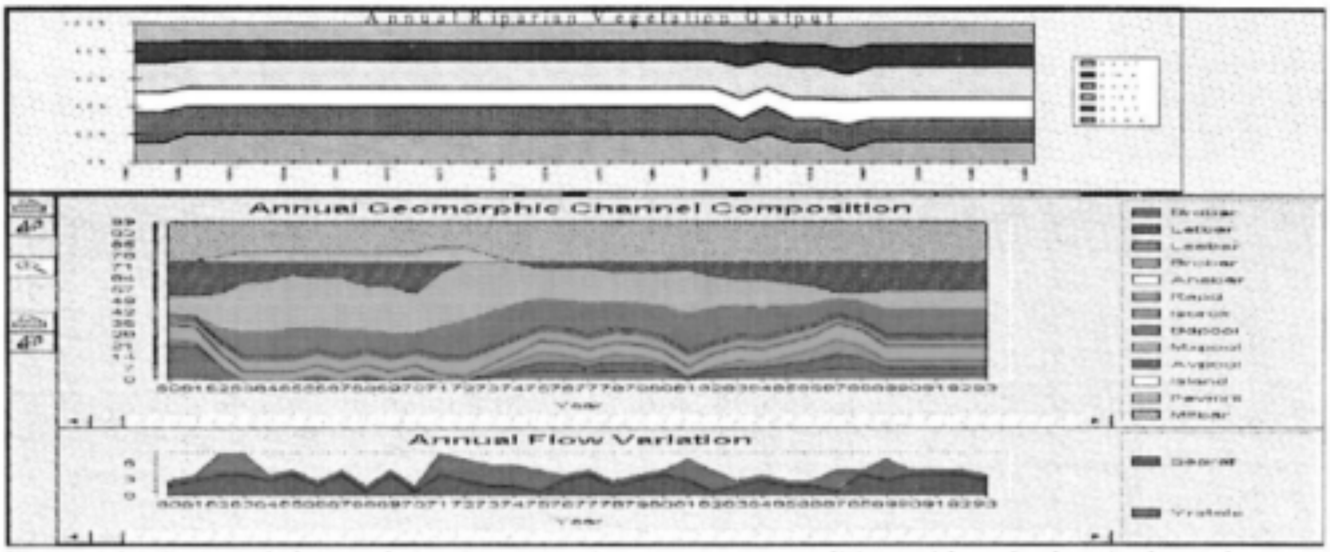


Figure 6.4a) Geomorphology and riparian vegetation response to conditions with no freshets in the pool rapid reach

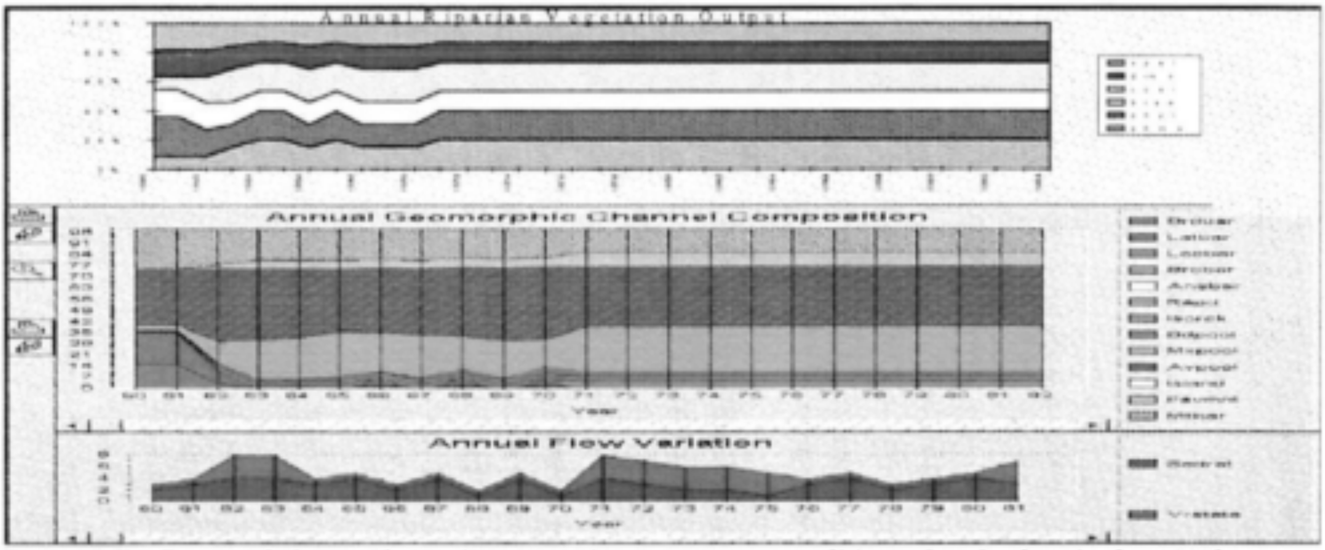


Figure 6.4b) Geomorphology and riparian vegetation response to conditions of no freshets in the mixed anastomosing reach

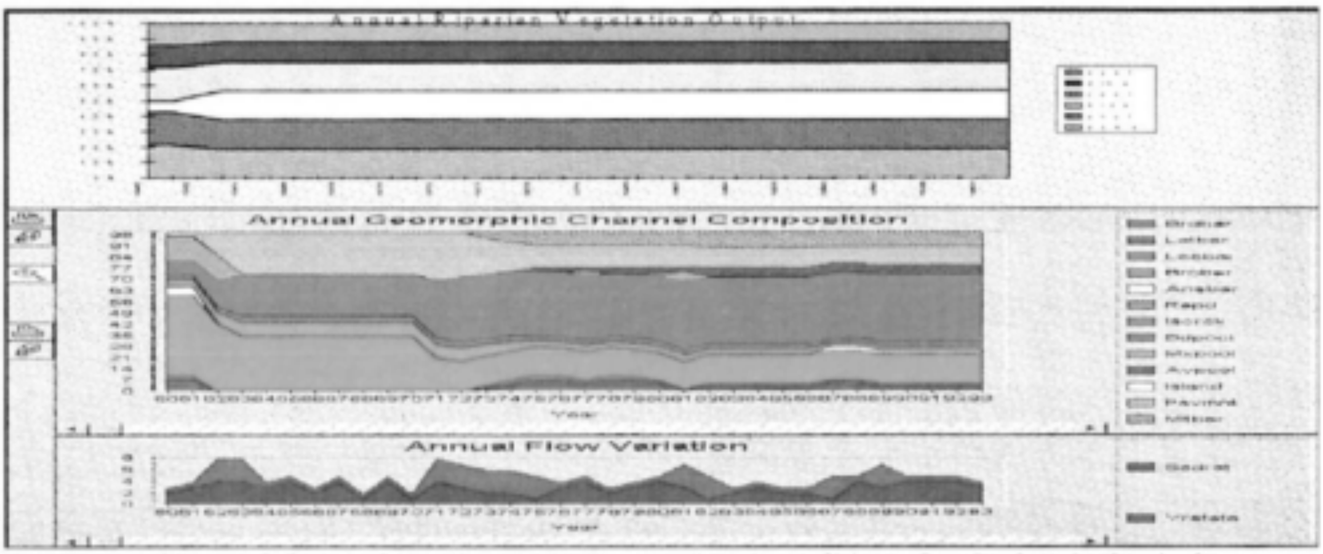


Figure 6.4c) Geomorphology and riparian vegetation response to conditions of no freshets in the single-thread reach

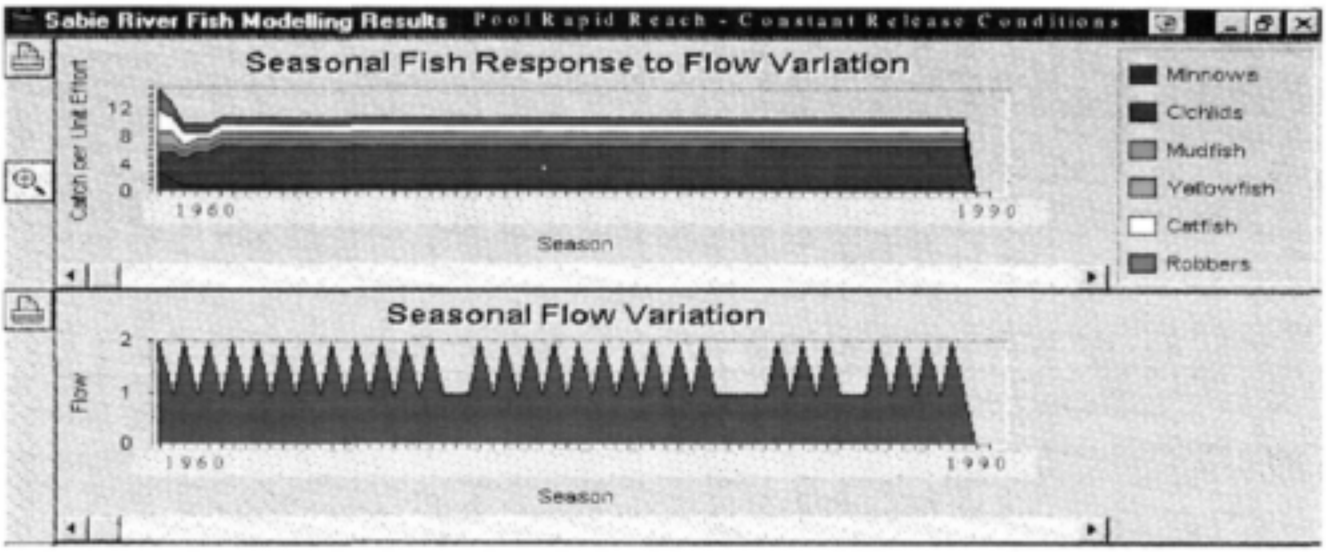


Figure 6.5a) Fish response to baseflow only conditions in the single thread reach

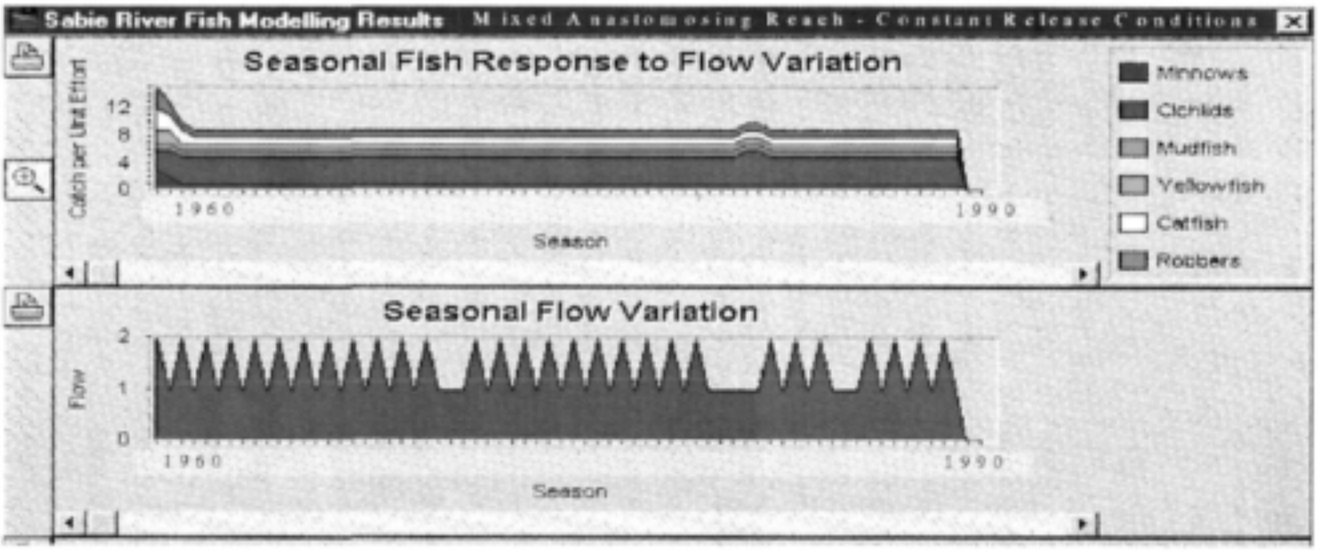


Figure 6.5b) Fish response to baseflow only conditions in the mixed anastomosing reach

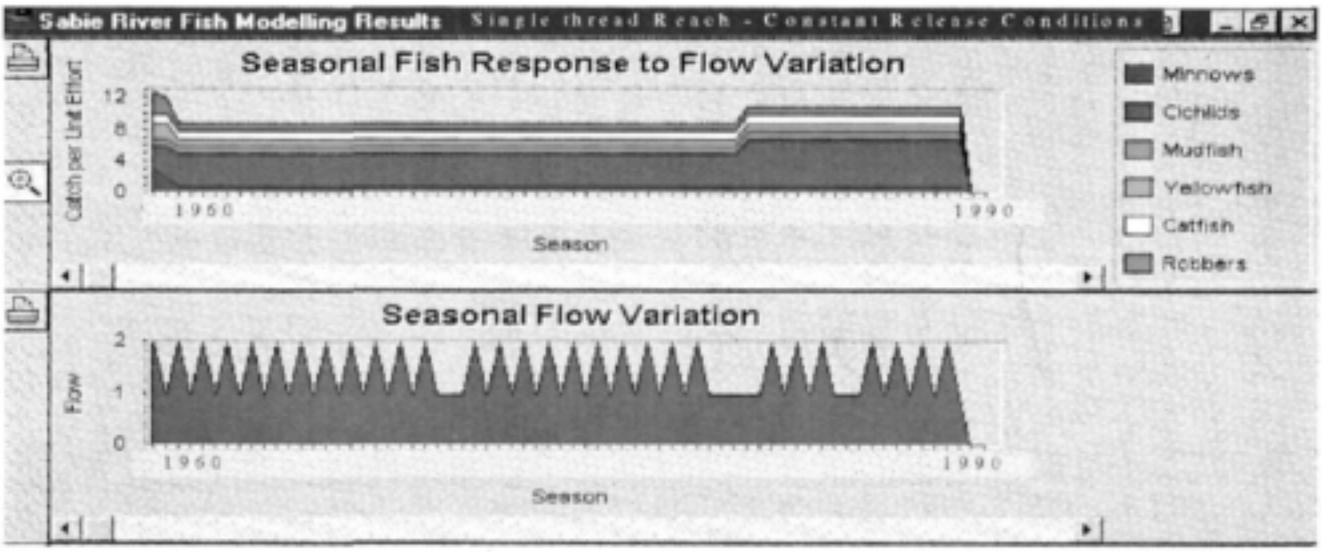


Figure 6.5c) Fish response to baseflow only conditions in the pool-rapid reach

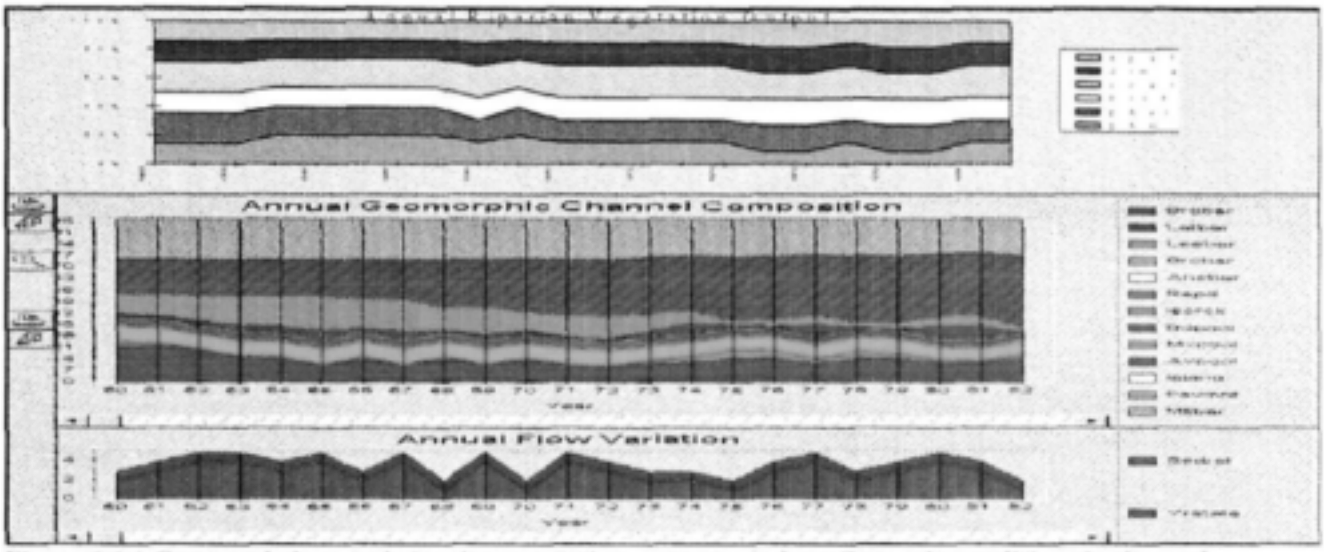


Figure 6.6a) Geomorphology and riparian vegetation response to base flow only conditions in the pool rapid reach

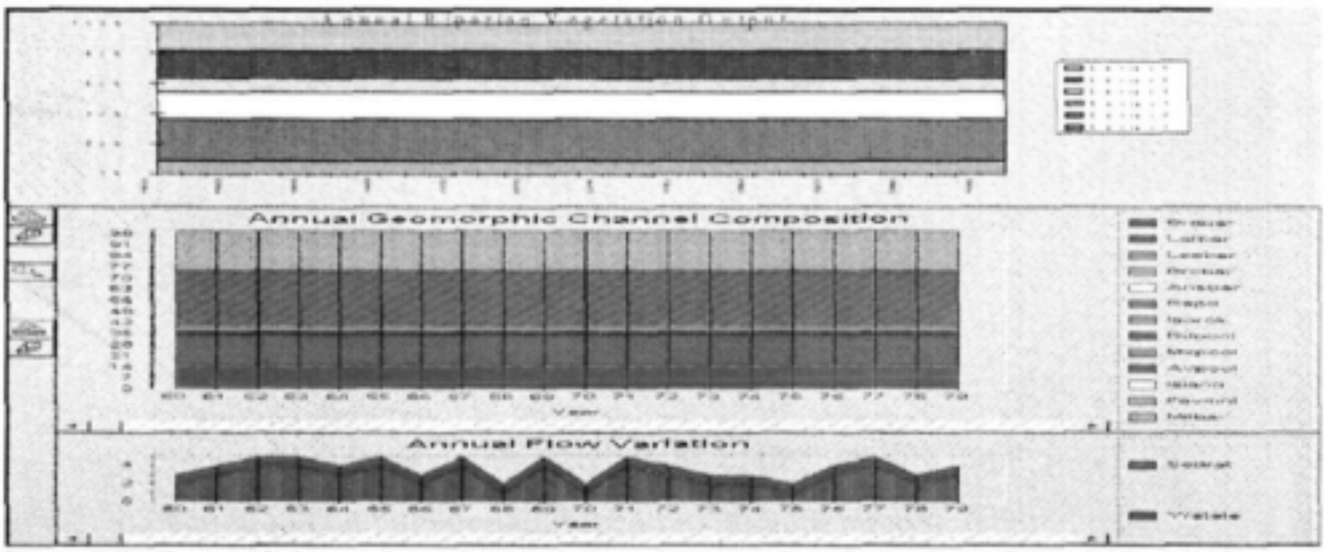


Figure 6.6b) Geomorphology and riparian vegetation response to base flow only conditions in the mixed anastomosing reach

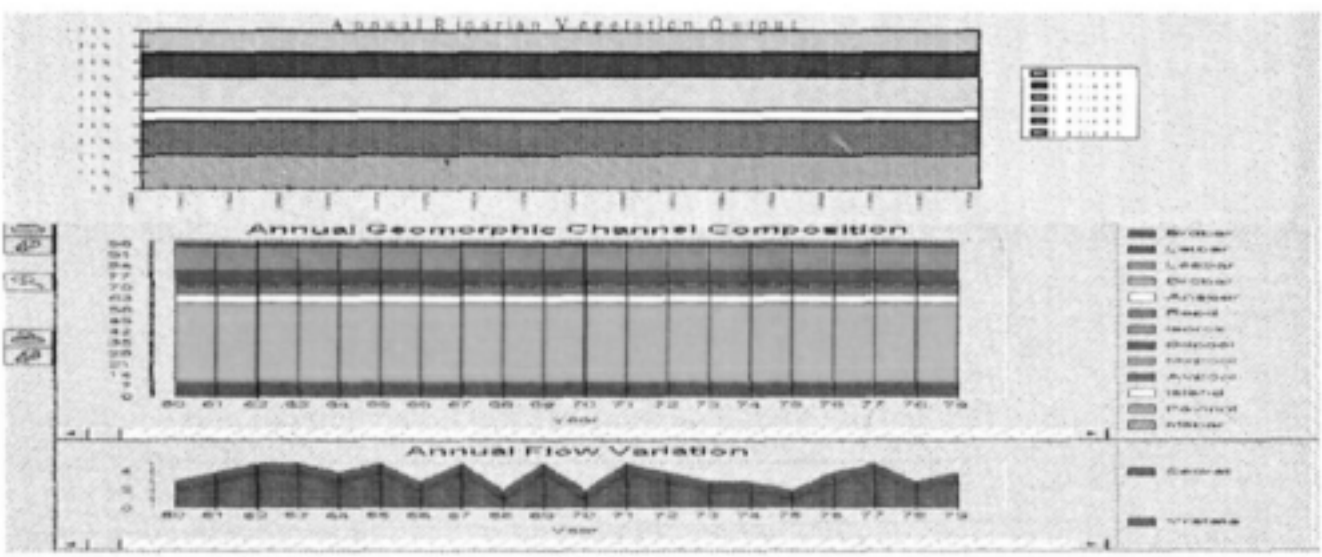


Figure 6.6c) Geomorphology and riparian vegetation response to base flow only conditions in the single thread reach

7 CONCLUSIONS, FUTURE MODEL REFINEMENTS AND FURTHER RESEARCH NEEDS

G.P.W. Jewitt, A.H.M. Görgens, J.A. Mackenzie, G. Heritage and D.C. Weeks

The project has been successful in achieving many of its aims and those of the KNPRRP. It has been successful in forging links between catchment hydrology, geomorphology and fish and riparian vegetation of the Sabie River, one of the aims identified by the project proposal. Furthermore, in terms of the KNPRRP, the modelling system provides a means of "predicting the response of systems to natural and anthropogenic factors affecting water supply" (Breen *et al.* 1994). A major and significant product of this project has been the development of expertise in integrative modelling of biotic and abiotic responses to changing catchment conditions in South Africa.

The models developed offered a preliminary tool to managers and scientists who may wish to explore the potential impacts of catchment changes on geomorphology, fish and riparian vegation of the Sabie River. The rules developed in the three models may be directly applicable to the Lowveld regions of the Sabie Catchment, including sections of the Sand River. Many of the rules will be applicable to the Lowveld regions of other rivers of the Kruger Park in their ability to predict a biotic response to similar abiotic conditions. In some of these rivers, the primary abiotic conditions to which the fish and riparian vegetation respond may not be temperature, flow variation and geomorphological composition of the channel, in particular in rivers where water quality problems are known to occur.

Some of the rules developed may be applicable to areas outside of the Lowveld regions of the KNP, however much testing would be necessary to establish this. However, far more transferable than the rules and models developed, is the **modelling methodology and expertise**. This development of QRBMs is possible wherever biotic responses to abiotic conditions are studied and have been identified. The level of resolution of the model developed will be dependent on the detail of the responses identified. The Sabie River and it's biota have been studied in more detail than most other rivers in South Africa, and the level of resolution of the input, output and rules developed in the modelling system reflect this. However, it is possible that far simpler models may be produced where less data are available, providing an expert is prepared to have a "mental model" expressed by way of a QRBM.

The models produced harness expert opinion pertaining to responses of the geomorphology, fish and riparian vegetation to variability of flow and sediment inputs. The state of captured expert knowledge in the field of geomorphology, fish and riparian vegetation ecology to these inputs is represented by the

QRBMs. Thus, many implicit assumptions have been made explicit. Model output is believed to be as accurate as the given expert opinion, with the advantage that it may now be relatively easily applied where an assessment of catchment development scenarios is required. The models are more accessible than the experts themselves; however, they are limited in their application to the knowledge captured by the rules.

The modelling system incorporates both "traditional" modelling techniques, in the form of the ACRU model and knowledge based systems. These have been integrated into a single modelling system forming part of the KNPRRP ICIS.

In addition to model development, a higher level goal of the BLINK project, was the development of an effective interdisciplinary project. The facilitation of successful interdisciplinary research is in effect, a form of resolution of a scale problem. It has been noted that higher levels of systems such as a river, are characterised by broad perspective and broad detail, while the lower levels have fine detail and narrow perspective. The focus of individual disciplines tends towards high detail levels of a system. ***The BLINK project builds on the belief that effective interdisciplinary research requires that participating individuals expand their vantage points toward levels which have broad perspective and relatively lower detail.*** In the BLINK project, the links between abiotic and biotic components required the movement of ecological, and to a lessor extent, geomorphological information to broader levels, where detail is obscured, but broad patterns were identifiable.

Various problems have been encountered in the project. The period of the project, i.e. one year, has been too short to fully explore and develop many of the new and innovative techniques utilised. Although the core groups established have been driven by a common goal, establishing fail-proof channels of communication amongst the scientists involved was at times difficult. This was exacerbated by the fact that members of the core groups were all housed in different organisations in different centres around the country and were all involved in other projects as well. The tragic death of Andrè van Niekerk in May 1996 deprived the project of an innovative geomorphologist at a critical stage of development. The assistance of George Heritage allowed for the eventual development of the geomorphology model and, subsequently, the riparian vegetation model.

These models were developed making extensive use of email. In the case of the geomorphology model, the core group was only able to meet once during the period of model development. Consequently, the geomorphology and riparian vegetation models have not moved beyond the prototype phase. They are useful assessment tools, but are still unstable and only moderate confidence may be expressed in the output from these models. Furthermore, confirmation of the results of these models is extremely difficult given the length of time required to observe geomorphic and riparian vegetation changes in the field. Consequently, space for time substitution techniques have been used to form the rules in these models and predictions made by the model have no directly observed basis for comparison.

In addition to the quantification of biotic responses to abiotic stimuli, many other benefits have been derived during the course of this project. These benefits include:

- the learning experience related to the explicit integration of hydrological, geomorphological and ecological information and the implicit integration of hydraulic information.
- new and different ways of using existing data and information.
- the development of new ideas and techniques.
- identification of areas where data are missing and new field work needed.
- confirmation of the importance of basic research and data collected in the field.
- confirmation of the importance of plausible conceptual models of processes to guide basic research and data collection.
- the development of expertise and understanding of the dynamics of multi-disciplinary interactions.
- development of new ways of thinking scientifically and conversing.
- making implicit assumptions more explicit.

In addition, use has been made of various recent technological innovations. These relate to methods of transferring information between model developer, modeller and user, and include:

- the extensive use of email as a communication tool between members of the core and workshop groups. The costs of regular physical meetings would have been prohibitive. However, email correspondence has limitations and the importance of workshop and group meetings has been explained in Chapter 1.3.
- development of new methods of displaying ecological information.
- the use of hypertext to explain the workings and output of the models.

The usefulness of these models needs to be assessed. It has been an interesting scientific exercise for many reasons. What uses, if any, do they have for management in their current form, and what is needed to make the models useful to managers? It is envisaged that the models will be used in an informed workshop environment where direct comparisons of the impact on fish for various flow regimes can be made. More specifically, discussion is needed regarding the usefulness of the information produced by this model. This could be beneficial in the interpretation of the results of the model output produced, such as the development of some form of integrity index to illustrate the level of disruption deemed "acceptable" to the fish groups concerned. However, the models do produce enough information for an ecologist to assess the acceptability of each of the flow scenarios simulated, and this form of interaction may in fact be preferable to the development of a computer generated suitability index.

7.1 FURTHER RESEARCH NEEDS

As mentioned previously, the limited period of the project has prevented the full exploration of many methods used in the development of these models. Although mentioned in the chapters pertaining to the models, these are listed here.

7.1.1 Hydrology

The hydrology rules developed use rather arbitrary definitions of freshets and flow indices and have been developed to fit the fish ecologist's perception of these. Hydrological input to the fish model would benefit by:

- characterisation of which flow level inundates fish breeding areas - thus allowing an ecological definition of a freshet to be built into the model rather than the present situation.
- further exploration of available hydrological data in order to refine the indexes developed for ecological classification of seasonal hydrology is necessary.

The generation of sediment from the hydrology model is largely untested - and in many ways untestable at scales finer than, say, $100km^2$. Refinement of the parameters used in the sediment generation routines of ACRU may follow the gathering of further data in this regard.

7.1.2 Geomorphology

The geomorphology model was primarily developed in its present form to provide input to the fish model. Input to the riparian vegetation model was a secondary consideration. This has created some inconsistency in the input to the riparian vegetation model as the geomorphological units produced as output from the geomorphology model are not always consistent with the desired input needs of the riparian vegetation model. This is a result of more attention being paid to the dynamics and make up of the geomorphic units found in the active/perennial river channel rather than those on the macro-channel bank.

Furthermore, the limited period of model development has resulted in a system that has not moved much beyond the prototype phase and produces unrealistic results under some circumstances. As noted in Chapter 3.6, the geomorphological model could be improved in the following ways:

- Continued testing and refinement of the operating matrices based on simulations of each of the 40 channel type segments on the Sabie River.
- Improved correlation between the morphologic unit and fish habitat composition through field data collection.
- An investigation of the dynamics of sediment erosion and deposition at each of the 40 channel type sections on the Sabie River utilising data already available.
- linking of up- and downstream channels and assessment of sediment movement between these.

7.13 Fish Model

The fish model has been the focus of much of the work undertaken in this project. Consequently, the assumptions made have been better explored and the model better tested than the geomorphology and riparian vegetation models.

Further development of the model should include;

- further exploration of the approach chosen to provide geomorphic input to the fish model.
- further mapping of geomorphological units in the field is needed in this regard.
- further exploration of the nature of FIN and confidence levels associated with it.

This may result in;

- a finer resolution of input of geomorphic information, i.e. utilise a FIN value for each time step of the model rather than a value for each reach (Figures 4.7 and 4.12).

A finer resolution of hydrological input to the model will decrease the sensitivity of the the model to the three input states currently used. A finer resolution of the ecological input should also be explored.

7.1.4 Riparian Vegetation Model

The riparian vegetation model is totally dependant upon the accuracy of the output from the geomorphology model for its own predictions. Thus, it suffers implicitly from the shortcomings of the geomorphology model and will benefit from any improvements. In particular, modifications to the geomorphology model to produce output of direct relevance to riparian vegetation will be a major improvement. Further improvements may include:

- the incorporation of direct hydrological influence.

- the inclusion of an explicit temporal scale for vegetation dynamics
- the inclusion of finer-scale vegetation dynamics such as regeneration and mortality. This will improve the resolution of vegetation responses and allow the model to react more rapidly.
- the incorporation of a geological influence.

7.1.5 Other Problem Areas

Further model development may result in more rules and a correspondingly more complex rule base. It is likely that future versions of this model will require the utilisation of an "expert system shell" which will enable the rules to be separated from the model code, and thus, stored more efficiently, as well as allowing relatively easy updating and maintenance of the rule base.

Despite the intention of making the modelling system as easy to use and as accessible as possible, the models have not been widely used and tested even within the KNPRRP. This is a result of many reasons, many of which stem both from the reluctance of many of the programme participants to engage computing systems and the lack of adequate computing facilities to allow them to do so. Consequently, the models have not been adequately tested and refinements that could stem from this process have not been initiated.

Water quality is recognised as a critical component missing from this modelling system. The lack of adequate information in this regard and the short time period of the project have precluded its inclusion. It is necessary that this problem is addresses by further developments, especially if the models are transferred to other catchments where water quality problems are prevalent.

7.2FINAL RECOMMENDATIONS

The following recommendations are considered the most important future research needs pertaining to further refinement and development of these models.

1. Intensive mapping of geomorphological units in the field in order to further explore the relationship between geomorphological units and fish habitat.
2. Further exploration of the idea that sediment substrate is an adequate indicator hydraulic conditions.
3. Exploration of the nature and confidence limits of FIN in these and other similar situations.
4. Incorporation of direct hydrological input into the riparian vegetation model.
5. Improved resolution of geomorphology output and subsequent improved input to the riparian vegetation model.

6. Further refinement and testing of the matrices which form the basis of the geomorphology model.
7. Linking of upstream and downstream reaches to allow for movement of sediment through the reach under consideration in the geomorphology model.
8. Refinement of hydrological input parameters to the fish model.
9. Inclusion of biotic responses to critical water quality parameters.

8 REFERENCES

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 Symposium on Spatial and Temporal Scaling of Ecological Processes in Freshwater Systems (1995) Hosted by the CRC for Freshwater Ecology, Monash University, Melbourne, Australia.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., A.S. Donigian, Jr. and R.C. Johanson. 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

Bloschl G. and Sivapalan M., (1995) Scale Issues in Hydrological Modelling: A Review *Hydrological Processes 9: 251-290*

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, USA.

Breen, C., Quinn, N.W. and Deacon, A. (1994) A description of the Kruger Park Rivers Research Programme (Second Phase) Collaborative report avail. Kruger National Park Rivers Research Programme, Pretoria, RSA.

Broadhurst, L. J., Heritage, G. L., van Niekerk, A. W. and James, C. S. (1995) Translating discharge into local hydraulic conditions on the Sabie River, an assessment of channel roughness, In

Proceedings, Seventh South African National Hydrology Symposium Rhodes University, Grahamstown, South Africa

Brookes. A. (1992) River channel change. In: River flows and channel forms: selected extracts from the rivers handbook, (Eds: G. Petts and P Calow), Blackwell science, Oxford. pp221-242.

Carter, A. J. (1995) A Markovian Approach to Investigating Landscape Change in the Kruger National Park Rivers. PhD Thesis. University of the Witwatersrand. Johannesburg.

Carter, A.J. & Rogers, K.H. (1995) A Markovian approach to investigating landscape change in the Kruger National Park. CWE Report 2/1995.

Chang, H. H. (1982) mathematical model for erodible channels. American Society of Civil Engineers, Journal of the Hydraulics Division, 108(HY5), 678-689.

Cheshire, P. E. (1996) Geology and geomorphology of the Sabie River in the Kruger National Park and its catchment area, *Water Research Commission Report K5/474/0/1 vol3*. Water Research Commission, Pretoria, South Africa

Chunnet, Fourie and Partners (1990) Water Resources Planning of the Sabie River Catchment. *Department of Water Affairs Report No. P.X.300/00/0490,* Vols 1 to 10.

Cobban, D. Dent, M.C., Horn, M., Van Rensberg, 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 Univ., Grahamstown , RSA

Cochnauer, T. (1976) Instream flow techniques for large rivers, in *Instream Flow Needs* (eds J.F. Orsborn and C Allman), pp 387-99, vol. II, American Fisheries Society, Bethesda, Maryland.

Cox, D.J. (1990) The art of scientific visualization. *Academic Computing* 46: 20-56 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. *Proc. ESRI Users Conference 1995*. http://www.esri.com/users/

Davis, A.M. (1992) Operational prototyping: A new development approach. IEEE Software 9 (5):70-79

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. (1996) Personal Communication, National Parks Board, Kruger National Park, RSA.

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.

Doolan J. and Fairweather, P. (1995) Linking the different spatial and temporal scales of research and management. Symposium on Spatial and Temporal Scaling of Ecological Processes in Freshwater Systems. Dec 6-8, 1995. Monash University, Clayton, Australia.

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

Fryer, G. (1987) Quamtitative and qualitative: numbers and reality in the study of living organisms. *Freshwater Ecology* 17: 177-189

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

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

Gore, J.A.and Nestler, J.M. (1988) Instream flow studies in perspective. *Regulated Rivers Research and Management* 2:93-101

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, Australia.

Greyling, A.J.(1996) Personal Communication. Ninham Shand Inc. Cape Town., RSA

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 Dision of Fisheries, Canberra, Australia.
http://www.ml.csiro.au/~bradford/public/GHAbstract.html

Hayes-Roth, F., Waterman, D.A. and Lenat, D.B. (Eds) (1983) *Building Expert Systems*. Addison Wesley, Reading, USA.

Heritage, G. L. and van Niekerk, A. W. (1994) geomorphological response of the Sabie River to changing flow and sediment regimes, In *Proceedings 50 Years of Water Engineering in South Africa SAICE*, Johannesburg 389-402

Heritage, G.L., van Niekerk, A.W. & 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 & Cote, Y. (eds), Proceedings of the Second IAHR Symposium on Habitat Hydraulics, Ecohydraulics 2000, pp A355-A366.

Holling, C.S. (1976) Adaptive Environmental Assessment and Management Chichester. J. Whiley and Sons.

Hoppe, R.A. (1975) Minimum streamflows for fish. Paper distributed at soils hydrology workshop, USFS, Montanna State University, 26-30 January 1976. Bozeman, Montana

Hughes, D A and Sami, K (1994) A semi-distributed, variable time interval model of catchment hydrology - structure and parameter estimation procedures. J. Hydrol., 155, 265-291.

Hupp, C.R. & W.R. Osterkamp (1985) Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. **Ecol**. 66(3), 670-681.

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/

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 Proc. Of The 3rd Modsim Conference Dec. 4-6, Univ. Of Newcastle, Newcastle, Australia

Jowett, I.G. (1989) *RHYHABSIM computer manual*, Freshwater Fisheries Centre, Riccarton, New Zealand.

Kale, V. S., Baker, V. R. and Mishra, S. (1996) Multi-channel patterns of bedrock rivers: An example from the central Narmada basin, India. *Catena*, 26, 85-98.

King, J.M. Schael, D and Tharme, R.E., (1996) Unpublished discussion document to the KNPRRP, Abiotic-Biotic Links project, KNPRRP, Pretoria, RSA.

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: *Proc. Sixth South African National Hydrological Symposium*. 8-10 Sept., 1993, Univ. of Natal, Pietermaritzburg, RSA.

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. Water Research Commission report 295/1/94, Pretoria, RSA..

King, J.M. Personal Communication, Freshwater Research Unit, University of Cape Town, RSA.

Klemes 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.

Krishnappan B G, (1981), *MOBED: Unsteady, non-uniform, mobile boundary flow model*, Users' Manual, National Water Research Institute, Burlington, Ontario.

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 framweowrk for multidisciplinary research. Unpublished paper. USGS, Denver, USA.

Levin, S.A. (1992) The problem of pattern and scale in ecology. *Ecology,* 73 (6): 1943-1967.

Loehle, C. (1987) Applying artificial intelligence techniques to ecological modeling. *Ecological Modelling* 38: 191-212.

Loh, D.K. and Rykiel, E.J. (1992) Integrating resource management systems: coupling expert systems with data-base management and geographic information systems. *Environmental Mgmt.*, 16: 167-177, 1992.

Loucks, D.P., Kindler, J. and Fedra, K. (1985) Interactive water resources modelling 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

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 SpatialModelling. http://kabir.umd.edu/SMP/ecohpc.html

Meentemeyer V., (1989) Geographical perspectives of space, time and scale *Landscape Ecology 3:(3/4)*

Milhous, R.T., D.L. Wagner and T.J. Waddle, (1981) *Users Guide to Physical Habitat Simulation System, FWS/OBS-81/43,* US Fish and Wildlife Service, Office of Biological Services.

Moon B.P., van Niekerk, A.W., Heritage, G.L., Rogers, K.H. & James, C.S. (In press) A geomorphological approach to the management of rivers in the Kruger National Park: the case of the Sabie River. *Transactions of the Institute of British Geographers*.

Nicolson, C.R. and James, C.S (1995) A qualitative approach to river process modeling In *Proceedings, Seventh South African National Hydrology Symposium* Rhodes University, Grahamstown, South Africa.

Norberg, J. and Elmgrin, G. (1996) Scale Dependencies on ecological process and pattern. http://www.ecology.su.se/norfa.htm

O'Keeffe , J.H. and Davies, B.R. (1991) Conservation and management of the rivers of the Kruger National Park: suggested methods for calculating instream flow needs. *Aquatic Cons: Marine and Freshwater Ecosystems*, 1:55-71, 1991.

Onstad, D.W. (1988) Population dynamics theory: The roles of analytical, simulation and supercomputer models. *Ecological Modeling* 43: 111-124.

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

Orth, D.J., (1987) Ecological considerations in the development of and application of instream flow habitats. *Regulated Rivers: research and managment* 1: 171-181.

Osborne, L.S., M.J. Wiley and R.W. Larimore, (1988) Assessment of the water surface profile model: accuracy of predicted instream habitat conditions in low gradient warmwater streams. *Regulated Rivers*, 2, 619-31.

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, USA.

Pattern, B.C. (1994) Ecological systems engineering: toward integrated management of natural and human complexity in the ecosphere. *Ecological Modelling* 75/76: 653-665.

Pollard, S.R, Weeks, D.C and Fourie, A. (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 2: Effects of the 1992 doroght on the fish and macro-invertebrate fauna WRC report294/2/96 Water Research Commission, Pretoria, South Africa.

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, USA, 1993.

Rodriguez-Iturbe and Gupta (1983) Special Issue "Scale Problems in Hydrology". *Jnl. Hydrology* 65: 400pp.

Rooseboom, A., Verster, E., Zietsman, H. L. and Lotriet, H. H. (1992) The Development of the New Sediment Yield Map of southern Africa, *Water Research Commission Report* No. 297/2/92.

Wadeson, R. A. and Rowntree, K. M. (1996) A hierarchical geomorphological model for the classification of South African river systems. In: Classification of rivers and environmental health indicators (Ed. M. C. Uys), Water Research Commission Report No. TT 63/94, pp49-67.

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 *Proc. Fourth South African National Hydrological Symposium* 20-22 Nov., 1989, Univ. of Pretoria, Pretoria, RSA.

Schael, D. (1996) Personal Communication, Freshwater Research Unit, University of Cape Town, RSA.

Schrader-Frechette, K.S. and McCoy, E.D. (1994) What ecology can do for environmental management. *Jnl. Environmental Mgmt.*, 41, 293-304, 1994.

Schulze, R.E.(1995) *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system.* Dept. Agric. Eng., Univ. of Natal, Pietermaritzburg, RSA.

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. Dept. Agric. Eng., Univ. of Natal, Pietermaritzburg, RSA.

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. Mgmt.*, 7(2&3), 1-13.

Starfield, A.M., Farm, B.P. and Taylor, R.H. (1989) A rule based ecological model for the management of an estuarine lake. *Ecological Modelling*, 46, 107-119.

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.

Tennant, D. L. (1976) , Instream flow requirements for fish, wildlife, recreation and related environmental resources. Fisheries, 1, 6-10.

Thiessen, E.M. and Loucks, D.P. (1992) Computer assisted negotiation of multiobjective water resources conflicts. *Water Resources Bull.* 28, 163-177.

Thoms, M.L., James, C.S., Moon, B.P. & 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. 19pp.

Tyson, P. D. (1987) *Climatic change and variability in southern Africa* Oxford University Press, Cape Town

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 Niekerk, A.W. and Heritage, G.L. (1994) Geomorphology of the Sabie River: Overview and classification. CWE Report No. 2/93, Univ. of the Witwatersrand, Johannesburg, RSA, 1993.

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. (1995) 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.

Vaskinn, K. A. (1985) , Fysisk beskrivende vassdragsdodell. Report A1, Norsk Hydroteknisk Laboratorium, Trondheim, Norway.

Wadeson, R.A. Geomorphological approach to instream flow environment. Sth. Afr. *Jnl. Aquatic Sci.*, 20, 38-61, 1994.

Walker, D.H. and Johnson, A.K.L. (1995) A toolkit approach to to developing decision support systems for integrated catchment management. In Proc. Of the 3rd MODSIM Conference Dec. 4-6, Univ. of Newcastle, Newcastle, Australia.

Waltho, N. and Kolasa, J (1994) Organization of instabilities in multispecies systems: a test of hierarchy theory. Proc. Natl. Acad. Sci. 91:1682-1685.

Warwick, C.J., Mumford, J.D. and Norton, G.A. (1993) Environmental management expert systems. *Jnl. of Environmental Mgmt.*, 39, 251-270.

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 report294/1/96 Water Research Commission, Pretoria, South Africa.

White, R. G. (1976) , A methodology for recommending stream resource maintenance flows for large rivers. In: Proc. of the Symp. and Spec. Conf. on Instream Flow Needs. (Eds: J. F. Orsbourne and C. H. Allman), Vol. II, pp 367-386, Amer. Fish Soc., Bethesda, Maryland.

Wiens J. A., (1989) Spatial scaling in ecology *Functional Ecology 3:( ) 385-397*

Wiens, J.A. (1997) Scientific Responsibility and Responsible Ecology, *Conservation Ecology 1:1*

Wilde, W.D. Australian expert systems for natural systems.(1994) *AI Applications in Nat. Res. Mgmt.*, 8, 3-12.

Wohl, E. E. (1992) Bedrock benches and boulder bars: Floods in the Burdekin Gorge of Australia. *Geol. Soc. Am. Bull.*, 104, 770-778.

Young, W.J. and Davis, J.R. (1995) Proposed environmental flows decision support system. In Proc. Of the 3rd MODSIM Conference Dec. 4-6, Univ. of Newcastle, Newcastle, Australia.

APPENDIX 1 - The October Workshop

PURPOSE OF THE WORKSHOP

The overall goal of the workshop was to investigate ways of linking predictions of changes in fish communities in the Sabie-Sand to predictions of geomorphological change. Goals which were to contribute to this included;

- reaching a shared understanding of the potential and limitations of the information on the geomorphology and fish communities in the Sabie system.

- reaching a shared understanding of the predictive potential and resolution of the two projects, and the scales at which these operate.

- to try to formulate some rules which can be incorporated into a rule-based system, which will eventually form a predictive model linking changes in flow patterns with changes in channel morphology, habitat availability and fish communities.

PARTICIPANTS

Prof. Jay O'Keeffe, Prof. Andre Gorgens, Prof. Kevin Rogers, Prof. Jackie King, Dr. George Heritage, Andre van Niekerk, Dez Weekes, Graham Jewitt, Craig Nicolson, Reinier DeVos, Mike Horn

WORKSHOP PROCEEDINGS

The workshop began with an overview of the KNPRRP, presented by Andre Gorgens. This focused on the necessary interactions between the various participants in order to fulfil many of the expectations of Phase II and the role of the DSS sub-programme in utilising information arising from these interactions.

This was followed by Graham Jewitt presenting an introduction to knowledge based predictive systems and the reasons why these could be useful in the KNPRRP. These were focused around the idea that relationships between abiotic and biotic components of an ecological system are understood in a rough and qualitative manner, rather than in a detailed and quantitative sense;

- In "traditional" models, relationships between components are largely mathematical.
- In knowledge based models, they are largely logical.

- Typically knowledge based systems have been applied to problems where;

- much of the information needed to solve the problem is heuristic (i.e. based on rules of thumb) rather than algebraic.
- information is likely to change either because of a need to explore alternative possibilities or because fresh information becomes available;
- this information is incomplete and uncertain;
- explanation of results/advice are required. i.e. not a "black box" .

These points described many of the problems facing researchers in the KNPRRP who are expected to produce tools which describe catchment biotic responses to abiotic variations.

Presentation of the fish and geomorphological "knowledge bases" followed. Dez Weekes of the IWR described collection and analysis of fish in the Lowveld rivers. As a result of this work, fairly detailed information on the distribution of fish in the Sabie-Sand exists, as well as detailed measurements of their habitat requirements in terms of flow depth, velocity, substrate and cover. The project extended through and beyond a major drought, so knowledge also exists on the changes in fish communities caused by persistent low flows. Tables showing general qualitative predictions of biotic response to different flow scenarios were presented. Several other results of interest were presented and Dez explained further his understanding of fish assemblage responses to changes in available habitat and to medium term hydrological variability.

George Heritage and Andre van Niekerk explained the approach followed in order to create a conceptual model of geomorphological change of the Sabie River. Their research strategy followed a stepped approach with a progression from description and structuring through process studies to quantitative modelling. The approach involved the detailed description of the river and an investigation of short-term changes in the geomorphology. These steps facilitated the classification of the river into ecologically relevant sections. Secondly, the dominant control factors on channel morphology were isolated from the many that are operating in the catchments. Combining the knowledge gained from these two exercises, allowed the development of a conceptual model of geomorphological change for the Sabie River. This model has been transformed into a model, using the data collected, allowing changes in the pattern of sedimentation to be predicted as a result of current and potential future flow and sediment regime.

Thus, the model provides a useful tool to enable the prediction of potential geomorphological change, at the scale of the channel type, in the Sabie in response to different flow scenarios on the Sabie and other rivers.

Discussion focused on making an estimate of available fish habitat according to the geomorphological classification of particular channel types. All discussions were based on the assumption that any model developed would be operating at the "representative reaches" in the Sabie River as identified by the CWE. It became apparent that making predictions of available fish habitat according to the channel type represented in the representative reaches would require detailed information not readily available. Thus, the focus shifted to making qualitative prediction of fish assemblages in May of each year according to the channel type. Andre and George provided broad descriptions of the geomorphological characteristics of the channel types. Based on these descriptions, fish assemblages were estimated by Dez Weekes for a variety of channel types depending on whether the previous year was affected by drought, was normal or was exceptionally wet. The May fish assemblage was selected as it provides the best "snapshot" or indicator of the fish community response to the previous years hydrology. Thus, the "skeleton" model was developed, where a prediction of a fish community assemblages could be made according to the geomorphic template (channel type) and the catchment hydrological responses.

The workshop closed with agreement amongst the participants that the workshop was a success. A "skeleton" of a model which formed a link between catchment abiotic and biotic responses had been formed. It was agreed that the idea of using qualitative or knowledge based predictions was useful and that attempts should be made to extend this approach beyond fish predictions to other catchment biotic components. The importance of the detailed research projects by CWE and IWR, which provided the knowledge base and enabled these links to be made was acknowledged by all participants.

FOLLOW UP

Since October, several follow up meetings have been held. This has resulted in several refinements to the "skeleton" model being made, particularly in the estimation of available fish habitat according to a changing geomorphology. Further refinements include more detailed predictions of fish response resulting from flow variations. A prototype predictive model of fish response to changing catchment scenarios will be presented on April 16th.

Appendix II - List of Participants

					Phone	Fax	Email
Dr	Harry	Biggs	KNP	013	7355611	65467	biggs@aqua.ccwr.ac.za
Prof	Charles	Breen	INR	0331	460818	460895	breen@inr.unp.ac.za
Dr	Andrew	Deacon	KNP	013	7355611	65467	
Dr	Mark	Dent	CCWR	0331	2605177	61896	dent@aqua.ccwr.ac.za
Prof	Andre	Gorgens	US	021	8084356	8084361	agorgens@maties.sun.ac.za
Dr	George	Heritage	Newcastle	0944191	2226350	2225421	george.heritage@newcastle.ac.uk
Mr	Mike	Horn	CCWR	0331	2605174	61896	horn@aqua.ccwr.ac.za
Prof	Chris	James	Wits	011			csj@civen.civil.wits.ac.za
Mr	Graham	Jewitt	US	021	8084365	8084361	jewitt@aqua.ccwr.ac.za
Dr	Jackie	King	UCT	021	6503626		jking@botzoo.uct.ac.za
Mr	James	Mackenzie	Wits	011	7162218		james@gecko.biol.wits.ac.za
Prof	Jay	O'Keeffe	RU	0461	22428	24377	jay@iwr.ru.ac.za
Ms	Sharon	Pollard	Wits Rural	01528	33991		sharonp@ilink.nis.za
Prof	Kevin	Rogers	Wits	011	7162360	4031429	kevinr@gecko.biol.wits.ac.za
Ms	Denise	Schael	UCT	021	6503633		dschael@botzoo.uct.ac.za
Mr	Andre	Van Niekerk	Wits	011	7162555		niekerk@civen.civil.wits.ac.za
Mr	Dez	Weeks	RU	0461	22428	24377	dez@iwr.ru.ac.za
Ms	Gayle	Rolando	FRD	012	4814103		gayle@frd.ac.za

APPENDIX III - Geomorphology Rules

MORPHOLOGIC CHANGE RULES FOR THE POOL-RAPID GENERIC CHANNEL TYPE:

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BRAIDBAR = BRAIDBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LAT/POINTBAR = LAT/POINTBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LEEBAR = LEEBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK COREBAR = BEDROCK CORE BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ANASTOMOSING BAR = ANASTOMOSING BAR + 1%

REASON:

AUTHOR:

George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

RAPID = RAPID + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ISOLATED ROCK = ISOLATED ROCK + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK POOL = BEDROCK POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MIXED POOL = MIXED POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ALLUVIAL POOL = ALLUVIAL POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:

Sediment Ratio = HIGH and Annual Flow = BASFLOW

ISLAND = ISLAND + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

PAVEMENT = PAVEMENT + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MACRO-CHANNEL LATERAL BAR = MACRO-CHANNEL LATERAL BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

MORPHOLOGIC CHANGE RULES FOR THE BRAIDED/SINGLE THREAD GENERIC CHANNEL TYPE:

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BRAIDBAR = BRAIDBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LAT/POINTBAR = LAT/POINTBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LEEBAR = LEEBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK COREBAR = BEDROCK CORE BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ANASTOMOSING BAR = ANASTOMOSING BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

RAPID = RAPID + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ISOLATED ROCK = ISOLATED ROCK + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK POOL = BEDROCK POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MIXED POOL = MIXED POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ALLUVIAL POOL = ALLUVIAL POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ISLAND = ISLAND + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

PAVEMENT = PAVEMENT + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MACRO-CHANNEL LATERAL BAR = MACRO-CHANNEL LATERAL BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

MORPHOLOGIC CHANGE RULES FOR THE ANASTOMOSING GENERIC CHANNEL TYPE:

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BRAIDBAR = BRAIDBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LAT/POINTBAR = LAT/POINTBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

LEEBAR = LEEBAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK COREBAR = BEDROCK CORE BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ANASTOMOSING BAR = ANASTOMOSING BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

RAPID = RAPID + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ISOLATED ROCK = ISOLATED ROCK + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

BEDROCK POOL = BEDROCK POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MIXED POOL = MIXED POOL + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

ALLUVIAL POOL = ALLUVIAL POOL + 1%

REASON:

AUTHOR:
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AUTHOR:
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RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

PAVEMENT = PAVEMENT + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

RULE:
Sediment Ratio = HIGH and Annual Flow = BASFLOW

MACRO-CHANNEL LATERAL BAR = MACRO-CHANNEL LATERAL BAR + 1%

REASON:

AUTHOR:
George Heritage & Andre vanNiekerk.

APPENDIX IV - Worked FIN calculation for *Barbus viviparus* for the generic pool/rapid reach.

CI codes	Habitat Preference	Habitat Occurrence	Habitat Quality
10	0.47	0.36	0.17
11	0.24	1.00	0.24
12	0.00	0.12	0.00
13	0.00	0.00	0.00
14	0.00	0.02	0.00
15	0.20	0.20	0.04
20	0.20	0.00	0.00
21	0.49	0.15	0.07
22	0.00	0.00	0.00
23	0.00	0.00	0.00
24	0.00	0.00	0.00
25	0.52	0.00	0.00
30	0.00	0.00	0.00
31	0.10	0.00	0.00
32	0.16	0.13	0.02
33	0.53	0.01	0.00
34	0.85	0.06	0.05
35	0.47	0.00	0.00
40	0.08	0.00	0.00
41	0.00	0.43	0.00
42	1.00	0.00	0.00
43	0.30	0.00	0.00
44	0.52	0.10	0.05
45	0.17	0.03	0.01
50	0.32	0.00	0.00
51	0.41	0.05	0.02
52	0.31	0.04	0.01
53	0.26	0.04	0.01
54	0.53	0.08	0.04
55	0.48	0.11	0.05
FIN is the sum of Habitat Quality			0.79

* Both Habitat preference and occurrence data are normalised.

Calculating FIN

The above table sets out actual values used in the calculation of FIN for *Barbus viviparus* in the pool/rapid generic reach type.

Channel Index codes (CI codes) define the available categories (Tab. 4.5). Habitat preference values derive from Suitability Index (SI) Histograms as prepared for defined, ecologically important, Lowveld species (Fig 4.7c). Habitat occurrence is measured from the breakdown of generic reach types into unique CI categories. Habitat occurrence is the measure of CI expected in the target reach. FIN is simply the sum of the products of habitat preference and habitat occurrence, for each unique CI code (Fig 1). This is calculated for each species for each generic reach type independently.

Because FIN is calculated from normalised values of both habitat suitability and occurrence, it is effectively unitless. A single FIN value has no meaning on its own, its only meaning is in relation to other FIN values. FIN values are calculated for each species independently. FIN values for those fish grouped are simply species FIN averages grouped.

$$\mathbf{FIN} = \sum_{\mathbf{CI=1}}^{\mathbf{n}} (\textbf{habitat pref . habitat occ})$$

Figure 1: Simple FIN formula

APPENDIX V Rules for the Fish Model

100 - Series of Rules for Minnows

RULE 101

IF the wet season is dry

THEN Minnow numbers decrease by one level (state)

Author: Dez Weeks

Explanation

Both the reduction or absence of freshettes and the reduction of inundated marginal vegetation, reduces the breeding potential and success of minnows.

RULE 102

IF the wet season is normal

THEN Minnow numbers increase by one level (state)

Author: Dez Weeks

Explanation

Occasional freshettes are characteristic of normal wet season flows. These flows both stimulate serial spawning minnows and provide access to marginal nursery habitats used by many minnow species.

RULE 103

IF the wet season is wet

THEN Minnow numbers increase by two levels (state)

Author Dez Weeks

Explanation

Freshettes occur regularly, and some large flow events are recorded. Minnows make use of the greatly increased inundated shallow water habitats and nutrient inputs as well as the regular spawning opportunities.

RULE 104

IF the dry season is dry

THEN Minnow numbers decrease by one level (state)

Author Dez Weeks

Explanation

The volume of habitat and cover available are greatly reduced. Predation increases on the non-breeding parent and juvenile minnow populations which are concentrated in the remaining habitats.

RULE 105

IF the dry season is normal

THEN Minnow numbers decrease by one level.

Author Dez Weeks

Explanation

Although low, the river is not abnormally so for this time of year. Predation outweighs recruitment in the non-breeding minnow populations which are concentrated in the remaining habitats.

RULE 106

IF the dry season is wet

THEN Minnow numbers are unchanged

Author Dez Weeks
Explanation

Extended or aseasonal rain events make more habitat available to the emerging young-of-the-year (YOY) allowing for better recruitment as well as extending the breeding season if elevated flow occur in the warmer months.

200 - Series of Rules for Minnows

RULE 201

IF the wet season is dry

THEN Cichlid numbers increase by one level (state)

Author: Dez Weeks

Explanation

Shallow, slow flowing habitats are increased by lower flows while the reduction/absence of freshettes allows the nest building cichlids undisturbed breeding opportunities. The warm but sluggish flows of a failed wet season greatly benefit breeding in all three important cichlids.

RULE 202

IF the wet season is normal

THEN Cichlid numbers decrease by one level (state)

Author: Dez Weeks

Explanation

Typically cichlids dominate the Lowveld assemblage prior to the summer rains. Early breeding success having been made possible by the warm but still slow-flowing and shallow character of much of the river. The arrival of the first rains prevent further population changes, with freshettes scouring many nests and juveniles and the remaining adults being confined to more limited quiet or backwater habitats.

RULE 203

IF the wet season is wet

THEN Cichlid numbers decrease by two levels (state)

Author Dez Weeks

Explanation

Typically cichlids dominate the Lowveld assemblage prior to the summer rains. Early breeding success having been made possible by the warm but still slow-flowing and shallow character of much of the river. The more numerous freshettes and high flows scours many nests and juveniles and the remaining adults being confined to more limited quiet or backwater habitats.

RULE 204

IF the dry season is dry

AND it follows a failed wet season

THEN Cichlid numbers increase by two levels (states)

Author Dez Weeks

Explanation

Progressive drought conditions with low base flows, and higher water temperatures extends the dry season breeding period of cichlids even further. Under extreme drought conditions and the formation off mostly pool habitats, Tilapia rendalli numbers start to reduce while Oreochromis mossambicus starts to breed explosively although now stunted in size. In the worst of conditions, O.mossambicus is singularly dominant.

RULE 205

IF the dry season is dry

AND it follows a wet or normal wet season

THEN Cichlid numbers increase by one level (state)

Author Dez Weeks

Explanation

Following a normal wet season, a normal dry season results in stable base-flows. By early summer with the warming of the river and prior to the rains cichlids take the opportunity to build their breeding nests in the abundant placid and shallow habitats.

RULE 206

IF the dry season is normal

THEN Cichlid numbers are unchanged.

Author Dez Weeks

Explanation

Although low, the river flows stronger than it usually does in the dry season with placid shallow habitats more limited and the effects of aseasonal early or late rains disruptive on the nest building cichli

RULE 207

IF the dry season is wet

THEN Cichlid numbers decrease by one level

Author Dez Weeks

Explanation

Although low, the river flows stronger than it usually does in the dry season with placid shallow habitats more limited and the effects of aseasonal early or late rains disruptive on the nest building cichli

300 - Series of Rules for Mudfish

RULE 301

IF the wet season is dry

THEN Mudfish numbers are unchanged

Author: Dez Weeks

Explanation

The large Labeo molybdinus adults require deep habitats while the juveniles need the substrate and cover provided by riffles. Both the absence of freshettes essential to trigger spawning, and the reduction of deep and riffle habitat limits breeding success.

RULE 302

IF the wet season is normal

THEN Mudfish numbers increase by one level(state)

Author: Dez Weeks

Explanation

With the occurrence of summer freshettes, spawning of the large L.molybdinus takes place out of the deeper pools to which they are normally confined. Later in the wet season, many YOY appear in riffle areas. L.molybdinus can attain breeding condition during drought conditions enabling them to exploit the first freshettes of the season.

RULE 303

IF the wet season is wet

THEN Mudfishnumbers increase by two levels (state)

Author Dez Weeks

Explanation

The increase in summer freshettes, particularly the passage of large flows, triggers massive spawning of L.molybdinus. Because of their large size and many small eggs shed, their potential for recovery following floods is marked. YOY are particularly numerous in shallow riffle habitats after good rains.

RULE 304

IF the dry season is dry

THEN Mudfishnumbers are unchanged

Author Dez Weeks

Explanation

As little/no breeding has taken place in the preceding failed wet season, the population recorded are mostly older or remnant fishes which are tolerant of the low-flow conditions, persisting in the deepest of pools or in loose substrate in flow.

RULE 305

IF the dry season is normal

THEN Mudfish numbers decrease by one level.

Author Dez Weeks

Explanation

Mudfishes decline from the elevated numbers seen after the preceding normal wet season. The many YOY found in shallow riffle habitat are reduced by the falling water levels and slower flows.

RULE 306

IF the dry season is wet

THEN Mudfish numbers are unchanged

Author Dez Weeks

Explanation

Although no breeding is expected, the population gains seen in the preceding wet season are not reduced as is typical of the dry season. This is due to higher flows and deeper flow habitat available and more YOY recruiting into the subadult populations.

400 - Series of Rules for Yellowfish

RULE 401

IF the wet season is dry

THEN Yellowfish numbers are unchanged

Author: Dez Weeks

Explanation

The large Barbus marequensis adults require deeper runs while the juveniles need the substrate and cover provided by riffles. Both the absence of freshettes essential to trigger spawning, and the reduction of deep and riffle habitat limits breeding success.

RULE 402

IF the wet season is normal

THEN Yellowfish numbers increase by one level (state)

Author: Dez Weeks

Explanation

With the occurrence of summer freshettes, spawning of the large-scaled yellowfish takes place. Later in the wet season, many YOY appear in the riffles.

RULE 403

IF the wet season is wet

THEN Yellowfishnumbers increase by one level (state)

Author Dez Weeks

Explanation

The increase in summer freshettes, particularly the passage of large flows, favours good spawning of B.marequensis. Because of their large size and many small eggs shed, their potential for recovery following floods is marked. YOY are numerous in shallow riffle habitats after good rains.

RULE 404

IF the dry season is dry

THEN Yellowfishnumbers are unchanged

Author Dez Weeks

Explanation

As little/no breeding has taken place in the preceding failed wet season, the population recorded are mostly older or remnant fishes which are tolerant of the low-flow conditions, persisting in the deep runs or in loose substrate in flow.

RULE 405

IF the dry season is normal

THEN Yellowfish numbers decrease by one level.

Author Dez Weeks

Explanation

Yellowfish decline from the elevated numbers seen after the preceding normal wet season. The many YOY found in shallow riffle habitat are reduced by the falling water levels and slower flows.

RULE 406

IF the dry season is wet

THEN Yellowfish numbers are unchanged

Author Dez Weeks

Explanation

Although no breeding is expected, the population gains seen in the preceding wet season are not reduced as is typical of the dry season. This is due to higher flows and deeper flow habitat available and more YOY recruiting into the sub-adult populations.

500 - *Series of Rules for Catfish*

RULE 501

IF the wet season is dry

THEN Catfish numbers decrease by one level

Author: Dez Weeks

Explanation

Chiloglanis anoterus is one of the few Lowveld species that is not resilient to drought. The species is most numerous in the cooler FHZ of the Sabie catchment although viable populations are found in Lowveld lose-substrate riffles were they occur. They are reduced in number should the wet season fail possibly due to the much warmer water temperatures experienced with summer drought flows, compounded by poorer oxygen regimes.

RULE 502

IF the wet season is normal

THEN Catfish numbers increase by one level (state)

Author: Dez Weeks

Explanation

C. anoterus utilises the relatively cool increased flows of the wet season when riffle habitat is deeper and flow velocity high. Parents care for a few large eggs and reproduction is expected to be slow. There number are expected to remain fairly static.

RULE 503

IF the wet season is wet

THEN Catfish numbers increase by one level (state)

Author Dez Weeks

Explanation

The added riffle habitat and the high flows available for a longer period enables C.anoterus to increase its numbers.

RULE 504

IF the dry season is dry

THEN Catfish numbers decrease by one level

Author Dez Weeks

Explanation

During drought low-flows, C. anoterus are concentrated into diminishing riffle habitat with deteriorating water quality. They are intolerant of warm, poorly oxygenated water and subsequent are reduced in numbers.

RULE 505

IF the dry season is normal

THEN Catfish numbers are unchanged.

Author Dez Weeks

Explanation

The YOY found surrounding riffles habitats following a normal to wet wet season are recruited into the riffle. Both adults and juveniles are concentrated but persist as long as low-flows are not extreme.

RULE 506

IF the dry season is wet

THEN Catfish numbers are unchanged

Author Dez Weeks

Explanation

A wet dry season, favours C.anoterus as they prefer higher flows. Although both juveniles and adults are benefited, they do not increase in number as they are not known to breed in the winter months.

APPENDIX VI - Rules for the riparian vegetation model.

Rules for the Breonadia salicina vegetation type:

IF the CBBI geomorphic state is 1, OR the MCB geomorphic state is 1, 2, or 5, OR the UBAI geomorphic state is 1 or 2,

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the B. salicina vegetation type occur in association with geomorphological units that are predominantly bedrock and associated with the active channel. Where the proportion of bedrock is very low or far from the active channel these species will not occur.

IF the BO geomorphic state is 1 or 2, OR the CBAI geomorphic state is 1, 2, 3, 4 or 5, OR the CBBI geomorphic state is 2, OR the MCB geomorphic state is 3 or 4,

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the B. salicina vegetation type occur in association with geomorphological units that are predominantly bedrock and associated with the active channel. Where the proportion of bedrock is low or far from the active channel, or where the proportion of alluvia is very high, these species will be uncommon and not in significant numbers.

IF the BO geomorphic state is 3 or 4, OR the CBBI geomorphic state is 3 or 4, OR the UBAI geomorphic state is 3, 4 or 5,

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the B. salicina vegetation type occur in association with geomorphological units that are predominantly bedrock and associated with the active channel. Where bedrock outcrops and consolidated bars with bedrock influence occur in fairly high proportions, B. Salicina will mirror this situation in its abundance i.e. will be intermediate in occurrence. Where the proportion of unconsolidated bars is medium to high, it is assumed that there will also be some bedrock that influences their formation, and so B. salicina will also occur there with an intermediate abundance.

IF the BO geomorphic state is 5, OR the CBBI geomorphic state is 5,

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the B. salicina vegetation type occur in association with geomorphological units that are predominantly bedrock and associated with the active channel. Where bedrock outcrops and consolidated bars with bedrock influence occur in large proportions, B. salicina will therefore be abundant in occurrence.

Rules for the Combretum erythrophyllum vegetation type:

IF the BO geomorphic state is 1 to 5, OR the CBAI geomorphic state is 1, OR the CBBI geomorphic state is 1, OR the MB geomorphic state is 1 or 2, OR the UBAI geomorphic state is 1 or 2

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the C.erythrophyllum vegetation type occur in association with geomorphological units that are predominantly alluvial and consolidated in nature, and are associated with mainly seasonal hydrological influence. This vegetation type will therefore not be present on bedrock outcrop because this substrate does not support its prevalence. It will also not occur at sites that are annually influenced by hydrology such as where consolidated and unconsolidated bars occur in low proportions close to the active channel.

IF the CBBI geomorphic state is 2 or 3, OR the MB geomorphic state is 3, 4 or 5, OR the UBAI geomorphic state is 3, 4 or 5

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the C. erythrophyllum vegetation type occur in association with geomorphological units that are predominantly alluvial and consolidated in nature, and are associated with mainly seasonal hydrological influence. As consolidated and unconsolidated bars increase to medium and high proportions respectively, so this vegetation type will begin to appear, but will be uncommon. Where there are large proportions of the macro channel bank, this vegetation type can also occur there, but will never be common.

IF the CBAI geomorphic state is 2, OR the CBBI geomorphic state is 4 or 5

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the C. erythrophyllum vegetation type occur in association with geomorphological units that are predominantly alluvial and consolidated in nature, and are associated with mainly seasonal hydrological influence. As consolidated bars with alluvial influence increase, the C. erythrophyllum vegetation type will respond accordingly by becoming intermediate because this is the preferred substratum. Where consolidated

bars with bedrock influence occur in high proportions, there will be enough consolidated alluvial substratum to support intermediate levels of this vegetation type.

IF the CBAI geomorphic state is 3, 4 or 5

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the C. erythrophyllum vegetation type occur in association with geomorphological units that are predominantly alluvial and consolidated in nature, and are associated with mainly seasonal hydrological influence. As consolidated bars with alluvial influence increase to medium or high proportions, the C. erythrophyllum vegetation type will become abundant as preferred substrate and temporal hydrological influence are met.

Rules for the Phragmites mauritianus vegetation type:

IF the BO geomorphic state is 1 or 2, OR the CBAI geomorphic state is 1, OR the CBBI geomorphic state is 1 or 2, OR the MB geomorphic state is 1, 2 or 5

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the P. mauritianus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly annual and seasonal hydrological influence. Species in the P. mauritianus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is ephemeral. This vegetation type is also not present where bars occur in low proportions, because such situations do not generally confer stability to flood resistance (being a reed vegetation type).

IF the BO geomorphic state is 3, 4 or 5, OR the CBAI geomorphic state is 2, OR the CBBI geomorphic state is 3 or 5, OR the MB geomorphic state is 3 or 4, OR the UBAI geomorphic state is 1, 2 or 5

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the P. mauritianus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly annual and seasonal hydrological influence. Species in the P. mauritianus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is ephemeral. Where bedrock outcrop areas are large enough to trap some sediment, and where bars begin to increase in size and stability, this vegetation type will start to occur, but will be uncommon.

IF the CBAI geomorphic state is 3, OR the CBBI geomorphic state is 4, OR the UBAI geomorphic state is 3 or 4

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the P. mauritianus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly annual and seasonal hydrological influence. Species in the P. mauritianus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is ephemeral. Where bars, both consolidated and unconsolidated with either alluvial or bedrock influence begin to reach proportions that confer their stability to hydrological disturbance, this vegetation type will begin to colonise and will occur with an intermediate abundance.

IF the CBAI geomorphic state is 4 or 5

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the P. mauritianus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly annual and seasonal hydrological influence. Although consolidated bars with alluvial influence will be predominantly ephemerally influenced by hydrology when occurring in high proportions, access to ground water is sufficient to support this vegetation type. Added to this, the stability of these geomorphic features in high proportions facilitates annual colonization and rhizome layering in newly trapped sediments in established reed beds. Species in the P. mauritianus vegetation type will therefore be abundant where these bars occur in high proportions.

Rules for the Phyllanthus reticulatus vegetation type:

IF the BO geomorphic state is 1, OR the MB geomorphic state is 1 or 2, OR the UBAI geomorphic state is 1 or 2

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the P. reticulatus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly seasonal and to some extent ephemeral hydrological influence. Species in the P. reticulatus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is annual.

IF the BO geomorphic state is 2, OR the CBAI geomorphic state is 1, OR the CBBI geomorphic state is 1, OR the MB geomorphic state is 3, 4 or 5, OR the UBAI geomorphic state is 3

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the P. reticulatus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly seasonal and to some extent ephemeral hydrological influence. Species in the P. reticulatus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is annual, and will be uncommon where bars are small (unstable) or where the macro channel bank occurs in large proportions.

IF the BO geomorphic state is 3, 4 or 5, OR the CBAI geomorphic state is 2 or 3, OR the CBBI geomorphic state is 2 or 5, OR the UBAI geomorphic state is 4 or 5

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the P. reticulatus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly seasonal and to some extent ephemeral hydrological influence. Species in the P. reticulatus vegetation type do not generally occur where bedrock is largely exposed or hydrological influence is annual. As bars increase in size and stability this vegetation type will become intermediate in occurrence, or where bedrock outcrop is large enough in extent to trap sediments.

IF the CBAI geomorphic state is 4 or 5, OR the CBBI geomorphic state is 3 or 4

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the P. reticulatus vegetation type occur in association with geomorphological units that are mixed alluvial and bedrock in nature, that are also mainly consolidated, and are associated with mainly seasonal and to some extent ephemeral hydrological influence. Species in the P. reticulatus vegetation type will be abundant where consolidated bars occur in large proportions, both bedrock and alluvial in nature.

Rules for the Diospyros mespelliformes vegetation type:

IF the BO geomorphic state is 1 to 5, OR the CBAI geomorphic state is 1, OR the CBBI geomorphic state is 1, OR the UBAI geomorphic state is 1 or 2

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the D. mespelliformes vegetation type occur in association with the macro channel bank, and to a less extent with geomorphological units that are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require fine sediments or non-alluvial soils. Where bars are small and unstable, and annually influenced by hydrological influence, this vegetation type will not be present.

IF the CBAI geomorphic state is 2 or 3, OR CBBI geomorphic state is 2 or 3, OR the UBAI geomorphic state is 3, 4 or 5

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the D. mespelliformes vegetation type occur in association with the macro channel bank, and to a less extent with geomorphological units that are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require fine sediments or non-alluvial soils. If bars (any) are large enough to be stable, seasonally to ephemerally influenced by hydrology, or to have sufficient sediment the species of this vegetation type may colonise, but will be uncommon.

IF the CBAI geomorphic state is 4 or 5, OR the CBBI geomorphic state is 4 or 5, OR the MB geomorphic state is 1 or 2

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the D. mespelliformes vegetation type occur in association with the macro channel bank, and to a less extent with geomorphological units that are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require fine sediments or non-alluvial soils. As bars increase still in proportion and are stable or if the macro channel bank occurs in low proportions, then this vegetation type will increase in its occurrence and become intermediate.

IF MB geomorphic state is 3, 4 or 5

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the D. mespelliformes vegetation type occur in association with the macro channel bank, and to a less extent with geomorphological units that are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require fine sediments or non-alluvial soils. Where the proportion of the channel that is macro channel bank is medium or high, species of this vegetation type will be abundant.

Rules for the Spirostachys africana vegetation type:

IF the BO geomorphic state is 1 to 5, OR the CBAI geomorphic state is 1, 2 or 3, OR the UBAI geomorphic state is 1, 2, 4 or 5

THEN the vegetation state will be NOT PRESENT

Author: James Mackenzie

Explanation:
Species in the S. africana vegetation type occur predominantly in association with the macro channel bank and are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require mainly non-alluvial soils. They are not present on most bars (or all macro channel floor features), especially where the hydrological influence is annual or seasonal, and where sediments are too coarse or unstable (loosely packed).

IF the CBAI geomorphic state is 4 or 5, OR the CBBI geomorphic state is 1 to 5, OR the UBAI geomorphic state is 3

THEN the vegetation state will be UNCOMMON

Author: James Mackenzie

Explanation:
Species in the S. africana vegetation type occur predominantly in association with the macro channel bank and are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require mainly non-alluvial soils. They are not present on most bars (or all macro channel floor features), especially where the hydrological influence is annual or seasonal, and where sediments are too coarse or unstable (loosely packed). When bars are large enough or have bedrock influence that confers stability however, this vegetation type may colonise, but will be uncommon.

IF the MB geomorphic state is 1 or 2

THEN the vegetation state will be INTERMEDIATE

Author: James Mackenzie

Explanation:
Species in the S. africana vegetation type occur predominantly in association with the macro channel bank and are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require mainly non-alluvial soils. If the proportion of the macro channel bank is low this vegetation type will only occur in an intermediate state of abundance.

IF the MB geomorphic state is 3, 4 or 5

THEN the vegetation state will be ABUNDANT

Author: James Mackenzie

Explanation:
Species in the S. africana vegetation type occur predominantly in association with the macro channel bank and are ephemerally influenced by hydrological disturbance. They do not occur on exposed bedrock, but require mainly non-alluvial soils. If the proportion of the macro channel bank is low this vegetation type will only occur in an intermediate state of abundance, but as the proportion of macro channel bank increases to medium or high then this vegetation type will become abundant.

APPENDIX VII The frequency and mean basal area ($mm^2.m^{-2}$) of each species in each vegetation type (first and second columns of each vegetation type respectively). An entry of - denotes 0. (Taken from van Coller and Rogers, 1996).

Species	Phragmites mauritianus vegetation type		Phyllanthus reticulatus vegetation type		Breonadia salicina vegetation type		Combretum erythrophyllum vegetation type		Diospyros mespiliformes vegetation type		Spirostachys africana vegetation type		n
Phragmites mauritianus	1.00	2819.6	0.87	349.4	0.41	102.6	0.32	25.3	-	-	0.03	7.1	105
Securinega virosa	0.61	515.0	0.78	56.2	0.05	0.8	0.16	5.4	-	-	0.15	4.2	69
Ficus capreifolia	0.31	6.3	0.09	21.4	0.02	0.1	0.12	16.9	0.06	3.7	-	-	23
Vitex harveyana	0.02	0.2	0.30	19.5	0.09	2.4	-	-	-	-	0.03	0.6	16
Phyllanthus reticulatus	0.35	16.5	0.74	42.4	0.27	9.7	0.16	2.2	0.18	0.9	0.23	7.1	77
Combretum microphyllum	0.02	2.1	0.13	3.2	0.04	0.2	-	-	0.06	0.2	0.02	0.2	9
Maytenus senegalensis	0.41	52.2	0.87	138.2	0.39	43.5	0.72	88.8	0.65	37.8	0.51	74.0	136
Grewia flavescens	0.06	3.1	0.09	85.8	0.32	31.6	0.08	1.0	0.41	14.1	0.35	8.7	62
Antidesma venosum	-	-	0.30	38.7	0.21	30.4	0.08	2.6	-	-	0.03	2.4	24
Syzygium guineense	0.43	47.3	0.35	100.7	0.63	1159.2	0.16	75.9	0.06	73.9	-	-	70
Salix mucronata	0.04	1.1	-	-	0.09	5.0	-	-	-	-	-	-	7
Breonadia salicina	0.24	117.9	0.04	6.7	0.80	797.2	0.12	67.6	0.12	128.4	-	-	63

Nuxia oppositifola	0.22	133.7	0.17	132.0	0.39	192.3	0.32	253.1	0.12	89.4	-	-	47
Kruassia floribunda	0.02	0.1	0.09	0.1	0.36	21.9	0.28	18.0	0.12	4.6	0.05	1.5	36
Pavetta lanceolata	0.04	0.2	0.09	2.5	0.02	0.1	0.56	44.8	-	-	0.03	0.7	22
Ficus sycomorus	0.02	6.6	-	-	0.02	32.2	0.24	144.8	0.06	139.5	-	-	9
Combretum erythrophyllum	0.31	116.7	0.04	529.3	0.09	128.2	0.80	1940.2	0.06	25.6	0.02	6.0	45
Lantana camara	0.04	1.5	0.13	17.4	0.13	3.9	0.64	194.2	0.24	16.3	0.30	21.6	58
Trichilia emetica	0.06	27.0	0.04	0.9	0.02	197.5	0.24	121.1	0.24	169.1	0.02	58.9	17
Acacia robusta	0.06	5.6	0.13	47.1	0.29	35.6	0.52	73.6	0.71	230.3	0.26	67.4	69
Acacia schweinfurthii	-	-	0.04	2.0	-	-	0.04	0.5	0.12	3.2	0.03	1.0	7
Diospyros mespiliformes	0.02	1.6	0.35	27.8	0.23	94.8	0.48	52.1	0.82	831.6	0.24	81.2	69
Capparis tomentosa	-	-	-	-	0.02	1.2	0.04	0.4	0.18	17.6	0.01	0.5	6
Cassine aethiopica	-	-	-	-	0.02	1.4	-	-	0.24	28.1	-	-	6
Terminalia sericia	-	-	-	-	-	-	-	-	0.12	4.5	0.06	3.2	8
Rhus pyroides	-	-	-	-	0.04	0.1	0.04	18.3	-	-	0.09	19.9	12
Ochna natalitia	0.02	0.2	-	-	0.07	4.5	0.08	0.4	0.35	7.2	0.15	11.2	26
Euclea natalensis	0.02	0.1	0.09	6.9	0.09	8.1	0.16	1.7	0.76	14.8	0.38	15.7	58
Rhus gueinzii	-	-	0.04	2.6	-	-	-	-	0.18	7.9	0.05	3.9	8
Sideroxylon inerme	-	-	-	-	0.04	0.4	-	-	0.24	37.3	0.06	9.2	11
Schotia brachypetala	-	-	-	-	-	-	-	-	0.12	129.7	0.03	1.0	6

Grewia hexamita	-	-	-	-	-	-	-	-	0.18	2.5	0.03	0.3	6
Euclea divinorum	-	-	-	-	-	-	0.08	-	0.18	17.5	0.08	13.6	12
Vangueria infausta	-	-	-	-	-	-	-	-	0.06	5.1	0.06	1.9	6
Sclerocarya birrea	-	-	-	-	-	-	-	-	0.06	0.9	0.15	129.6	14
Lippia javanica	-	-	-	-	0.04	1.4	-	-	-	-	0.29	4.3	27
Strychnos spinosa	-	-	-	-	-	-	-	-	0.06	6.0	0.14	20.4	13
Strychnos madagasceriensis	-	-	-	-	-	-	-	-	0.12	10.8	0.06	15.1	7
Ehretia amoena	-	-	-	-	-	-	-	-	0.06	4.2	0.10	1.8	10
Dalbergia melanoxylon	-	-	0.04	1.9	0.02	0.7	-	-	-	-	0.09	3.7	10
Ziziphus mucronata	0.02	1.8	-	-	0.04	1.8	-	-	0.12	0.4	0.27	30.4	28
Gardenia volkensii	-	-	-	-	-	-	-	-	0.12	0.4	0.15	7.7	15
Dichrostachys cinerea	0.12	5.5	0.04	0.1	0.04	0.1	0.12	5.5	0.47	19.6	0.65	90.1	76
Combretum imberbe	-	-	-	-	-	-	0.04	2.0	0.06	260.2	0.09	55.7	10
Combretum apiculatum	-	-	-	-	-	-	-	-	-	-	0.10	2.9	9
Lonchocarpus capassa	0.02	2.9	0.04	4.5	0.04	4.8	0.04	7.8	0.06	0.6	0.31	81.0	33
Acacia tortilis	-	-	-	-	-	-	0.04	5.1	-	-	0.07	4.5	7
Acacia nilotica	-	-	-	-	-	-	-	-	-	-	0.07	5.3	7
Acacia nigrescens	-	-	-	-	-	-	0.04	5.1	0.12	39.7	0.19	38.9	19
Peltophorum africana	-	-	0.04	7.8	0.02	0.1	0.04	1.3	0.06	16.6	0.09	33.5	12

Albizia forbesii	-	-	-	-	-	-	-	-	0.06	3.0	0.07	44.8	7
Spirostachys africana	-	-	-	-	-	-	0.04	4.2	0.24	50.3	0.30	217.6	31
Ptaeroxylon obliquum	-	-	-	-	-	-	-	-	-	-	0.10	14.1	10
Grewia bicolor	-	-	-	-	0.02	0.2	-	-	0.06	0.8	0.29	17.6	27
Combretum hereroense	0.02	3.0	-	-	-	-	-	-	0.06	8.0	0.15	32.1	15
Commiphora glaucescens	-	-	-	-	-	-	-	-	-	-	0.07	1.8	6
Acalypha glabrata	-	-	-	-	-	-	0.12	25.1	-	-	0.05	20.9	7